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# Energy security and climate change mitigation: The interaction in long-term global scenarios

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# General abbreviations

BP: British Petroleum

CCS: carbon capture and storage

CP: climate policy

ECN: Energy Research Center of the Netherlands

FAR: IPCC First Assessment Report

GARP: Global Atmospheric Research Programme

GHG: greenhouse gases

HHI: Herfindahl-Hirschmann Index

IAM: Integrated Assessment Model

IEA: International Energy Agency

ICSU: International Council of Scientific Unions

IIASA: International Institute for Applied Systems Analysis

IPCC: Intergovernmental Panel on Climate Change

MOSES: Model Of Short-term Energy Security

OPEC: Organization of Petroleum Exporting Countries

ppm: parts per million

PURPA: U.S. Public Utility Regulatory Policies Act

RES: renewable energy sources

SAR: IPCC Second Assessment Report

SOS: security of supply

SWDI: Shannon-Wiener Diversity Index

TPES: Total primary energy supply

UNEP: United Nations Environment Programme

WMO: World Meteorological Organization

# Model and project abbreviations

GCAM: Global Change Assessment Model

GEA: Global Energy Assessment

IMAGE: Integrated Model to Assess the Global Environment

LIMITS: Low climate IMpact scenarios and the Implications of required Tight emission control Strategies

MESSAGE: Model for Energy Supply Strategy Alternatives and the General Environmental Impact

ReMIND: Regional Model of Investments and Development

RoSE: Roadmap to Sustainable Energy

TIAM-ECN: TIMES Integrated Assessment Model Energy Centre of the Netherlands

WITCH: World Induced Technical Change Hybrid model

# Abbreviations in scenario names

450: stabilizing atmospheric concentration to 450 ppm $CO_2$-equivalent in GEA, LIMITS, and ROSE

550: stabilizing GHG atmospheric concentration to 450 ppm $CO_2$-equivalent in ROSE

ATR: advanced transport in GEA

BAU: business as usual (no climate policies) in ROSE

CCS: carbon capture and storage in GEA

CTR: conventional transport in GEA

DEF: default median economic growth rate in ROSE

FsGr-R: fast economic growth rate in ROSE

HI Fs-R: high fossil resource availability in ROSE

limitBE: limited bioenergy in GEA

limitRES: limited renewable energy sources in GEA

LO Fs-R: low fossil resource availability in ROSE

LO oil: low oil availability in ROSE

MOD: moderate policy (national climate policies without global stablization) scenario in ROSE

noBCCS: no bioenergy carbon capture and storage in GEA

noNUC: phase out of nuclear energy in GEA

SlGr-R: slow economic growth in ROSE

StrPol-L: stringent policies (national climate policies without global stablization) in LIMITS

# Abstract

The connection between climate mitigation and energy security is crucial for linking the global problem of climate change to national energy interests but is far from trivial. While energy security is an immediate concern of ensuring general stability of energy systems, climate change mitigation is a long-term issue requiring massive transformations. Moreover, while energy security emerged as a policy problem which only recently drew scholarly attention, climate change emerged as a scientific curiosity and only recently entered the policy arena. These different realities result in a gap between energy security and climate change research.

This thesis contributes to bridging this gap by analyzing energy security in 70 global scenarios from six integrated assessment models. I develop an energy security assessment framework which is generic enough to be relevant under radically different energy systems yet rooted in historic energy security concerns. The framework introduces the concept of vital energy systems and three perspectives on energy security: sovereignty, robustness and resilience. I use 31 indicators to test the effect of different climate policies on energy security under different assumptions of economic growth, fossil fuel availability and technological choices.

I find that stabilizing the greenhouse gas concentration at 450 ppm $CO_2$-eq. leads to a reduction in global energy trade by 20%–70% by 2050 and 50%–85% by 2100 compared to the baseline. Oil extraction drops from a maximum of 100% of proven reserves and resources in the baseline to 50% under climate policies. Fossil resource availability and GDP growth affect energy trade in the baseline but not in climate stabilization scenarios. Climate policies lead to an increase in diversity of energy options in electricity generation and transportation. There are certain qualifications to these energy security gains depending on technological choices and time horizons analyzed.

Climate policies lead to lower imports and higher energy diversity in the E.U., China and India. However, for the U.S. and traditional energy exporters, climate stabilization would likely cause a loss of energy exports which could significantly affect the geopolitics of climate negotiations.

**Keywords:** energy security, climate change, energy scenarios

# Acknowledgements

Almost a decade ago, when I was finishing my Bachelor's degree, a PhD student told me that doctoral studies are like a journey to a deep coal mine with only a toothpick as a tool. In undergraduate and even Masters' education, we travel well-trodden paths with our professors shining the torch on where to go and how to get there. In a PhD this all changes. And we are left at the bottom of a deep hole with a toothpick, ourselves, and the occasional passer-by with some pointers and if we're lucky a bit of encouragement.

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# Chapter 1

# Introduction

Energy security and climate change are the two largest challenges facing energy policy-makers. Reliable energy services are integral to economic growth, national security, and political stability. At the same time, without a massive de-carbonization of energy systems, society could face tremendous social and environmental risks from climate change. The academic community often advises policy makers that these two challenges need to be addressed both simultaneously and immediately (GEA 2012). Any national policy addressing climate change will only be enacted and implemented if it does not jeopardize the energy security of that nation. This means that the acceptability of a global climate regime will depend in part on its impacts on energy security. Understanding such impacts is thus key to designing effective climate mitigation policies.

Despite the seemingly abundant literature on both climate change and energy security, there is surprisingly little systematic scholarly investigation of the interaction between these two topics. Many scholars repeat (or encourage) political rhetoric which, at least in the West, either uncritically portrays climate mitigation and energy security policies as 'co-benefiting' each other or even lumps them together as part of a single problem (e.g. in the widely used notion of 'sustainable energy systems' or in the idea that energy security has an 'environmental dimension').

## 1.1 Complementary or competing challenges?

However, even presenting energy security and climate mitigation as a single problem does not negate the fact that there are few, if any, natural complementarities between these two challenges. Energy security is an urgent and immediate driver of energy policies that scientists nevertheless often view as ‘slippery’ or ‘fuzzy’ (Chester 2009). Failure to address energy security can result in tangible consequences today, tomorrow or next month, i.e. when a policy maker is still in office. The overall priority for energy security, often supported by strong political and economic interests, is stability (or predictable expansion) of energy systems. In contrast, climate change is crisply defined by scientists but is less understood by and less relevant to immediate concerns of the majority of policy makers. The consequences of climate change will impact ‘future generations’ rather than the current electorates (Wunsch, Schmitt, and Baker 2013). Addressing climate change requires profound transformation, rather than stabilization, of energy systems and thus is rarely supported by vested political and economic interests. Thus, the relationship between climate change and energy security is both extremely important and far from trivial.

## 1.2 Difficulties of connecting energy security and climate change mitigation

This thesis aims to contribute to a more rigorous and systematic understanding of the interaction between climate change and energy security. The first challenge which I face is that, as already mentioned, energy security is a fuzzy political concept whose meaning depends on its context (Chester 2009; Cherp and Jewell 2011a). This fuzziness means that it is often used as part of political rhetoric to advance different agendas. Paul Joskow, an economist and scholar on energy issues with over four decades of experience observed that:

> There is one thing that has not changed since the early 1970s. If you cannot think of a reasoned rationale for some policy based on standard economic reasoning then argue that the policy is necessary to promote ‘energy security’.(Joskow 2009, 7)

As a result, marginal energy issues are often co-opted into the energy security agenda. For example, in a recent article, Sovacool (Sovacool 2011b, 7476–7477) proposes 21 dimensions of energy security and over 320 indicators ranging from "energy literacy of users" to the "Transparency International corruption perception index". But surely there are boundaries for energy security. My thesis shows one way that such boundaries can be drawn in an academically rigorous way in order to support credible conceptualization and assessment of energy security.

Another challenge is that energy security and climate change are dealt with in different epistemic communities which have different relationships with the relevant policy arenas. Energy security emerged as a policy problem before the first World War when the British navy switched from domestic coal to imported foreign oil (Yergin 1991, 2006) and thus has strong roots in international relations, conventional military security, and political science (Klare 2002). Since then, it has been expanded to encompass concerns about critical infrastructure (Amin 2002; Farrell, Zerriffi, and Dowlatabadi 2006) and resource scarcity (Meadows et al. 1972) with roots in engineering and natural sciences. During the 1990s it also embraced ideas about market dynamics (Helm 2002) and resilience (Stirling 1994) from economics and complex systems theory.

In contrast, climate change emerged as a scientific possibility at the turn of the last century when Svante Arrhenius, a Swedish scientist, calculated the theoretical warming which could result in doubling the $CO_2$ in the atmosphere and only became framed as a policy problem at the end of the 20th century. The climate change epistemic community is still dominated by natural scientists with a recent infusion of engineering and economic thought. Thus, the development of real-life energy security concerns was formative to how energy security has been conceptualized and studied; for climate change, the formative arrow runs the other way: the development of climate change science led to a formulation of the policy-problem of how to decrease greenhouse gas emissions. As a result of these distinct evolutions combined with the specific nature of each problem, energy security and climate change studies have different scholarly traditions. My thesis contrasts these traditions to show where and how they can connect to enrich each other.

## 1.3 Dealing with these difficulties

In the Literature Review and the Methodology chapters I explain how I overcome these two challenges: the fuzzy nature of energy security and the difference between the energy security and climate change scholarly traditions. In order to deal with the fuzzy nature of energy security, I conceptualize it based on an historic analysis and the identification of relatively timeless themes (Cherp and Jewell 2011b). To quantify these concerns, I draw on the burgeoning literature on energy security indicators.

One of the key findings from the historic analysis is that energy security concerns have always been associated with "vital energy systems". Thus I define energy security as a "low vulnerability of vital energy systems". This is one of the most generic definitions since the energy security concerns which I am interested in exploring (those which may evolve under a radical energy transformation over the next 100 years) have a high degree of uncertainty. Another key aspect of my analysis is that I apply the indicators to a set of energy subsystems in order to track both how existing concerns evolve but also whether new concerns could emerge. Thus, I develop an approach to conceptualizing and assessing energy security for energy systems whose configurations may be radically different from the present in a way that is still relevant and rooted in major policy concerns.

I address the second challenge by identifying Integrated Assessment Models (IAMs) as a bridge between the scientific problem of climate change and the concrete reality of the energy system. During my thesis I worked with the IAM community to quantitatively characterize a set of energy futures—both in business-as-usual and climate policy scenarios[1]—under economic, resource, and technological constraints. At the heart of my thesis is the quantitative analysis of energy security in some 70 scenarios of energy futures in the 21st century generated by six leading IAMs.

1. In this thesis "climate policies" refers to both climate stabilization through a global carbon tax regime and relatively short-term national targets which countries pledged in Copenhagen during the last Conference of the Parties such as increasing renewable energy or energy efficiency.

## 1.4 Research questions and thesis structure

The main research question is: **how would climate mitigation policies affect energy security?** This overarching question is broken into several subquestions:

- **A.** under different climate stabilization targets;
- **B.** under different GDP growth and fossil fuel availability assumptions;
- **C.** under different technological limitations;
- **D.** in major economies; and
- **E.** with respect to energy export revenues.

This introductory chapter is followed by a Literature Review examining the origins of these questions and the previous approaches to answering them. The next chapter explains the Methodology which contains both a theoretical framework for conceptualizing energy security, a framework for assessing energy security under Integrated Assessment Models, a description of the study design and its limitations. The following Results chapter is structured according to energy security concerns, and a Discussion chapter contains more explicit answers to the research question as well as the sensitivity of these answers to sub-questions. The last chapter contains a Summary and Conclusion of the thesis and its contributions as well as an agenda for further research.

# Chapter 2

# Literature review

An extensive scholarly literature addresses climate change and an almost equally large amount of research deals with energy security. Energy security studies can range from conventional (military) security analysis to grid engineering reports. Similarly, climate change literature covers issues as diverse as energy system futures and glacial retreats. The focus of my literature review is to look at both climate change and energy security as *energy policy problems*. This chapter is structured as follows. I start with an intellectual history of energy security from its beginnings with oil and geopolitics to the "new" energy security of an increasingly interconnected and complex world. I then discuss the literature on conceptualizing and measuring energy security from the past ten years. For climate change I describe how it went from a scientific question to a policy problem and I explain how scenarios generated by Integrated Assessment Models have become one of the main tools to frame this problem. I conclude with a discussion of the existing literature on the interaction between climate change and energy security while also pointing out the gaps in the literature which my thesis addresses.



## 2.1 Energy security: from geopolitics to complexity

Energy security concerns have always been a major driver of energy policy. This section traces the development of energy security as a policy problem from the importance of *oil* security during the two World Wars to the *new* *energy security landscape* which has emerged since the turn of the century. This story is cumulative in nature. New concerns do not replace old ones but rather add to them. This cumulative history has led to fuzzy boundaries of energy security and confusion among scholars about what it means. Nevertheless, the historical narrative is clarifying both in how energy security concerns have changed over the last century and what the concept might mean in the future.

### 2.1.1 War and the geopolitics of oil

According to Daniel Yergin, the father of modern energy security studies, energy emerged as a national security issue in the early 20th century when Winston Churchill switched the Royal Navy from domestic coal to imported oil (Yergin 2006, 69). This very evolution can tell us something about energy security, both as a policy area and as an academic discussion: it revolves around vital energy systems and their vulnerabilities. In World War I, the vital energy system which Churchill was concerned with was the supply of oil for the navy and the perceived vulnerability was exposure of oil wells to enemy attacks.

One key aspect to the importance of energy security in World War I was contemporary globalization which facilitated flows of financial capital and commodities between countries. Following World War I, globalization abated and fears grew that high financial flows had contributed to the first World War (Rowe 2005). Furthermore, during this time period, many industrialized economies were able to source oil and other energy resources from colonies. Without the intense international trade and economic growth, energy security also receded into the background between the wars. However, it was during this time that the first oil embargo was proposed for political means. When Italy invaded Ethiopia in 1935 the League of Nations threatened Mussolini with an embargo (Yergin 1991, 332). Mussolini managed to avoid an embargo through political maneuvering, however, the risk was not lost on him. In a conversation with Hitler, he said that if the oil embargo had gone ahead he would have had to "withdraw…within a week" which would have been an "incalculable disaster for me!" (332). Thus, even though the embargo didn't materialize, the threat of it emphasized the strategic importance of oil.

During World War II, oil's strategic importance only grew. When the War started in 1939, over half of Germany's oil was supplied by oil fields near Ploesti in Romania, which in 1940 after the Nazi-Soviet Pact became too close for comfort to Soviet troops (Yergin 1991, 334). Hitler told Mussolini, "the life of the Axis depends on those oilfields" (335) and it was this fact, combined with the desire to capture the Caucasian oil fields, which certainly went into the calculations to invade the Soviet Union (334). The control of oil resources was also central in the Pacific theater between the U.S. and Japan over the control of the Dutch East Indies (today Indonesia) (310–311).

Following World War II, energy security reemerged in public discourse particularly in Europe which did not have its own fossil fuel resources and could no longer source its fuels from colonies. The geography of oil trade had significantly shifted with the Middle East playing an increasingly larger role (Secretariat for the Economic Commission for Europe 1955, 3–4). However, save for high oil prices immediately following the war years (when the industry had to readjust itself) there was relative abundance of oil and confidence in its security (Yergin 1991, 409 & 499–518). In fact, the U.S. and Europe both switched a lot of its electricity and industrial activity from coal to oil since it was cheaper, cleaner and, ironically more secure, since it was not plagued by the coal miner's strikes (543–545) as well as "high prices and irregularities in supplies" (Industry Division of the Economic Commission for Europe 1954, 7). With the growth of the automobile in the post war decades and the importance of oil in electricity and industry, the fuel became central to economic growth and prosperity, not only for the mobility of armed forces as during the Wars.

The 1970s shook the confidence in the security of the oil market. The Arab oil embargo, which lasted from October of 1973 to March of 1974 strangled the world economy. The imposition of the "Arab oil weapon" threatened the "general wealth, well-being and power of numerous nation-states and peoples, but also, more specifically, their national defense and security" (Paust and Blaustein 1974, 439). The following fall, the International Energy Agency (IEA) was founded to provide a counterbalance to the power of the Organization of Petrol Exporting Countries (OPEC). The IEA facilitated the emergence of a liquid global oil market. The 1973 embargo as well as the following disruptions of oil supplies, such as from the Iranian

Revolution of 1979, also sparked an increase in energy modeling activities in government and academia. The Energy Modeling Forum, which would later become a focal point of Integrated Assessment Models (see page 42), was established in 1979 as a way to compare modeling results and challenges (Sweeney and Weyant 1979, 2). Additionally, oil importing countries began to replace oil with natural gas and nuclear power in electricity generation (International Energy Agency 2011) as well as promote more energy-efficient vehicles to minimize the impact of potential oil disruptions.

### 2.1.2 Peak oil and resource scarcity

Another prominent energy security concern has been resource scarcity. In the words of Daniel Yergin "in the background of [energy security] concerns—but not too far back—is the anxiety over whether there will be sufficient resources to meet the world's energy requirements in the decades ahead" (Yergin 2006, 70). Thomas Malthus was one of the earliest scholars to formulate a theory of scarcity. A contemporary of William Godwin and Jean-Jaques Rousseau, Malthus' early writings argued that populations grow in places and during times of abundance until the size of the population outstrips the available resources (Malthus 1798).[2] While Malthusian theories largely focused on the availability of land and food, they identified the main factors which may lead to disruptive scarcity: population (consumption) growth and limited resources.

A second early scholar to shape the field of resource scarcity was Harold Hotelling, an American economist and the father of resource economics. His seminal paper "The Economics of Exhaustible Resources" was published in 1931, about a decade after a period of anxiety over resource availability which ensued as a result of the roaring economic growth in the 1920s (Devarajan and Fisher 1981, 65). The paper was soon forgotten but rediscovered in the 1970s when concerns over scarcity came to the fore. In it he asks a series of questions about the optimal extraction for a specific mining company but also about how resource depletion relates to the public good and how it should be regulated (Hotelling 1931, 139).

2. Though in later writings he ultimately rejected this "scarcity theory" for a "surplus theory" which he developed and published in the early 1820s.

Marion King Hubbert published a seminal paper in 1956 applying the theory of scarcity to energy resources. He observed that once production reaches half of the reserves it becomes more difficult to produce and the rate of production declines. As a result the pattern of production "peaks" when about half of resources are used up. He predicted that the United States' crude oil production would peak between the 1965 and 1970 and the world's around 2000 (Hubbert 1956, 21–27). Hubbert was initially chastised for his theory and predictions, however when his prediction for the U.S. came true in 1970, there was a shift in thinking about resource availability and a fear about the future. Eventually Hubbert's insights gave rise to the peak oil theory (explained on page 19).

In the late 1960s and early 1970s with the advent of modern computers the first assessments of global resource scarcity were made. Before this period, the post WWII years had been dominated by the idea of divided worlds and systems: the free Western world and the communist world behind the iron curtain; the natural world and the human world. Thus these decades saw a shift in thinking towards seeing the planet as one interconnected system. One of the earliest quantitative scenarios based on this idea, the seminal *Limits to Growth*, was published in 1972. The report showed that the exponential growth of consumption could not continue forever given limited resources and the limited capacity of ecosystems to absorb waste and pollution. Economic growth would inevitably "peak" and be followed by a steep and disruptive decline (Meadows et al. 1972, 129–134). It's important to note that the peak and decline predicted in the *Limits to Growth* has nothing to do with the peak oil although similar systems factors may underlie it. Additionally, the *Limits* used one generic "resource" and did not specifically speak about any energy resources such as oil.



### 2.1.3 Markets

The establishment of a global oil market, with the IEA to support its functioning, shifted the discussion away from the "oil weapon" and towards various aspects of energy market operations. The discourse about energy markets cannot be discussed without discussing electricity. While in the first half of the 20th century, oil was integrally linked to national security, electricity was seen as integral to human progress. This section describes the history of regulation of electricity in the U.S. and the U.K. which were among the first countries to set up large electricity generation and transmission systems to subsequently deregulate these industries. As soon as electricity was introduced in the late 19th century, it captured the U.S. imagination and was predicted to fundamentally change the American way of life (Hirsh 1989, 28). As electric dreams became a reality, they changed everything from the factory floor to how domestic tasks were done at home. Once electricity became essential for supporting critical functions of modern society, it became a *vital energy system* and as a result, its security became a major state policy concern.

In the late 19th century, electricity companies were small and numerous. For example, in 1892 Chicago (the American birthplace of the electricity industry) had over 20 electricity companies in spite of the fact that only 5,000 people had electric lights (less than 1% of the one million plus population) (Hirsh 2002, 17). Up until the 1880s and 1890s, power stations were reciprocating steam engines which were highly inefficient and small. In 1884, the invention of the steam turbine changed the economics of electricity production. Steam turbines offered economies of scale and incentivized power producers to capture a larger piece of the market for much greater profits with marginally higher costs. Samuel Insull was one of the first to realize this in the United States when he acquired virtually all the power producers in Chicago (21), a city which would later give birth to the intellectual movement which challenged these integrated monopolies. Ultimately, Insull's moves led to cooperation between the electricity companies and the regulators. This ushered in the creation of public service commissions to oversee electricity utilities which was similar to how the biggest natural monopoly of the day, the railroad was regulated (21–24). A similar process of consolidation happened in England (though several decades later) with the Electricity Act of 1947 which consolidated over 500 electricity generation and distribution companies and brought them under state control.

Following consolidation, electricity was generally seen as a "natural monopoly" through much of the 20th century. Electricity companies, it was believed, were most efficient when they could take advantage of economies of scale, and due to their position needed specific regulation (Posner 1969). After World War II with privately-owned vertically-integrated monopolies in the U.S. and most of Europe, the customer bore the risk of investments (Helm

2002, 176). In exchange, regulation limited rates of return to prevent large electricity monopolies from abusing their power. Hirsh describes legislation in the United States as "reinforcing the truth that electricity companies were natural monopolies" (Hirsh 1999, 30). The discourse on natural monopolies dominated legislation and academic discourse until 1970.

The theory of natural monopolies was challenged in the 1970s with the birth of the Chicago school. Alfred Kahn, an economics professor and later federal regulator was one of the first to question why natural monopolies exist and to suggest that there may be a continuum between monopolies and free market competition where the two can coexist (Kahn 1970). In 1971, George Stigler, a leading thinker at the Chicago school of economics, published a seminal article explaining how industry and other special interest groups influence regulation to be beneficial to them (Stigler 1971). Thus began a dialogue lasting through the 1970s and 1980s questioning the role of regulation in protecting the public versus private interests and mapping winners and losers in different groups (Peltzman 1976). This dialogue marked a a distinct departure from the pre–1970 era and opened the doors for de-regulation and privatization of electricity and other energy industries.

While the ideas of market reform came from the U.S., it was on the other side of the Atlantic in the United Kingdom where a power system would first be de-regulated, partially as a result of threats to security of electricity supply. When Margaret Thatcher came into power in 1979 the biggest energy security threat was coal-miner strikes. At this time, most of the U.K.'s electricity was produced from coal and the nationalized industry was "peculiarly vulnerable to union power, vested interests, capture and poor management" (Helm 2002, 175). Thus, to dissipate their power, she led market reform for gas to compete with coal in the market place. At around the same time, the Public Utility Regulatory Policies Act (PURPA) passed in 1978 in the U.S. The act set the stage for the unraveling of electricity monopolies by allowing for independent power producers (Hirsh 1999, 71). Twelve years later, in 1992, the Energy Policy Act ordered electricity transmission and distribution monopolies carry these independent power producers.

Coinciding with the shift to liberalized electricity markets (and alternative sources) was a drop in demand and an increase in supply of oil (Yergin 1991, 717). The recession of the early 1980s suppressed demand in the industrialized world and also the debt-laden developing countries who had to survive higher interest rates. At the same time, new oil production came online in Egypt, Malaysia, Angola and China while the OECD saw developments in the North Sea, Mexico, Alaska and even the lower 48 states. Thus, while the 1970s had been dominated by fears of consumers having access to oil, the 1980s were years of "abundant energy" (Helm 2002, 174). These market fundamentals meant that the name of the game was to be competitive in a glutted market (Yergin 1991, 721).

Adding to these pressures was an increase in resource nationalism in exporting countries. Up until this point, international oil companies ushered their own crude through the entire chain of production: from extracting the reserves in particular countries to refining and finally selling it at company-owned petrol stations.[3] During this time, spot markets saw less than 10% of internationally traded oil (722). However, after exporting countries nationalized oil reserves, international oil companies were forced to find a new raison d'être. No longer able to rely on crude oil from fields they owned, companies began to buy and sell on the spot market such that by 1982 the crude oil spot market had grown to half of all oil traded.

The market ideology is also evidenced in policy interventions. The establishment of the IEA ensured that if there were another oil embargo (such as the Arab oil embargo in 1973), there would be enough strategic reserves to ensure the continuity of market supplies. Additionally, the IEA's influence on the oil market, would go beyond its formal mandate. Leading up to the Iran-Iraq war in 1979, oil markets spiraled into a panic as two of the main oil producers teetered on the brink of war (712). However, when war finally broke out in 1980, governments, working within the IEA framework were able to convince oil companies to draw down stocks rather than push the market into another upward spiral (711). The IEA has repeated the same approach several times.



3. See for example George Keller, the chairman of Chevron who was quoted in Yergin: "The concept I was taught was that you moved your own crude through your own refining and downstream system...It was so obvious that it was a truism." (Yergin 1991, 723).

### 2.1.4 Small is beautiful: the resilience of energy systems

The transition to a market ideology in energy policy in the 1970s and the 1980s was based on the argument that markets would by and large ensure energy security. A tandem discourse emerged in the early 1980s about energy security which was consistent with the market discourse. The argument was that for too long energy security professionals and policy makers have focused on threats rather than diminishing the damage done by disruptions. Three books were published in the United States in 1981 and 1982 that focused on what today would be called the "resilience" of energy systems, or their ability to respond to disruptions.

*Energy and Security* which, in spite of its title, deals almost exclusively with oil (Deese and Nye 1981). It argues that the United States focuses too much on decreasing oil imports and not enough on increasing the country's ability to cope with a disruption in oil supplies. The authors largely focus on short-term shocks and argue that long-term solutions such as fuel conservation and synthetic fuel programs will not help curtail the economic impact of an oil embargo. Rather, they say, the U.S. must focus on building up its own strategic petroleum reserves and those of its allies in order to be equipped for an oil embargo.

Two reports commissioned by the U.S. Department of Defense around the same time and later published as books, focused on the vulnerability of energy infrastructure to attacks and accidents.[4] *Energy, Vulnerability, and War* discusses potential attacks on energy systems and options to address these risks (Clark and Page 1981). It then rates energy technologies in terms of vulnerability on the basis of: degree of centralization, local operation and maintenance, and other factors. In contrast to *Energy and Security*, Clarke and Page are critical of the strategic petroleum reserves because they rely on large centralized systems which are vulnerable to attack. The second infrastructure-focused report was republished as the seminal *Brittle Power: Energy Strategy for National Security* and also favors small, decentralized systems. The authors of this report argue that energy systems should be redundant, modular and diverse to be able to respond to various threats and uncertainties (Lovins and Lovins 1982, 179–182). Both of these reports

4. Farrell, Zerriffi, and Dowlatabadi (2006, 425–427) discusses the historical context of each of these reports

were clearly influenced by ideas of resilience from ecology such as Holling's seminal article *Resilience and Stability in Ecosystems* (Holling 1973).

These early studies of vulnerability and resilience reinforced a move away from state-controlled energy. For example, Lovins and Lovins praise PURPA as an approach to support distributed generation and move away from large power plants (Lovins and Lovins 1982, 278 and 297). These early studies provided captivating stories of the perils of centralized infrastructure. *Energy, Vulnerability, and War* described terrorist attacks on energy systems in Libya and the Soviet Union while *Brittle Power* documented accidents in, attacks on and near misses from around the world related to mainstream energy systems. The conceptual alternative to centralized "brittle" systems which can result in nightmare scenarios is the concept of "distributed energy systems", possibly influenced by the idea that *Small is Beautiful* (Schumacher 1973). For this intellectual tradition, the utopia of a decentralized modular system with a smaller environmental footprint presents a solution to the security and environmental problems associated with existing energy arrangements. While these books lay out a number of arguments for efficiency, renewables, and decentralization, they do not quantify the scale of the required changes or necessary investments.

Thus, while the 1970s was dominated by the Arab oil embargo and calls for deregulation and liberalization of energy systems in developed countries, in the 1980s energy security thinking was enriched by the analysis of how the resilience of energy systems could be increased, often in connection with the operation of energy markets:

> [T]he question is not whether there will be events that could threaten energy supply—for surely there will, be they political, military or technological—but rather how resilient energy markets themselves will be and how effective energy security measures will prove. (Yergin 1988, 112)

In the 1990s, this idea of resilience of energy markets came into sharper focus. Preparing for disruptions is explicitly linked to the idea that the resilience of markets will be crucial to ensuring energy security in the 1990s. The seminal work to come out of this period was Andy Stirling's work on measuring the diversity of electricity systems (and energy systems in general) with concepts and indices from ecology (Stirling 1994, 1998). The quantification of the resilience of an energy system is a continuation of the intellectual tradition from the resilience literature of 1980s discussed above.

### 2.1.5 "New" energy security

Over the last decade, energy security has reemerged on the political stage with anxiety about rising demand in emerging economies; high and volatile oil prices; increasing dependence on imported natural gas in Europe, and the vulnerability of the increasingly complex energy infrastructure to terrorism and other threats. Additionally, the energy system has become more interconnected with related infrastructures such as telecommunications, water supply, and the Internet which means that a failure in one system can trigger failures in other systems (Amin 2002; Rinaldi, Peerenboom, and Kelly 2001). Not only that, but the energy markets, financial markets, and fast communications mean that news of an electricity blackout in Europe can impact markets in North America (Yergin and Frei 2006). The following sections discuss the concerns and discourses which dominate this new energy security landscape.

*Back to geopolitics*

In most of the post-war period energy security concerns were primarily associated with oil as a primary resource (although coal was also of concern in the U.K. in the 1970s and early 1980s). However later in the 20th century, natural gas started to be increasingly used as a 'cleaner' and cheaper alternative to coal in electricity generation. A series of large pipelines was built to connect gas fields in Northern Russia and Siberia to the European parts of what was then the Soviet Union, Central and Eastern Europe and, eventually, to Western Europe. Following the end of the Cold War, Europe was soon again divided along the lines of NATO and EU membership. In this geopolitical context, rising import dependency on Russian gas in Europe raised fears over the possibility of Russia using an "energy weapon" against Europe much like the Arabs used the oil "energy weapon" in the 1970s. In two reports commissioned by the Swedish Department of Defense and carried out by the Swedish Defense Research Institute, Robert Larsson documented more than 40 disruptions of Russian gas imports to Europe.

At the same time he pointed out that exporting energy to Europe is of such a high economic significance to Russia that any sustained embargo against Europe as a whole is unlikely (Larsson 2006, 2008).[5] The Russian-Ukrainian gas disputes in 2006 and 2009 highlighted that there are challenges to importing natural gas which come not from the energy exporter but rather from transit countries.

Another development in the first decade of the 21st century was rapidly growing demand in China, India and other emerging economies (Yergin 2006; Klare 2008). Klare's book *Rising Powers Shrinking Planet* tells a story of scarce resources and future conflicts over them (including the major ones, China and the U.S.) exacerbated by environmental degradation (Klare 2008).[6] Rapidly growing Asian demand affected the energy security landscape in two main ways. First it caused a "demand shock" where the annual growth growth rate in petroleum demand was twice that of the previous decade (Yergin 2006, 72). Second, it meant that a lot of the oil-importing nations did not hold strategic petroleum reserves under the auspices of the IEA (Yergin 2006; Yergin and Frei 2006). When the IEA was founded in 1973, its member countries accounted for about 80% of oil demand, while today they account for only some 50% ( IEA (2011a; 2011b, calculated from)).[7]

### *Markets, volatility and the economic side of energy security*

Recent energy security discussions are also revisiting the role of the market in energy security. Low oil prices led to under-investment in the 1990s, which combined with the rapidly growing demand of the 2000s has resulted in high and volatile oil prices over the last decade. The volatility of oil prices was also linked to the growing influence of financial markets on these prices. The "financialization" of oil markets (Tang and Xiong 2010) was demonstrated by correlations between oil prices and non-energy commodi-

5. See also a similar viewpoint expressed by Goldthau (2008).

6. His new book tells a different story about resources and emphasizes that while unconventional resources are available (at least in some cases) in "great abundance,...exploiting them is usually more expensive and environmentally risky than using conventional fuels" (Klare 2012, 127).

7. The IEA has pursued a policy of cooperation but not yet membership extension to countries which represent new centers of demand including: India, Indonesia, Chile, and China among others. Scholars have also reflected on how the IEA can and should change in this landscape of changing demand (Colgan 2009).

ties (Silvennoinen and Thorp 2010) and the breakdown in the correlation between oil prices and inventories (Masters 2008). Whatever the real reason for oil price volatility, policy makers and mass media found it convenient to blame it on international 'speculators', thus increasing calls on policy makers to ensure price stability through increasing state control.[8] This coincided with the debate over whether de-regulation of electricity systems leads to their decreasing vulnerability (Yu and Pollitt 2009).

This is just one element of the debate over the economic side of energy security. Many researchers followed Kendell (1998) distinquishing between economic and physical risks to energy systems (sometimes called market versus supply as in Gupta (2008)). For example the Australian Government's National Energy Security Assessment looked into 'adequacy', 'reliability' and 'affordability', with adequacy and reliability covering the physical aspects and affordability covering the economic dimension (Australian Government Department of Resources Energy and Tourism 2009).

One of the most widely-cited definitions of energy *in*security is "the loss of economic welfare that may occur as the result of a change in price or availability of energy" (Bohi and Toman 1996, 1). Needless to say, 'economic welfare' is difficult to define in terms other than market failure or imperfection. However, there is a growing and far from precise rhetoric on how energy security implies *affordable*, *reasonable*, *fair*, *competitive* or *cost-efficient* prices. For example, the IEA defines energy security as "the uninterrupted availability of energy sources at an affordable price" (IEA n.d.).

Many scholars disagree with the utility of introducing such terms in the energy security debate. For example, Keppler (2007a) argues that it is impossible to delineate physical energy concerns from economic ones. Furthermore, low energy prices are "as dangerous to energy security as high prices" because they can lead to underinvestment in resource development and infrastructure (Alhajji 2008, 4). Price caps on electricity in China in 2011 led to electricity shortages in the summer of 2012 because there was a shortage of generation capacity. And evaluating the "competitive" or "cost-efficient" nature of energy markets is futile since since there are no perfect markets. Take for instance the oil and gas markets. Neither is a

8. There have clearly been actual cases where liberalization actually does lead to market manipulation such as in the case of Enron (Weaver 2003).

perfect competitive market since the oil market is dominated by OPEC, a cartel, and gas prices in many countries are indexed to oil prices (Löschel, Moslener, and Rübbelke 2010a, 1666). A detailed analysis of actual energy security policies in the UK, Sweden and the European Union, argued that policy makers are more concerned with 'stable' and 'competitive' (i.e. protecting vital industries in their jurisdictions) than with 'low' or 'affordable' energy prices (Lilliestam, Patt, and Cherp, *under review*).

An elegant way of linking economic and geopolitical aspects of energy security is offered by Greene (2010) who proposes that instead of focusing on the elusive and likely impossible "oil independence" it is more useful to analyze at which level of dependence economic costs would be minimal. Along those lines he defines oil independence as:

> For all conceivable future world oil market conditions, the potential costs of oil dependence to the U.S. economy will be so small that they will have no effect on its economic, military or foreign policies. (1614).

The advantage of this approach is that it considers the affect energy dependence has on a country. The elegance of this proposal is that it brings together economic, energy and political realities. The disadvantage, as Greene admits, is that the cost of oil dependence is not (yet) measurable.

### *Revisiting scarcity and critical infrastructure*

At the same time, fear of the "limits" and peak oil was reinvigorated as the world approached the turn of the century, which is when Hubbert predicted global crude oil production would peak. In fact one article even argued that *The Limits to Growth* was largely accurate in terms of resources (Hall and Day 2009, 235–236). Campbell and Laherrère (1998), two seasoned geologists with over four decades in the oil industry used Hubbert's method with updated numbers and predicted that the world's conventional oil production would peak before 2010; a similar prediction was published in *Science* the same year (Kerr 1998). These predictions argued that the remaining oil will increasingly be produced in the Middle East which would strengthen the region's geopolitical power. The idea of "resource wars" was further articulated by Michael Klare (Klare 2002) and exacerbated by concerns about rising demand from China (Klare 2008). Several social scientists have taken peak oil as a given and researched how the idea came to be accepted (Bardi 2009) or how it may affect different countries and economies (Friedrichs 2010).

However, on the other side of the question are scholars who criticized the peak oil theory for discarding technological development (Bentley and Smith 2004) and unconventional reserves (Rogner 1997; Odell 2004; McKenzie-Brown 2008). In Rogner's view, the production of oil will plateau rather than peak as more unconventional resources enter the game and demand responds to prices (Rogner et al. 2012). The recent rise in unconventional oil and gas especially in the U.S. seem to confirm this theory. Peak oil has also been criticized as not accounting for the role oil companies (Bridge and Wood 2010) play in bringing new resources to the market.

Finally, the vulnerability of infrastructure was exposed in the first decade of the 21st century. The 911 terrorist attacks brought terrorism to the forefront of policy-makers' minds, particularly in the United States. The twin hurricanes Katrina and Rita in the summer of 2005 exposed the vulnerability of oil refineries to natural disasters. Finally, the electricity blackout which spread across the eastern U.S. in the summer of 2003 and then also across Europe and Moscow the same year exposed the fragility of electricity systems.[9] Farrell et al. have suggested that the conflagration of these forces means we need to choose between pouring more money into protecting the existing brittle infrastructure and adopting a "new paradigm of energy security based on soft-fail infrastructure" (Farrell, Zerriffi, and Dowlatabadi 2006, 461).

### 2.1.6 Conceptualizing energy security

Amidst these new challenges, policy and scholarly discourse began to emerge to look at "new energy security". Until the early 2000s, "energy security" essentially meant security of oil supplies.[10] But after the turn of the century policy-makers and scholars alike begin to grapple with a new notion of energy security based on increasing interconnections and institutions which

9. The California electricity crisis two years earlier in 2000 and 2001 was due to market manipulations and actually influenced the discussions surrounding the market and energy security rather than the critical infrastructure discussion.

10. See for example Daniel Yergin's "Energy security in the 1990s" which talks almost exclusively about oil (Yergin 1988).

were built for a different energy security landscape. This section discusses the scholarly debate which has unfolded amidst this growing complexity. Both policy and academic literature have sought to address two interconnected tasks: to conceptualize energy security and to quantitatively assess or measure it. Whereas new conceptual schemes aim to make sense of the increasing complexity of energy security issues, quantitative metrics aim to cut through this complexity by reducing it to a set of numbers and indicators, or in some cases to a single "index".

*Why conceptualize?*

So why does energy security suddenly require academic conceptualization? One reason is the increasing complexity of energy systems. In a policy brief for the World Economic Forum, Yergin and Frei lay out the integrated nature of energy risks today "in which a break at any point in the supply chain can reverberate throughout the system" (Yergin and Frei 2006, 4). Even the IEA, whose very raison d'être is to ensure functioning oil markets has begun to discuss "comprehensive energy security" (Tanaka 2010; IEA 2011c). Thus, one driving force for the increase in conceptualization is the increasing complexity and interconnections of energy security which render the existing energy security institutions unprepared and ill-equipped.

Another reason to academically conceptualize energy security is that it means different things when applied to different timeframes, energy sources, and in different countries (Chester 2009). The contextual nature of energy security means that there is no universal way to measure it or even define it (Cherp and Jewell 2011a). Indeed scholarly and grey literature together offer over 30 definitions of energy security since 2000 (see Winzer (2012, 42–43) or Sovacool (2011a, 3–6) for compilations of definitions), compared to one definition from the 1990s .

The third driver for the new conceptualizations of energy security is the failure of traditional approaches to deal with the new landscape. International relations offers insight into dealing oil dependency and asymmetric power balances as well as trade embargoes and the "energy weapon" (Paust and Blaustein 1974). Where this discipline falls short is that it is inclined to ascribe all risks to geopolitical factors and generally does not give enough weight to the impact of price fluctuations, investment levels, and technological developments. For example, in "Rhetoric versus reality: Russian threats to European energy supply" Goldthau (2008) argues that the biggest threat to Russian gas supply to Europe is in fact under-investment in upstream production rather than geopolitical factors. This disciplinary approach tends to have a static view of the world in relation to technology with actors providing the main risks of disruptions.

The natural sciences and engineering can provide insight in risks related to infrastructure and technologies, but these disciplines usually do not take into account politics and markets. For example, the California electricity blackouts in 2000–2001 were not caused by a technical failure but rather by market manipulation (Weaver 2003). Additionally, concerns about peak oil have been strongly criticized by economists as neglecting the fact that when oil prices rise reserves increase (Rogner et al. 2012, 435–437).

Economics made its contribution to energy security during and after deregulation of energy and electricity markets. Indeed much of the literature on energy security over the past two decades has framed energy security in economic terms which started with Bohi and Toman's (Bohi and Toman 1996) seminal *The Economics of Energy Security* (see page 18 for more details). Several authors have followed in this tradition. Awerbuch recommends constructing electricity generation portfolios using a mean-portfolio variance method, often used in financial portfolios to ensure that assets do not co-vary, instead of the least-cost approach which currently dominates electricity investment decisions (Awerbuch 2006; Berger 2003). He and his co-authors argue that by ensuring that energy source prices in an electricity portfolio do not co-vary, in the long-run, the whole portfolio will be less costly. While economists can help identify market failures, as a discipline, economics is less equipped to deal with politics, irrational choices, public good dilemmas and as a result fails to explain certain policy choices.

### *Drawing the boundaries of energy security*

With the complexity of the new energy security landscape, researchers and policy makers alike are faced with the challenge of drawing a boundary between energy security and other energy policy concerns. Unfortunately most energy security studies are not reflective in this respect. Most of the literature does not address the underlying epistemological question of whether energy security is an objective property of an energy system or a subjective perception of social actors.

The most common approach in the literature is to mix opinions of various actors with facts and observations about energy systems. The results tend to be long indiscriminate lists of energy security concerns without explicit explanation of why a particular factor was included or excluded (Bambawale and Sovacool 2011; Sovacool 2011b; APERC 2007). This approach has been criticized for uncritically selecting respondents (e.g. respondents who do not live in the jurisdiction in question or who have little experience of dealing with energy security), for not asking the stakeholders to prioritize among concerns they mention and for not systematically dealing with conflicting opinions (Cherp 2012).

A debate on including environmental concerns as an aspect of energy security is one of the most intensive scholarly battles concerning the boundaries of the concept of *new energy security*. In a review article on measuring energy security, Sovacool and Brown remark that “environmental stewardship” and the “importance of sustainability” is “promoted by about one-fourth of the examined articles…” (Sovacool and Brown 2010, 84). They then offer a questionable justification for why these concepts should be included as one aspect of security. They cite reports from each of these groups and claim that “[e]ven groups, such as the International Energy Agency, and former American defense secretaries John Deutch and James Schlesinger have noted that mitigating and adapting to climate change must be considered a part of any attempt to create energy security” (84). While both reports they refer to do talk about emissions, neither report argues that $CO_2$ emissions are an energy security risk. The title of the IEA report in fact is *Energy Security and Climate Change: Assessing Interactions* and it looks at how energy security and climate change play out under different energy scenarios (Lefèvre 2007). The Schlesinger report talks about considering emissions and environmental consequences when evaluating energy security policies but doesn’t say that emissions are part of energy security.[11]

11. Sovacool and Brown also claim that a report written by retired U.S. Army Officers argues that: “global climate change, along with related water, waste, agriculture and deforestation challenges, act as ”threat multipliers“ impinging on energy security worldwide” (Sovacool and Brown 2010, 84). This statement is a stretch because, while the report does characterize climate change “a threat multiplier for instability in some of the most volatile regions of the world” (CNA Military Advisory Board 2007, 44), the only direct comment on energy security comes from a retired U.S. Navy Admiral’s opinion page

There has been some push-back in scholarly literature about including environmental considerations as part of energy security. Winzer (2012) suggests excluding sustainability issues from the concept of energy security because it leads to confusion and double counting. Some have argued that "factoring climate change into the energy security debate is based on flawed logic, selective information, and weak conjunctions" (Luft, Korin, and Gupta 2011, 43). Thus there is no scholarly agreement on treating climate change as an energy security issue. Even if environmental concerns are excluded from energy security issues, scholars still face long lists of seemingly disconnected energy security concerns. To deal with this problem, they often try to classify them into 'dimensions' or 'aspects' of energy security with catchy names that appeal to common sense. For example, the four A's of energy security: 'availability, accessibility, acceptability and affordability' were originally proposed by APERC (2007) and later used by Kruyt et al. (2009) and in a slightly modified form by Hughes (2012). In spite of its ubiquity, there is little justification for why these four dimensions are used and not others. With a bit of digging it turns out that the four A's actually comes from the field of health. In fact the original framework was five A's of health care access (including 'accomodation') (Penchansky and Thomas 1981). It iss of course possible that this overlap is a mere coincidence but more likely that a stakeholder in the APERC process borrowed from the health work from interaction with the UN or WHO, particularly given the high number of citations of the original framework (>300 in Web of Knowledge and ∼800 in Google Scholar).

For some authors, contributing to the theory of energy security seems to mean adding such dimensions. For example, Alhajji (2007) distinguishes six dimensions of energy security: the 'economic, environmental, social, foreign policy, technical and security'. Von Hippel et al. (2011) also start with six dimensions of energy security: 'energy supply, economic, technological, environmental, social/cultural and military/security'. Vivoda (2010) refers to von Hippel's dimensions but basically doubles it to eleven: 'energy supply, demand management, efficiency, economic, environmental, human security, military-security, domestic socio-culture-political, technological, international, policy'. And Sovacool (2011b) doubles this again to about twenty

in the report stating that "our national security is inextricably linked to our country's energy security" (CNA Military Advisory Board 2007, 41).

dimensions.[12] At this rate, by 2015 we will have over 300 dimensions of energy security and need to formulate dimensions of dimensions to understand them!

While such classifications help in attracting attention of policy makers and the public to different aspects of energy security, they are at best only the first step on the way to develop a systematic scientific understanding of energy security challenges (and at worst not relevant to this task at all). This is because the basis for these classifications is rarely systematically justified: they often seem almost as arbitrary as the lists of energy security concerns which they seek to structure. Proposed classifications rarely reflect an underlying physical or political reality. Take for example the 'acceptability' dimension from the four A's; concerns in this dimension could range from geopolitical unwillingness to import energy from unfriendly suppliers to ethical, environmental and social concerns. Moreover, classification is not integration. Placing several concerns in one group does not necessarily help us to understand them better or to develop integrated solutions (Cherp and Jewell 2011b).

Nevertheless, there are several promising attempts to construct a theory of energy security based on general systems principles rather than on analysis of empirically observable threats. For example, Keppler offers a risk management framework for analyzing energy security which is "built around notions of flexibility, diversification, responsiveness, impact reduction, rather than an excessive focus on any single measure of risk" (Keppler 2007b, 20). His three dimensions of energy security: geopolitical, technical and economic are close to the three perspectives on energy security which I use in this study (Cherp and Jewell 2011b). Stirling (2013) proposes a framework which incorporates energy security into broader concepts of technological vulnerability, sustainability and transformations. He classifies the risks into short-term 'shocks' and long-term 'stresses' and the style of action as 'control' and 'response'. The 2 x 2 matrix of shocks–stresses and control–response gives four strategies: stability, durability, resilience and robustness as well as 'no-regret strategies' such as "enhancing equity; en-

12. Sovacool's dimensions are: 'availability, dependency, diversification, decentralization, innovation, investment, trade, production, price stability, affordability, governance, access, reliability, literacy, resilience, land use, water, pollution, efficiency, greenhouse gas emissions'.

gaging stakeholders; promoting learning; catalysing reflexivity and fostering diversity".

*Measuring energy security*

A large part of the literature of energy security deals with measuring energy security through quantitative metrics or indicators. There are two major drivers to explain this pre-occupation with indicators. One is that indicators help to cut through complexity by reducing it to a few numbers (which can be further manipulated to produce even fewer numbers called combined indices as I explain below). The second reason for indicator popularity is that they give an impression of objectivity. During my internship at the IEA, a colleague even articulated an intent to put energy security into a "straight jacket" in order to evaluate it separately from subjective factors (which begs the question about where the line is between objective and subjective attributes of energy security).

**The down to earth approach.** There are several genres of studies involving quantitative measurements of energy security. Some of the studies use already widely accepted indicators to analyze an energy security problem. This is frequently the case in assessments of national energy security where national policy makers, who actually deal with energy security on a day-to-day basis, conduct an energy security assessment (Australian Government Department of Resources Energy and Tourism 2009; Wicks 2009; Jewell 2011b). When policy makers who actually deal with energy security shape an assessment there is little room for adding superfluous concepts or unnecessary indicators.

**An indicator (or two) for each concern.** On the other side are studies, coming from the academic literature which propose new indicators often in connection with their own conceptualizations of energy security (Vivoda 2010; von Hippel et al. 2011; Sovacool and Mukherjee 2011). These scholars seem to be influenced by Jan Tinbergen who argued for having a single policy target for each policy tool (Tinbergen 1952). For this genre of literature, conceptualizing energy security as a problem is a means to get to the ultimate end: measures of energy security. Take for example, how Sovacool and Mukherjee define their ultimate aim in “Conceptualizing and measuring energy security”:

> Summarizing the various dimensions and components of energy security is helpful in identifying major themes. However, more useful still is correlating these dimensions with usable metrics and indicators that can be utilized to assess national energy security policies and performance (Sovacool and Mukherjee 2011, 5346).

**Compound indices.** Related to this are studies which aim to preform some mathematical operation on a set of indicators to ‘integrate’ the concerns into a single number. In the same way as pooling together different energy security concerns into dimensions, this approach is thought to be more understandable for policy makers by pulling indicators into indices to reduce the amount of numbers which need comprehension. For example, Jansen, van Arkel, and Boots (2004) integrate an indicator measuring the diversity of energy options with indicators for import dependence, resource scarcity and political instability to produce what they call a ‘compound diversity indicator’ (originally proposed in Jansen, van Arkel, and Boots (2004) and used in McCollum, Krey, and Riahi (2011) and Kruyt et al. (2009)).

There are at least three problems with such compound indices. The first one is that they clearly misrepresent energy security in certain cases. The compound index mentioned above, which only considers diversity of domestic sources, would have the same value for this case as for a county which relies on a single exporter of a single fuel, which intuitively is much more vulnerable. Secondly, including ‘political stability of suppliers’ in a calculation (Jansen, van Arkel, and Boots 2004; Kruyt et al. 2009) can be justified for current energy security but cannot be credibly projected into the future (which is nevertheless done in Kruyt et al. (2009), 2176). Political stability indices are tenuous enough when dealing with the current world state of affairs but presuming they can tell us anything about the political stability of a country in one, two or even three decades is downright foolhardy.

The more theoretical problem with this approach is that it uncritically blends different policy and scientific paradigms. For example, the ‘compound diversity index’ is based on Stirling’s diversity index. Pursuing diversity as a strategy is to hedge against ignorance and uncertainty. Justifying the use of diversity indicators, Stirling (1998, 19) quotes the Tao te ching with: "knowing ones ignorance is the best part of knowledge". By mixing some of the lesser parts of knowledge with the "best part", a compound diversity index defeats the purpose of using diversity as a strategy to hedge against uncertainty. Likewise, it may defend the strategy of being self-sufficient in favor of hedging against ignorance and the inherent unpredictability of energy systems.

More recent examples of creating a composite energy security index in the academic literature range from a "simple scoring exercise" in Sovacool and Brown (2010) to a more complicated "ordered weighted average" in Badea et al. (2011). The simple scoring exercise involves taking two time steps of ten indicators for 22 OECD countries and assigning a −1 if the indicator worsened overtime, 0 if it stayed the same and +1 if it improved; then all of the results are summed. In this analysis the authors also compare these results to the results using z-scores, which represent the number of standard deviations each normalized indicator is away from the mean for each country. The difference between the results of the two methods are quantitatively and qualitatively very different, indicating that the method is not robust. The Sovacool and Brown analysis also suffers from no justification for equal weighting of all indicators or for why indicators are either excluded or included.

Adding complexity to the math of combining indicators does not necessarily improve the resulting index. In Badea et al. (2011) the ordered weighted average, (1) ranks the countries for each indicator; (2) sorts ranks for each country in descending order (from the worst rank to the best rank among the peer-group); and (3) determines the weight for the rank of each indicator by what the authors call the "risk-averse level of the decision-maker". If a decision-maker is highly risk-averse, the rank of the worst-ranked indicator is 100% of the final score; if a decision-maker is highly risk-prone, the rank of the best-ranked indicator is 100% of the final score. This methodology has several problems. Firstly, indicators are valued as having different weights for each country but equal importance overall.[13] Secondly, since the index

13. Since the weighting of each indicator is based on the relative-ranking of a country's indicators relative to its peers, each indicator has a different weight for each country. This also means that all indicators are essentially valued with equal importance thus the risk of having a high carbon intensity is considered just as risky as having a high import dependency.

is based on ranks rather than indicator values, the distance between each country is assumed to be equal. For example, for crude oil import dependency, the distance between the United States (61%) and Hungary (83%) would be valued the same as the distance between the Slovak Republic (95%) and the Czech Republic (96%). In other words, complex mathematics can hide but not eliminate assumptions and choices made in preparing compound indices. Arguably, many of these assumptions should be made by policy makers with relevant mandates rather than by academics fiddling with numbers.

Aggregation can also be found in the policy literature. According to the Institute for 21st Century Energy, the U.S. energy security risk in 2011 was "101.3" (Energy, institute for 21st Century and US Chamber of Commerce 2012). This is a unit-less measurement which is a weighted normalized average of all the indicators they use. According to the Forward "Policymakers and regulators should take heed, as the numbers tell the story plainly and objectively" (4). The problem is that while the *numbers* are not subjective, the selection of *which* numbers to use and the method of aggregation is!

Bollen, Hers, and van der Zwaan (2010) use another compound indicator to represent disutility of energy supply insecurity in the MERGE integrated assessment model. Their indicator combines import dependence of a particular fuel, share of this fuel in TPES and energy intensity. Each of these parameters is normalized to the base year value and risen to an arbitrary degree[14] before the resulting values are multiplied by each other. For use in the model, the indicator is also multiplied by a scaling factor of 0.005 to reflect the willingness to pay for avoiding energy imports. Though such a single index is useful for modeling purposes, in my analysis it makes more sense to consider import dependence and energy intensity as separate and distinct values in order to better distinguish between various types of vulnerabilities of future energy systems.

In sum, compound indices aim to provide a simplified, comprehensive and objective picture of energy security. For the most part, however, they fail. Because on top of the arbitrary list of indicators is an equally-arbitrary method of aggregation which does not reflect any underlying energy or po-

14. This value is 1.1, 1.2 and 1.3 in their main analysis and between 2 and 3 in their sensitivity analysis.

litical realities. No techniques consider how resilience capacities can balance these energy security risks. Finally, in the quest of an integrated picture, this approach generally obscures trade-offs between diversity, import dependency, political stability, scarcity and other considerations rather then clarifying policy choices.

**Insights from the indicator literature.** Though I do not directly use complex indicators in this thesis, my work significantly benefited from many useful insights about energy system vulnerabilities and how they can be evaluated proposed in the literature with the aim to develop such indicators. For example, the Supply/Demand index (Scheepers et al. 2007) offers a useful perspective on integrating supply risks with end-user resilience capacity. Le Coq and Paltseva (2009) construct an index which reflects interactions over the entire energy supply chain—from import diversification and political stability of suppliers to risks from transit countries and the economic impact of a supply disruption.

These energy systems approaches inspired the energy security analysis in the *Global Energy Assessment* (Chapter 5 (Cherp et al. 2012) and Chapter 17 (Riahi et al. 2012)), my own work at the IEA on energy security indicators (Jewell 2011b) and the method used in this thesis. The IEA Model on Short-term Energy Security (MOSES) presents an alternative for mathematical aggregation discussed in the last section (Jewell 2011b; IEA 2011c). Instead of aggregating indicators using a mathematical formula, I used indicators to group countries with similar risks and resilience capacities, which I called "energy security profiles". In this way we made the subjective judgements about energy security and produced an evaluation which reflected the underlying energy realities of the IEA member countries.

My IEA work also built on an insight from the oil vulnerability index of oil-importing countries (Gupta 2008). Gupta uses nine indicators to formulate an overall index of oil vulnerability. She observes that indicators for oil vulnerability often correlate with each other, so she uses principle component analysis to remove this co-variation from her dataset before aggregating the indicators. While using this specific technique was not appropriate in my own work, the issue of co-variation influenced the way MOSES was structured.

In addition to the overarching energy systems approach from the indicators literature, there are a number of specific discussions which illuminate certain aspects of energy security. For example, the discussions between Andy Stirling and Shimon Awerbuch, two colleagues in Britain, on how to hedge against uncertainty in energy portfolios have interesting implications for what uncertainty is in energy systems and how it can be measured (Stirling 2008). As explained in this thesis on page 22, Awerbuch, thought that electricity generation portfolios should be balanced using a mean-portfolio variance method to ensure that the prices of the electricity generation sources do not co-vary (Berger 2003; Awerbuch 2006). This approach was criticized by Stirling who argued that ensuring energy security means guarding against uncertain risks which cannot be predicted through historical price variations (Stirling 2010, 1623). Their disagreement points to an interesting question in energy security: is uncertainty something we can predict from the past or are we completely ignorant about the future?

**Conceptual reflections on indicators.** With the burgeoning literature on indicators, there is some epistemological reflection on their nature and use. To begin with, there are some attempts to classify indicators. For example, Sovacool and Mukherjee distinguish between *simple* and *complex* indices based on how they are calculated arguing that an indicator is complex if it is an "aggregate indicator that includes the measurement of multiple variables" (Sovacool and Mukherjee 2011, 5353). I find this distinction arbitrary since even the simplest indicator is an aggregation of multiple variables. For example, import dependency is an aggregation of imports from various sources as well as domestic use in different sectors. Löschel, Moslener, and Rübbelke (2010b) distinguish between *ex-ante* (calculated for a given future scenario) and *ex-post* (calculated for historical data) indicators. While the distinction is logical, I am not sure how useful it is, particularly given their formulation of the usefulness of *ex-post* indicators: "to assess whether energy security existed in the past" (Löschel, Moslener, and Rübbelke 2010a, 1666). Rather I would argue that ex-post indicators could be used to test the utility of indicators by correlating them with established disruptions.

The system boundaries to which energy security indicators are applied (Cherp and Jewell 2011a) as well as the conceptual boundaries of energy security itself (Winzer 2012) greatly impact the result of a quantitative assessment of energy security. Chester (2009) argues that the definition of energy security (and as result its indicators) is shaped by the specific energy mix of the jurisdiction which is using it. As a result, she argues that it is not possible to formulate a universal definition of energy security. Cherp and I go further than this to say that the quest for a universal indicator or index of energy security is flawed (Cherp and Jewell 2011a). Energy security indicators, we argue, relate to a story (or stories) which policy-makers can understand and should be analyzed within the relevant context. For example, import dependence relates to the suffering from an oil embargo while the age of power plants can be a sign of a blackout risk. However, neither indicator can be analyzed in isolation. Import dependence must be analyzed in conjunction with domestic demand and import infrastructure while power plant age must be analyzed in conjunction with electricity investment and generation diversity. Our more recent publication (Cherp and Jewell 2013) argues that the focus of efforts to quantify energy security should be shifted from indicators to assessment frameworks. We propose and explain in detail an energy security assessment framework, illustrating it by examples from MOSES, GEA and several of my studies of future energy security which form the basis of this thesis.

### *Summary of recent energy security literature*

In summary, the increasing complexity of energy security in recent years has led the scholarly community to seek new ways to conceptualize and measure this 'fuzzy' concept in a policy-relevant and intellectually sound way. Unfortunately, many of such attempts have not been policy relevant or scientifically rigorous or both. The attempts to expand the boundaries of energy security by including environmental and social concerns have been academically criticized on the basis of their methodology and have largely been ignored by policy makers. Efforts to develop 'aspects' or 'dimensions' of energy security have failed to explain, clarify or predict real policy concerns. The quest for perfect indicators which has dominated much of the literature has proven largely futile and the literature has rarely been reflective of the relationship between energy security concerns as experienced by policy makers and the sets of numbers produced by mathematical manipulations.

Nevertheless, the recent literature contains several insights useful for the purpose of this thesis. First of all, it portrays energy security as a highly contextual concept emerging at the interface of political concerns and objective vulnerabilities of energy systems. Second, it emphasizes the systemic nature of energy security where different risks, vulnerabilities, resources, infrastructure and institutions affect each other. It is these two insights that I use to develop the methodology for this research in chapter 3.

## 2.2 Climate change: from scientific puzzle to policy problem

Earlier this year U.S. President Barack Obama articulated the need to "respond to climate change" with a "transition" to "sustainable energy sources" in his inaugural address (Obama 2013). When the President of the United States mentions climate change in arguably one of the most important 15 minute speeches of his entire career, there is no doubt that it is on the policy agenda. But how and when did climate change make it into the policy arena and how did it become an energy policy issue? This section describes the history of how climate change went from the *Annals of Chemistry and Physics* in the 1820s to the inaugural podium of the President of the United States almost 200 years later. This is crucial to understanding the link between climate change and energy security because once climate change becomes an energy policy problem it has a bearing on energy security.

### 2.2.1 The early science of the greenhouse effect

The science which led to the discovery of climate change began in the 19th century with the discovery of the greenhouse effect and the first calculations of the possibility of human-induced climate change. Joseph Fourier determined that the Earth should be much colder than it is given its size and distance from the sun; he considered multiple causes, one of which was what we know today as the greenhouse effect (which he eventually decided was *not* a cause) (Fourier 1827, 1824). John Tyndall, a British physicist was the first to prove that the atmosphere absorbs heat though the scientific community had been speculating about it for years (Tyndall 1872). The 19th century closed with the first calculations of human-induced climate change published by the Swedish scientist Svante Arrhenius with the calculations of doubling $CO_2$ or the "2 x $CO_2$" experiment which would become prominent in early climate debates (Arrhenius 1896).

### 2.2.2 Science advances, policy stays still

The 1960s and 70s ushered in a new era for climate research with advances in climate observations as well as increased global cooperation and research. In 1960 Charles David Keeling was the first to document the rise in $CO_2$ concentration on Manu Loa, Hawaii (Keeling 1960). That same year the U.S. launched its first meteorological satellite. This technological advance was extremely important politically since it was the first time space technology was used for a peaceful purpose. The event marked a unique opportunity in international cooperation, having happened during a brief thaw in the relations between the U.S. and the U.S.S.R. In a speech before the UN General Assembly in 1961, John F. Kennedy talked about this opportunity for cooperation: "We shall propose further cooperative efforts between all nations in weather prediction and eventually in weather control" (Kennedy 1961). The idea of scientific cooperation was carried on by Lyndon B. Johnson, Kennedy's successor, in a 1966 speech in which he called for scientists from the East and West to work together (Raiffa 1992). This idea would eventually lead to the foundation of the International Institute for Applied Systems Analysis (IIASA): a non-governmental institution where, for the first time scientists from both sides of the Iron Curtain collaborated. It is at IIASA that 40 years later I conducted the core part of my analysis, using some of the most advanced Integrated Assessment Models for analyzing the interaction between climate and energy systems.

The United States was the first country to publish a government report on climate change. In 1965 President Johnson commissioned a report on environmental quality from the President's Science Advisory Committee (United States President's Science Advisory Committee and Environmental Pollution Panel 1965). Thus, in parallel to the advances in climate science a discussion on the emerging scientific topic began in policy circles. While the main report focused on local water and air pollution, a 20-page appendix discussed carbon dioxide and global warming with startling conclusions:

> Through his worldwide industrial civilization, Man is unwittingly conducting a vast geophysical experiment. Within a few generations he is burning the fossil fuels that slowly accumulated in the earth over the past 500 million years...By the year 2000 the increase in atmospheric $CO_2$...may be sufficient to produce measurable and perhaps marked changes in climate, and will almost certainly cause significant changes in the temperature and other properties of the stratosphere. (Revelle et al. 1965, 126–127)

The Appendix, written by some of the leading climatologists of the day (including Keeling who had been responsible for the $CO_2$ measurements in Manu Loa and Antarctica) did not make a big splash in the political sphere. However, in a 1965 statement eerily similar to today's discourse, Adelai Stevenson, a prominent American politician, said:

> With our limited knowledge of [the Earth's] workings, we should not experiment with its great systems in a way that imposes unknown and potentially large risks for our future generations. In particular, we cannot presume that, in order to decide whether to proceed with the $CO_2$ experiment, we can accurately assess the long term costs and benefits of unprecedented changes in global climate. (quoted in Bolin (2007, 34) from the Council of Environmental Quality (1981)).

Thus, while there were early signs of a political recognition of the existence, and potential importance of climate change there were not policy discussions of the problem during the 1960s.

While political progress was limited in the 1960s, climate research experienced rapid growth with new international programs, advanced modeling, increased empirical observations and more access to satellite technology. Early climate research was mostly in the meteorological community within the International Union of Geodesy and Geophysics. With the growing importance in space technology for making observations and gathering data, the Inter-Union Committee on Atmospheric Sciences (CAS) was set up in 1964 to work between the meteorological community and the space exploration community. CAS was the first of a series of global programs to work on the environment and was instrumental in getting meteorologists and climatologists recognized as potential consumers of the new satellite data (Bolin 2007, 22). The Committee started the Global Atmospheric Research Programme (GARP) in 1967 to study atmospheric processes with the eventual objective to make global atmospheric models to improve weather forecasting (24). In 1973, GARP focused in on climate change and determining whether it was a man-made or natural phenomenon (29). In 1975 the first three-dimensional general circulation model of global climate was published (Manabe 1975). That same year Bryson published "A perspective on climatic change" in *Science* with a series of questions which scientists are still wrestling with (Bryson 1974): (1) How large must climate change be to be important? (2) How fast can the climate change? (3) What are the causal parameters, and why do they change? (4) How sensitive is the climate to small changes in the causal parameters?

During the early 1970s, the scientific community was in conflict over whether the planet was facing long-term global warming or cooling. Milutin Milancovic, a Serbian astronomer, mathematician and geologist, first proposed that variations in the Earth's climate were due to changes in the Earth's orbit (Milanković 1941). But it was not until the advent of deep-ocean coring that a team of geologists was able to prove that without any interference from humans, the Earth would face extensive glaciation in the Northern Hemisphere in the next several thousand years (Hays, Imbrie, and Shackleton 1976). With this seminal discovery, during the 1970s more and more scientists began to think it was more likely that the planet would warm in the coming decades rather than cool (Peterson, Connolley, and Fleck 2008) and scientists beyond the climatology community, most notably geologists and ecologists, began to make observations about the increasing $CO_2$ concentrations in the atmosphere.

Government funding for climate research also began to grow and match the interdisciplinary nature of the problem. The U.S. National Oceanic and Atmospheric Administration was founded in 1970 which would soon host one of the biggest climate modeling efforts: the Geophysical Research Dynamics Laboratory located at Princeton University. Throughout the 1970s the U.S. National Science Foundation also funded three additional modeling efforts (Hecht and Tirpak 1995). However, while scientists saw a growth in government funding for their work politics and policy were still limited to providing funding and discussing the results of various reports (Bolin 2007, 31).[15] Nevertheless there were at least some scientific voices towards the end of the decade which called for political action warning that "a wait-and-see policy may mean waiting until it is too late" (Suomi 1979).

The decade closed with the World Climate Conference which is emblematic of the 1970s: it did not call for any specific policy actions but instead set up the World Climate Programme and a series of workshops under the World Meteorological Organization (WMO), the United Nations Environment Programme (UNEP), and the International Council of Scientific Union (ICSU) which would become known as the Villach series borrowing its name from the meeting location. The concluding "Appeal to Nations" from the World Climate Conference is rather vague in its plea for countries to:

> (a) take full advantage of man's present knowledge of climate; (b) to take steps to improve significantly that knowledge; (c ) to foresee and to prevent potential man-made changes in climate that might be adverse to the well-being of humanity (WMO 1979, 713).

Thus, although there was more knowledge of the climate problem, there were still no concrete calls for political action from a broad base of scientists.

### 2.2.3 Climate change enters the policy arena

While the 1960s and 70s saw the development of interdisciplinary and international research on climate change and an increased interest in the issue through National Academies of Sciences and government funding agencies, in the 1980s the issue entered mainstream politics. During the second half of the U.S. Carter Administration, two laws were passed which would bring the climate problem into the scope of action of the U.S. federal government. The National Climate Program Act of 1978 established the National Climate Program (NCP) Office and Policy Board to prepare a plan for expanding federal research, research funding, and monitoring related to climate change and oversee its implementation (*P.L. 95-367 National Climate Program Act* 1978). The U.S. Energy Security Act, enacted after the oil embargoes of the 1970s, had provisions to support domestic energy production from renew-

15. Some of the most notable reports during the 1970s include two reports by the National Academy of Sciences (United States Committee for the Global Atmospheric Research Program 1975; Geophysical Research Board 1977) and a report by the Australian Academy of Sciences examining the affect climate change might have on agriculture and energy in Australia (Sciences, Australian Academy of 1976).

ables and fossil fuels alike. But it seems there were already concerns about what the production of synthetic fuels might mean for climate change. The Act:

> Directs the Director of the Office of Science and Technology Policy to enter into an agreement with the National Academy of Sciences to carry out a comprehensive study of the projected impact, on the level of carbon dioxide in the atmosphere, of fossil fuel combustion, coal-conversion and related synthetic fuels activities. Requires a report be submitted to Congress resulting from the study which shall include certain recommendations. (*S.932 Energy Security Act* 1980).

The report which was written as a result of the U.S. Energy Security Act was published in 1983 (National Research Council (US) Carbon Dioxide Assessment Committee 1983) and is frequently cited as a turning point in the climate change field from purely scientific to policy-oriented (Nierenberg, Tschinkel, and Tschinkel 2010; Peterson, Connolley, and Fleck 2008; Pomerance 1986). That same year the U.S. Environmental Protection Agency (EPA) published another report *Can we delay a greenhouse warming?* which was the first attempt to see whether specific policies could delay a temperature rise over the next 120 years (Seidel, Keyes, and Strategic Studies Staff Office of Policy and Resources Management 1983). Hecht and Tirpak have described this one-two punch as a yellow flashing light for policy-makers from the National Academy of Sciences study and a red flashing light from the EPA study "raising the specter of a world on a collision course between the need for energy derived from coal and a global warming of potentially catastrophic proportions" (Hecht and Tirpak 1995, 380). Thus, one of the studies drawing policy-maker's attention to climate change was commissioned and delivered as part of the efforts to boost national energy security.

By the mid 1980s a consensus on the significance of human-induced climate change was emerging among scientists. Between 1980 and 1985, the Villach conference series, organized by the WMO, UNEP and ICSU, led to a statement from an international group of scientists that "in the first half of the next century a rise of global mean temperature would occur which is greater than any in man's history" (ICSU, UNEP, and WMO 1986, 1). Part of the rising concern at this time came from a paper published earlier that year which argued that trace gases amplify the greenhouse effect caused by carbon dioxide by 50% (Ramanathan et al. 1985). In 1985, the Villach group recommended that "scientists and policymakers should begin active collaboration to explore the effectiveness of alternative policies and adjustments" and that they should consider the Villach assessment "in their policies on … [the] control of emissions of radiatively active gases" (ICSU, UNEP, and WMO 1986, 3). Thus in the first half of the 1980s, climate change went from being primarily a scientific area of study to one that was clearly recognized as important for policy action.

Not unlike the weather events which have risen climate on the policy agenda over the past year, a series of weather events converged in the years immediately following Villach which brought attention to the issue in the news media and on the international policy agenda. North America experienced intense heat waves in 1987 and 1988: Hurricane Gilbert inflicted more than $1 billion in damage in the Caribbean; a rare hurricane occurred in the English Channel; and a large chunk of ice about 100 miles long and 25 miles wide broke off Antararctica (Agrawala 1998, 608). During this time the leadership in the field of climate change shifted from ICSU (a scientific body) to UNEP (an intergovernmental organization) (608) (thus further underlining the shift of climate change from primarily a scientific issue to a policy issue).

At this time, senior UNEP officials were sailing high from the success of the Vienna Convention on ozone and wanted to replicate it with climate change. In fact, in their long-term planning documents from 1985, UNEP called for a climate change convention. It also began lobbying for one within the international community and with senior U.S. officials (Hecht and Tirpak 1995; Agrawala 1998). While the U.S. leadership agreed that climate change was a policy issue, they disagreed with Tolba, the Executive Director of UNEP on the next course of action. Tolba was pushing for a climate convention. However,

> [T]he mood of senior officials in Washington was that the underlying scientific evidence for global warming was inconsistent, contradictory and incomplete and did not justify policy actions that likely would be expensive. The Department of Energy felt strongly that the Villach report was inadequate because it was not prepared by government officials. (Hecht and Tirpak 1995, 380-381)

In spite of the lukewarm feeling towards climate change in Washington, it is clear that by 1986, the issue had arrived inside the beltway around the U.S. capitol. Several Congressmen and Senators began to pressure the White House to take Action and speak out about the importance of the climate problem (Hecht and Tirpak 1995, 381). And in the hot summer of 1988 James Hansen testified before Congress that global warming would be evident within the next several decades (Hansen 1988) based on the first climate prediction from a GCM (Hansen et al. 1988).

The State Department took a leading role in negotiating the terms of an international climate change assessment because they believed that climate change was positioned to become a controversial political issue quickly (Bolin 2007, 46). With U.S. support for an international scientific assessment, WMO and UNEP decided in 1987 to organize an intergovernmental assessment panel on climate change and after consultations between the WMO and its member countries, the Intergovernmental Panel on Climate Change (IPCC) was formed in 1988. Political support for addressing the climate problem was very high in the beginning but Bert Bolin, the first chairman of the IPCC notes that government officials were naive about how profound this problem was and how difficult it would be to address (54).

The fact that climate change entered the policy arena already in the 1980s does not mean that there has been a universal political agreement on this topic. While a scientific consensus on climate change had emerged by the mid–2000s (Oreskes 2005; Anderegg et al. 2010), right wing political groups in the U.S. tried to debunk this consensus (McCright and Dunlap 2000) and conservative American think tanks were central in producing the majority of the climate skeptics literature over the last three decades (Jacques, Dunlap, and Freeman 2008). As a result, public opinion on climate change remains divided (Doran and Kendall Zimmerman 2009) which impedes political action. Thus, for climate change this has meant scientists coming to grips with messy political realities of interest groups and policy making and the role of scientists in this landscape.

### 2.2.4 Scenarios for mitigating climate change

Once there was scientific consensus on climate change, the attention turned to the magnitude of the problem ("How warm will the world get if we continue on the same development path?") and to potential solutions ("What can we do about it?"). Both are about long-term futures and thus scenarios and models of future developments quickly became central to dealing with these questions.

Scenarios are a classic way to deal with the future. Already the *Art of War* written about two and a half centuries ago by Sun Tzu, a Chinese philosopher and government official, discusses the importance of thinking out alternative futures in order to identify the best strategy. Various representations of possible futures from the religious descriptions of the Apocalypse, to social utopias and science fiction, have been always an element of human culture. However, it was only in the late 1960s and early 1970s that scenarios became prominent in modern scientific literature. Herbert Kahn and Anthony Wiener of the RAND corporation, first formally defined scenarios as: "hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision-points" in order to determine how a situation might unfold and what alternatives each actor has at each step (Kahn and Wiener 1967, 6). This definition is similar to Porter's widely used definition of a scenario as: "an internally consistent view of what the future might turn out to be—not a forecast, but one possible future outcome" (Porter 1985, 446). The emphasis in each of these definitions is determining *alternative* futures. Kahn goes on to present "surprise-free" quantitative scenarios as well as "nightmare scenarios" depicting discontinuities in current trends. His work deals mostly with major world forces such as economic growth, development and the geopolitical chess board.

In the turbulent '70s, scenario planning came to the fore in business, futures studies and in relation to climate change. Discontinuities in predictable pathways (such as the oil crises of the 1970s) ignited the interest in the ability of scenarios to help prepare for alternative futures. Shell oil company used scenario planning following the oil crisis of 1973 to position itself for different market developments (Wack 1985b, 1985a). The head of the scenario planning unit at Shell later described scenarios as "a tool for ordering one's perceptions about alternative future environments in which one's decisions might be played out" (Schwarzt 1991, 4). As one consequence of the oil embargo the Energy Modeling Forum was also established to compare scenarios by different modeling groups (Sweeney and Weyant 1979). This Forum later played a critical role in developing and harmonizing various scenarios involving climate change and alternative energy development pathways and still has one of the strongest convening powers in the scientific community.

In the early 1980s, scenario thinking was already used to portray alternative futures of global energy systems (Hafele 1981; Goldemberg et al. 1985, 1987). Development of quantitative scenarios of global futures was greatly facilitated by the advent of global models, such as The Limits to Growth (Meadows et al. 1972). The models helped answer the *what-if?* questions posed by scenario thinkers. By taking different factors and interrelations into account, they allowed for greater precision in understanding potential behavior of complex systems.

Both global models and scenario ideas were used by climate scientists and gained particular prominence in the IPCC. From its inception, IPCC work was structured into three working groups: the scientific assessment of climate change focused on the nature of the warming (Working Group I); impact analysis of warming (Working Group II); and response strategies (Working Group III). Scenarios played a role in all working groups but in different ways. Working Group I relied on stylized models of the Earth system focused on what the climate would look like if $CO_2$ doubled (Manabe and Wetherald 1967; Wetherald and Manabe 1988; Manabe and Wetherald 1975; Sellers 1969; Mitchell, Senior, and Ingram 1989; IPCC Working Group I 1990). Working Group II's work was more qualitative since at that time there were few climate change scenarios available (Bolin 2007, 63).

Working Group III tread on scientifically uncharted territory in terms of scenario formulation (65). Initially $CO_2$ emissions were calculated based on projections of energy demand in turn based on past growth rates (Hafele 1981). However, this approach had led to past overestimates of emissions because it didn't take into account technological change and thus was not encouraged by the IPCC (Bolin 2007, 65). Thus, the IPCC commissioned a group of scientists to carry out a modeling exercise and design a set of scenarios. The focus of these scenario exercises was to formulate alternative futures and incorporate uncertainties. The first results of five scenarios (two business as usual scenarios and three different climate policy scenarios) were published in the *First Assessment Report* (Tirpak and Vellinga 1990). Two years later, a suite of six scenarios was published which represented various economic, population, and technological uncertainties (Legget et al. 1992).

### 2.2.5 Integrated assessment models

With these early scenario development projects from the IPCC a new scientific community was born: the integrated assessment modeling community. This community included mathematical modellers exposed to knowledge from different fields such as demography and economy, land-use, climate, technology studies and energy systems analysis and interested in developing quantitative models portraying the interaction between all these factors. Moss et al. (2010, 750) describe Integrated Assessment Models (IAM) as follows:

> Integrated assessment models represent key features of human systems, such as demography, energy use, technology, the economy, agriculture, forestry and land use. They also incorporate simplified representations of the climate system, ecosystems, and in some cases, climate impacts. These simplified representations are calibrated against more complex climate and impact models. Because of their breadth, these models integrate information needed to study the interactions of human systems (including potential climate policies) and environmental processes that affect climate change and its impacts. Integrated assessment models typically disaggregate the world into a dozen or more regions with time steps of about a decade. Integrated assessment models are used to develop emissions scenarios, estimate the potential economic impacts of climate change and the costs and benefits of mitigation, simulate feedbacks, and evaluate uncertainties.



Thus, IAMs were not only able to link emissions scenarios with expected climate change but also do the reverse task of depicting scenarios of development of energy systems compatible with certain climate goals. As a result they are able to connect the long-term and abstract problem of climate change to the concrete reality of the energy system.[16]

Over the 1990s, the integrated assessment modeling community grew. The *Second Assessment Report* (SAR) described 22 IAMs in some state of development (Weyant et al. 1996, 382) and “championed” them as a “principle tool” of analysis of climate change (Schneider and Lane 2005, 49).[17] By 1998 over 400 quantitative energy scenarios had been documented by the IPCC database ( Morita and Lee (1998) cited in Nakicenovic et al. (2000)). There was also a reflection within the community of the “growing pains” (Rothman and Robinson 1997, 23) which the field was experiencing as a “growing child on its way to maturity” (Rotmans and VanAsselt 1996, 327). The field as a whole came to believe that a “prerequisite” to success for IAMs was “building up political and scientific credibility” (335).

As the field developed, it moved from a dialogue between scientists to (at least an attempt) of a dialogue between science and policy (Schneider and Lane 2005, 44–45). Even the table of contents of IPCC reports reflect the shift of scientists writing for each other to writing for policy makers. In the SAR, the Chapter on *Integrated Assessment of Climate Change* focuses on explaining IAMs (Weyant et al. 1996); by 2007, results from IAMs are presented in a chapter called *Energy Supply* (Sims et al. 2007). The turn of the century was a watershed moment for the integrated assessment community with the publication of the Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart 2000) and the energy scenarios in the *World Energy Assessment* (Nakicenovic et al. 2000), the field firmly established itself as the leader of climate mitigation research. The SRES also was the first time that the quantitative and qualitative traditions were combined to present detailed numerical depictions of the future with underlying story lines for each one (Nakicenovic et al. 2000).

The reason for the large number of IAMs is that there is no single correct method to depict the complex reality of climate change and its uncertainties. The models are different with respect to their purposes, assumptions, source data and the methods of calculation. Although several classifications of

16. *Stabilization wedges* are another tool that has been used to connect climate change to the energy system (Pacala and Socolow 2004) but this approach has been criticized for being dependent on the order of analysis and for not considering costs.

17. Although the field of IAMs had grown, the SAR did not publish a new set of scenarios partly because of political opposition from lobbying groups (Bolin 2007, 91–92).

IAMs have been attempted (e.g. Weyant et al. (1996)[18] and Schneider (1997)[19]), there is no single agreed classification. All classifications are imperfect because most models can be run in different modes for different purposes. Because all of them are dynamically evolving and learning from each other most simplistic historical distinctions are rendered obsolete. For example, the previous influential distinction between 'top-down' (economic) and 'bottom-up' (engineering) models[20] is no longer relevant since most energy-economic models today used in IAMs are hybrids (Clarke et al. 2009). Models are discussed in more detail in subsection 3.4.1.

In summary, by the last decade IAMs had become one of the most influential methods to link climate change knowledge to energy policy. They provide the most concrete and credible guidance on changes to energy systems which are necessary to achieve climate goals. As I will explain in the next section, it is therefore not accidental that most advanced studies of future energy security rely on IAMs.

## 2.3 Linking energy security and climate change

Today both energy security and climate change are central to energy policy and addressing either of them will inevitably affect the other one. The earlier intellectual tradition of connecting energy security and environmental concerns was to describe a distant energy utopia or nightmare where all such concerns are simultaneously resolved or exacerbated. In this line of thinking, scholars start with a vision of a "more resilient energy future and then mak[e] that vision into a reality" (Lovins and Lovins 1982, 334). The emphasis here is on the *vision* of a future "that may seem too good

18. Weyant et al. (1996, 371) describe *policy optimization models* which "optimize key policy control variables, ...such as carbon taxes,... to meet a policy goal" versus *policy evaluation models* which project the "consequences of specific policies".

19. Another classification distinguishes models based on the level of integration from *first generation unintegrated premethodological assessments* to *fifth generation largely integrated climate impact policy assessments* (Schneider 1997). The problem with this classification scheme is that it implies that scientists should strive for, in my reading, ultimately a simulation of reality.

20. The systems engineering or "bottom-up" approach includes a detailed representation of energy technologies (sometimes down to each individual power plant or oil refinery) and attempts to simulate energy system behavior, often through optimization (e.g., maximization of consumer-producer surplus or minimization of system costs given specified demands for energy services) (Wing 2006).

to be true" but which can be reached with "trial, error and hard work" (Lovins and Lovins 1982, 334). In these distant futures, energy systems are clean and secure and typically are based on distributed domestic renewable energy and are highly energy efficient. On the other hand, Klare (2008) describes a geopolitical jockeying for energy which will simultaneously exacerbate political tensions and destroy the planet.

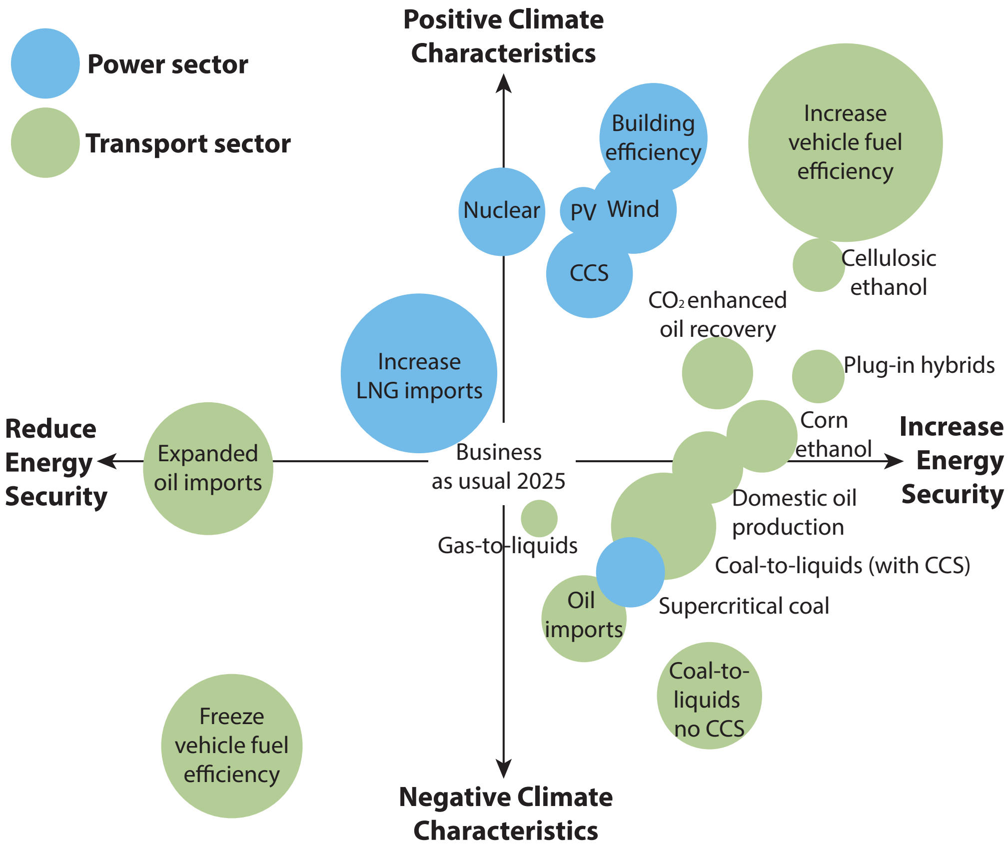
Another way of thinking about energy security and climate change is often described in terms of a trade-off space. In this approach, climate policies can be evaluated individually based on their impact on energy security. This has been used both in academic (Brown and Huntington 2008) and policy-oriented (Logan and Venezia 2007) literature to conceptualize the effects different energy policies would have on energy security and climate goals (see for example Figure 2.1). This approach is a very effective didactic tool to think about different energy technologies and policies. It works well when climate policies lead to incremental changes in energy systems and when energy security concerns are relatively static. Its big drawback is that it is not equipped to deal with a radically different energy system and the policies are not anchored in an integrated picture.[21]

Whereas utopian thinking works with a very distant future, the trade-off space is effective at working with policies in the current reality. The problem is that neither strategy is able to fully analyze the impacts of a low-carbon energy transition. The utopian approach is unable to connect to current realities and potential transition pathways while the trade-off space approach is unable to deal with an energy system (and energy security concerns) which are radically different from today's. This disconnect can explain why a lot of the literature connecting energy security and climate change is done with IAMs which are rooted in present realities and at the same time capable of depicting distant futures.

There have been several studies addressing long-term energy security in various global energy and climate scenarios summarized in Table 2.1. One of the earliest studies compares the cost of implementing climate policies in the short term (by 2010) with and without energy security policies, which they stylize as taxes on imported fuels (Huntington and Brown 2004; Brown

21. Similar to wedge analysis (Pacala and Socolow 2004), this approach fails to take into account system dynamics by dealing with each technology in a piecemeal isolated fashion.

**Figure 2.1:** An example of the energy security–climate change trade-off space




Note: Figure is modified from Logan and Venezia (2007, 3)

and Huntington 2003). Another approach is to look at the economic cost of oil price hikes with and without a climate policy (Maisonnave et al. 2012; Rozenberg et al. 2010) or the economic costs of not exploiting fossil fuels versus suffering through climate change (Nel and Cooper 2009).[22] One popular line of inquiry in this genre is to quantify co-benefits of climate policies by comparing the cost of implementing climate policies and energy security policies on their own versus simultaneously (Bollen, Hers, and van der Zwaan 2010; McCollum et al. 2013; McCollum, Krey, and Riahi 2011) in order to illustrate the "synergistic" nature of different energy policies. The goal of these studies dictates their excessively stylized representation of energy security (e.g. through monetization or using aggregated indices)

22. While Nel and Cooper view unused fossil fuels as an economic cost, Turton and Barreto argue that resources in the ground act as an energy security buffer against price and energy disruptions (Turton and Barreto 2006).

which can provide useful insights into potential synergies and tensions between climate and energy security agendas but are not sufficient to understand nuanced impacts of climate policies on the future energy security landscape.

The few studies that do aim to depict energy security under climate policies focus on only one energy sector (e.g. electicity in Grubb, Butler, and Twomey (2006), oil in Rozenberg et al. (2010) or fossil fuels in Lefèvre (2010) and Lefèvre (2007)) or a single region or country (e.g. the E.U. in Costantini et al. (2007), Criqui and Mima (2012) and Kruyt et al. (2009), the UK in Grubb, Butler, and Twomey (2006) and India in Shukla and Dhar (2011)). They also tend to only address selected energy security concerns (e.g. diversity in Grubb, Butler, and Twomey (2006), energy resource scarcity in Turton and Barreto (2006) and Rozenberg et al. (2010)), and imports in Criqui and Mima (2012)). Nevertheless, the literature contains a wide range of indicators of energy security on which I draw in this thesis. What the literature does not provide is a systematic framework to analyze energy security under climate concerns.

In addition to the literature on evaluating future energy security in IAMs, there is a more developed literature analyzing the effect climate change policies might have on energy export revenues. This discussion emerged during the Kyoto Protocol negotiations as major oil and gas exporters expressed concern that the Protocol would decrease their energy export revenues. Thus, several studies focused on the effect the Kyoto protocol would have on the revenues for OPEC countries (Ghanem, Lounnas, and Brennand 1999; McKibbin et al. 1999) but there are also studies which look at what would happen to the revenue of energy exporters due to carbon taxes or climate stabilization (Haurie and Vielle 2011; van Vuuren et al. 2003); under technological uncertainties (Johansson et al. 2009; Persson et al. 2007; Bartsch and Müller 2000); and with different degrees of cartelization (Berg, Kverndokk, and Rosendahl 1997b). There is, however, no comprehensive comparison and synthesis of these studies. The literature also does not systematically explore whether the carbon market could be used to compensate energy exporters.

**Table 2.1:** Previous studies on energy security under climate policies

| | | Energy security focus | | | |
|---|---|---|---|---|---|
| **Study & Model** | **Time horizon** | **Sectors** | **Geography** | **Concerns** | **Measurement** |
| Huntington and Brown 2004 welfare economic model | 2010 | oil, gas & coal | regional | import dependence | tax on fuel imports, total cost of climate mitigation |
| Grubb, Butler, and Twomey 2006 UK *DTI* scenarios | 2050 | electricity | U.K. | electricity security | electricity diversity of production |
| Turton and Barreto 2006 *ERIS* an energy system model | 2100 | oil, gas & hydrogen | regional | scarcity & supply shocks[a] | resource to consumption ratio for oil and gas, hydrogen production volume |
| Costantini et al. 2007 comparison of IEA, IIASA, IPCC, and U.S. EIA scenarios | 2030 | oil & gas (o&g) | global & E.U. | scarcity, geographic concentration of supply, import dependence | E.U. o&g reserves, geographic distribution of o&g reserves & production, gas trade, E.U. net import dependence, E.U. share of global o&g imports, value of o&g imports, E.U. o&g intensity[b] |
| Rozenberg et al. 2010 *IMACLIM-R* an energy-economy model | 2050 | oil | global | oil scarcity, uncertainty of oil resources | cost of oil scarcity & climate policies on Gross World Product |
| Bollen, Hers, and van der Zwaan 2010 *MERGE* an energy-economy model | 2100 | oil & gas | regional | import dependence & scarcity | compound index with import dependence, share of that fuel in TPES and energy intensity & gas, global oil reserves at the end of the century |
| Lefèvre 2007, 2010 *WEO* energy-economy model | 2030 | oil, gas & coal | regional | import dependence | concentration of og&c suppliers, political stability of suppliers, proportion of gas which is pipe-based |



*continues on next page*

| Study & Model | Time horizon | Energy security focus<br>Sectors | Geography | Concerns | Measurement |
|---|---|---|---|---|---|
| Kruyt et al. 2009 *IMAGE/TIMER* energy-economy model | 2050 | TPES, oil, gas & coal (og&c) | global, E.U. | import dependence, scarcity | global og&c reserves, E.U. og&c reserves, E.U. import dependence, E.U. import dependence of oil & gas, trade in energy carriers, E.U. fuel supply concentration, compound index with diversity, import dependence, resource depletion and political stability of suppliers $I_4$ from Jansen, van Arkel, and Boots 2004, 21-22 |
| Badea et al. 2011 *PRIMES* | 2030 | TPES, oil, gas & coal | E.U. | security of energy supply | energy intensity, carbon intensity, oil, gas & coal import dependence, diversity of TPES, electricity, & transport demand |
| Maisonnave et al. 2012 *GEM-E3* an energy system model | 2100 | oil & gas | E.U. | oil price shocks | cost of oil price rise with and without EU climate policy |
| Criqui and Mima 2012 *POLES* an energy system model | 2050 | oil, gas & coal (og&c) | global & E.U. | import dependence, trade disruptions | global trade pattern for og&c, international prices of og&c, E.U. imports for og&c, E.U. import value for og&c |
| McCollum et al. 2013 *MESSAGE* an energy-economy model | 2100 | TPES | regional | import dependence & diversity | regional import dependence, TPES diversity, compound index with TPES diversity and import dependence $I_2$ from Jansen, van Arkel, and Boots 2004, 23-25. |

Notes:
[a] "Security of supply" policies are pursued in import dependent regions (OECD, Central and Eastern Europe, and Centrally-planned Asia, which is primarily China) by maintaining *buffers* of oil and gas (see main text for a discussion of buffers).
[b] Oil & gas intensity refers to oil & gas consumption per unit of GDP.

## 2.4 Summary of literature review

This literature review shows that energy security emerged as a policy problem at the beginning of the last century but it was only shaped as an area of academic study over the last three or four decades. Initially oil security dominated the policy agenda due to its centrality to the military and navy during both World Wars. During the prosperous 1950s and 60s, with low energy prices and abundant supplies, concerns about energy in advanced industrial economies were low. The Arab oil embargo in 1973 changed all that and brought oil again into the center of energy security concerns. With the U.S. facing declining oil production, anxieties rose over the ultimate "limits" of the Earth's resources and the Western World's exposure to the so-called "energy weapon" of the Arabs. The ethos of deregulation swept into electricity and oil markets. The IEA was formed to balance OPEC and ensure a liquid oil market and electricity markets were liberalized. The dismantling of these vertically-integrated monopolies in electricity and high investment levels in oil production in the 1970s gave way to low energy prices and abundant supply through the 1980s and '90s. At the same time scholars and policy-makers started asking how to build energy systems and markets which are *resilient* against multiple and partially unknown threats.

Over the last decade, energy security has re-emerged on the top of the political agenda. With rising Asian demand, an increase in energy price volatility, concerns about exposure of critical infrastructure and greater interconnectedness, energy security concerns are more numerous and more complex than ever before. Scholars and policy-makers are grappling with this "new energy security". There are debates about its boundaries, how to measure it and how to manage it as a policy problem. The energy security indicators and frameworks in the literature rarely reflect underlying energy system or political realities. Nevertheless, the literature on energy security indicators offers several important ideas which I use in my thesis. For one, energy security is a property of the whole energy system, thus different parts of the energy supply chain need to be examined when evaluating energy security. Secondly, energy security reflects both context-sensitive vulnerabilities of energy systems and highly contextualized policy concerns and thus can be better measured with flexible assessment frameworks rather than through sets of generic indicators.

The literature review also shows that although scientists are sounding the bell louder then ever for policy action on climate change, this science-policy problem is very different from energy security. First recognized as a scientific problem it only entered the policy arena in the 1980s. Once there was scientific consensus on climate change, scenarios and models quickly became central to answering the question of how to mitigate climate change. These discussions are dominated and guided by Integrated Assessment Models since they are able to connect the abstract goal of climate mitigation to concrete realities of the energy system.

Today's energy policy makers must manage the increasingly complex threats to energy security and the growing imperative to mitigate climate change. But how do these two challenges interact? Are they complementary? Or incompatible with each other? There is an intellectual tradition to envision an energy utopia where all energy problems are addressed and to work towards that future. On the other hand, there is a more down-to-earth approach which describes these two challenges in a trade-off space between energy security and climate change for different technologies and policies. The utopian approach connects to a very distant future but is unable to relate to today's energy realities while the trade-off space works with incremental changes but is unable to deal with a radically different energy system. Thus, to bridge this divide a lot of the literature looking at the interaction between energy security and climate change is done with IAMs which are able to depict a radically different energy future which meets the current known constraints.

The IAM literature on energy security and climate change either focus on the energy security co-benefits of pursuing climate change or the energy security implications of climate scenarios. While these approaches partially demonstrate synergies between energy security and climate change mitigation they mostly focus on present concerns: oil and gas imports, long-term fossil-fuel availability, overall energy dependence and electricity diversity. However, if energy systems are to undergo radical transformations (for example, if oil is no longer the dominant fuel in the transport sector), present concerns might subside and new ones may emerge.

This study builds on and develops the existing literature in several ways. Following the well established tradition I use IAMs as a source of data on future energy systems (with and without climate constraints). However, I go beyond the existing studies in several important ways. First, instead of proceeding from a set of indicators, my thesis relies on a systematic and rigorous energy security assessment framework which allows me to take into account both generic and context-sensitive aspects of energy security. Most of the existing studies project current energy security concerns into the future and thus do not account for the possible emergence of new energy security concerns associated with energy systems which are radically different from those of today. I use only those indicators which are relevant and credibly modeled in Integrated Assessment Models (and thus omit for example political stability which is used in Kruyt et al. (2009)).

Secondly, I expand the scope of energy security from 'security of supply' to 'vulnerability of vital energy systems' which can include energy carriers, infrastructure and end-uses, shown to be key for energy security concerns in many countries (Cherp et al. 2012; Farrell, Zerriffi, and Dowlatabadi 2006). Third, my study expands the geographic focus from a single region or country to include the global energy system and four major economies: China, India, the E.U. and the U.S. I also expand the analysis to include several scenarios from six different Integrated Assessment Models (IAMs). This comparative approach (both between models and regions) allows me to depict the global energy security landscape under climate policies as well as the uncertainties within this picture, and to identify potential regional energy security winners and losers under climate policies.

# Chapter 3

# Methodology

As the previous chapter showed, energy security emerged as a policy problem and only later became a scientific area of study while climate change was formulated as a scientific problem and only later entered policy agenda. This chapter moves from the historical roots of these problems to the practical challenges of bridging the divide between climate change and energy security. I discuss how I resolve this challenge in this thesis to deal with the specific research question. Then I present the energy security assessment framework and describe the study design with an overview of the models and scenarios.

## 3.1 Challenge of linking energy security and climate change

The scientific representation of energy security has always trailed its political definition. In contrast, the "politics" of climate change have always trailed the scientific debate. As a result of their different histories, these two problems are rooted in different disciplinary communities and have different disciplinary connections. Additionally, the nature of the challenges mean that energy security is a short-term national issue while climate change is a global long-term issue.

### 3.1.1 Disciplinary divide

A prerequisite to understanding an interdisciplinary issue is understanding its disciplinary roots which are connected to the language and world view of those who research it. Energy security is linked to conventional security, international relations, and critical infrastructure protection. The link between conventional and energy security pertains to the importance of access to and control over fossil fuel resources. Estimates in the literature put the cost of protecting U.S. oil supply to be as high as $500 billion/year (Copulos 2007, 2003; Crane et al. 2009; Stern 2010; Delucchi and Murphy 2008; Dancs, Orisich, and Smith 2008). A flip side of this is that for resource-rich countries, oil prices have a significant impact on military spending and the overall government budget (International Institute for Strategic Studies 2011; Crane et al. 2009).

On the other hand climate change is linked to a group of natural science disciplines often called Earth Sciences. As discussed in chapter 2, international research on climate change was originally coordinated by the World Meteorological Organization and was dominated by atmospheric scientists. As the consensus has emerged that climate change is happening, the discussion has shifted to identifying uncertainties and analyzing how other systems (including ecosystems, the hydrological cycle, the cryosphere and weather patterns to name a few) affect or could be affected by climate change. A central part of the discussion on climate mitigation is land use change and agriculture since together they account for about 30% of greenhouse gas (GHG) emissions (Barker et al. 2007). Geology and ocean studies are other natural sciences which contribute to understanding climate change. More recently, economics and a variety of social sciences entered the area of climate change studies to understand how human civilization can adapt to and/or mitigate it.

Bridging the obvious divide between these two academic traditions requires identifying common ground. Since energy systems are at the heart of both topics, energy technologies, resources and investments are pertinent to both. Solving both the climate and energy security challenges requires an understanding of technology, resource use and institutional choices which can mitigate climate change challenge without compromising (and preferably enhancing) energy security.

### 3.1.2 Different scales

Energy security is largely a national-level issue while climate change is primarily a global one. The national focus of energy security is not surprising given that as a **security** issue it is linked to the very raison d'être of nation states. As a result, most energy security assessments are done at the national level. This includes assessments comparing several countries (Jewell 2011b; Scheepers et al. 2007; Sovacool and Brown 2010) as well as those which are focused on a one (Australian Government Department of Resources Energy and Tourism 2011; Wicks 2009; Energy, institute for 21st Century and US Chamber of Commerce 2012). While the treatment of energy security as a national issue is almost ubiquitous, there are discussions in the literature about the "scale" of energy security (Pasqualetti and Sovacool 2012). It is not uncommon for supra-national regions such as the European Union or Nordic countries to address their common regional energy security. On the other hand, Hughes (2010) uses the example of oil supply in Canada (with Western Canada being an oil-producing region and provinces in the East being net importers) to argue that energy security should be considered as a sub-national issue. This pragmatic approach is reflected in some national policy documents, for example, Australia's analysis of its disconnected regional natural gas markets (Australian Government Department of Resources Energy and Tourism 2011).[23] In contrast to energy security, climate change is global in nature since GHG emissions affect the atmosphere as a whole, no matter where they are emitted. Emissions will need to be cut globally to prevent climate change. This means that efforts to combat climate change need will likely need to be based on international agreements rather than solely national policy goals.

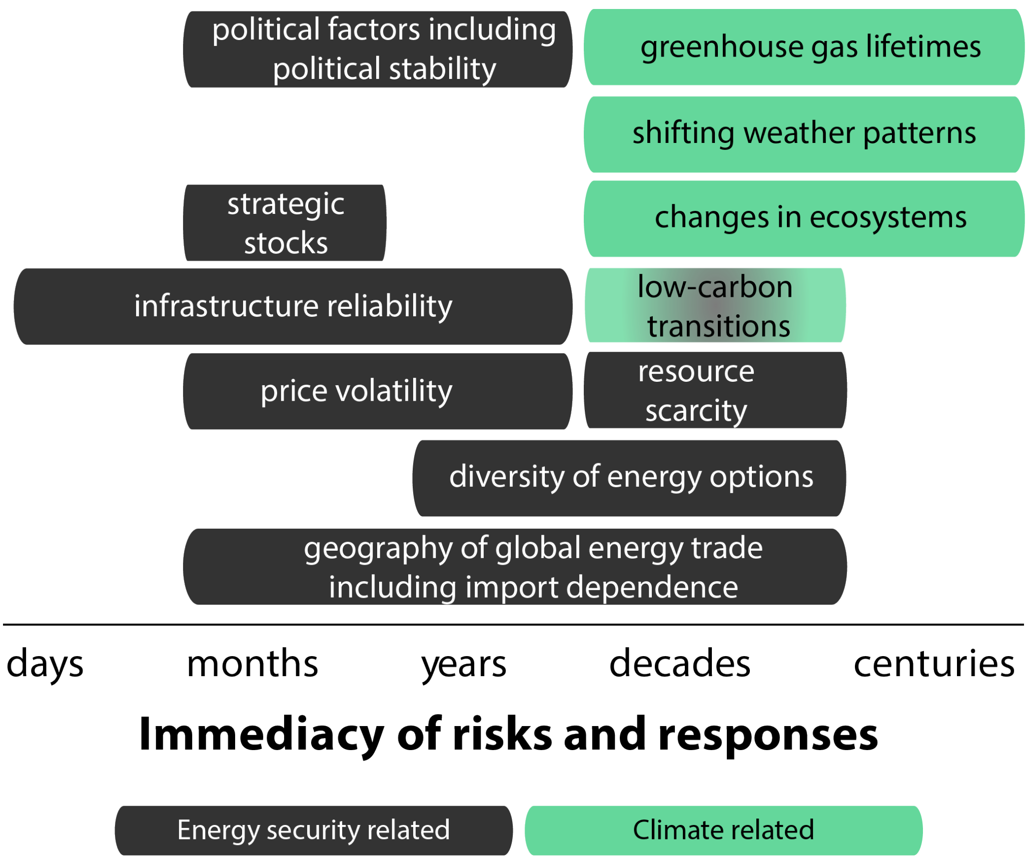
### 3.1.3 Different time horizons

Temporally, energy security and climate change differ both in *when* risks could materialize and *how long* the consequences would last. While both energy security and climate change are policy problems which are inherently about the future, energy security has a shorter time scale (Figure 3.1). For

23. The issue of "scale" has also been attempted at the household-level issue (Sovacool 2011c); but there's no evidence that policy-makers distinguish between what Sovacool calls "security of energy services and uses within urban households" and energy access.

example, the IEA's model for short-term energy security "focuses on short-term energy security: vulnerability to physical disruptions that can last for days or weeks" (Jewell 2011b, 7). On the other side of the spectrum is the concept of "long-term energy security" which, while never explicitly defined, seems to imply security over years to decades (Jansen, van Arkel, and Boots 2004; Jansen and Seebregts 2009). The *Global Energy Assessment* recently defined concerns ranging between: *shorter-term* issues such as import dependency and infrastructure reliability; to *medium-term* issues such as domestic resources/consumption and rising demand which can stress a country's infrastructure; and *longer-term* issues such as global oil scarcity and changing weather patterns. This conceptualization is closest to Stirling who distinguishes between *shocks* which are "short-term transitory perturbations" and *stresses* which are "long-term pressures...reflecting underlying shifts in conditions" (Stirling 2013, 7). Both GEA's longer-term issues and Stirling's stresses span a period of several years to a few of decades.

**Figure 3.1:** Time-horizons for energy security and climate change risks



Policy instruments and policy-driven (national) reports give a similar range of answers on the time dimension of energy security. The IEA countries' oil reserves must be at least 90 days of supply; in other words the IEA member countries must be prepared to respond to an oil supply disruption of no more than 3 months. National policies sometimes address longer-term issues such as energy conservation and more recently innovation. In the U.S., the *Energy Policy and Conservation Act of 1975* (*S.622 Energy Policy and Conservation Act* 1975) established both the U.S. Strategic Petroleum Reserve (a short-term policy response) and fuel economy standards (a longer-term policy response). More recently, the *Energy Independence and Security Act of 2007* (*H.R.6-2 Energy Independence and Security Act of 2007* 2007) focused on fuel economy standards, the production of biofuels, and energy efficiency in public buildings all of which are relatively longer-term policy responses to both short and long-term issues (import dependence, growing demand, and domestic energy intensity). Australia organizes its National Energy Security Assessment (Australian Government Department of Resources Energy and Tourism 2011), in terms of "Current issues (2009)", "Short-term" (5 years), "Medium-term" (15 years), and "Long-term" (>15 years) time horizons. The U.K.'s recent energy security strategy focuses on "both the short and longer term, looking as far ahead to 2050" (Great Britain Department of Energy and Climate Change 2012, 5). An earlier U.K. energy security assessment, published by the Prime Minister's office focused on 2030 as the year of analysis (Wicks 2009), similar to the widely influential World Energy Outlook (IEA 2012d).

The tendency to focus on shorter time scales in energy security is understandable for two main reasons. First energy security assessments tend to focus on the development of existing concerns which means they can only deal with the near-term, when the energy system is not likely to be radically different from today's. Secondly these time horizons are in line with the time horizon of investment which is at most a couple of decades. Thirdly, policymakers are naturally concerned about disruptions of energy systems which may occur during their terms in office (which focuses them on a really short time horizon indeed).

In comparison to energy security, climate change is a long-term problem both in terms of when it is likely to arise and the duration of consequences. For one, climate change is affected by the lifetime of $CO_2$ and other greenhouse gases in the atmosphere. Most $CO_2$ stays in the atmosphere for several decades but a fraction lasts for thousands of years (Archer et al. 2009). For non-$CO_2$ greenhouse gas species, the atmospheric lifetime varies between less than a decade to several centuries (Khalil 1999; Montzka, Dlugokencky, and Butler 2011). Secondly, there is a lag between the rate of response of the climate to greenhouse gases concentrations in the atmosphere. Even if all GHG emissions stopped tomorrow, the Earth would continue warming for several decades and could stay at this warmer temperature for thousands of years (Archer and Brovkin 2008; Matthews and Caldeira 2008). Thirdly, there is a lag between climate change and the ecosystem response to it (Cramer et al. 2001; Neilson et al. 2005). Fourthly, there is a lag time over which emissions can be curtailed. In the *Global Energy Assessment* (GEA) scenarios, which are one set of energy scenarios which meet at 2°C temperature target, emissions peak in 2020 (Riahi et al. 2012) but there are also ‘delayed action’ scenarios where peak occurs much later (I analyze some of them in this thesis).

Finally, there is a political process which will affect how soon a climate agreement could be reached. For example, at the Durban UNFCC meeting in December of 2011, all countries agreed to cutting GHG emissions for the first time. The catch? The next major milestone is an agreed roadmap by 2015 which will articulate how countries can begin cutting emissions starting in 2020. Thus, it is unlikely that any political action will be taken before the beginning of the next decade. Whatever, the case, the configuration of energy systems up to the year 2100 and beyond will matter for climate change. For example, many GEA scenarios point to the need for large ‘negative’ emissions in 2100.

In summary, as illustrated in Figure 3.1, energy security concerns and responses generally have shorter time horizons than climate change concerns and responses. The overlap occurs on the scale of decades. The figure also illustrates that the central element linking energy security and climate change is low-carbon energy transitions. That is why my analysis focuses on the time scale comprising several decades and revolves around low-carbon transitions as further explained in the next section.

## 3.2 Bridging energy security and climate change through integrated assessment models

The discussion from the previous section identified the three challenges with linking energy security and climate change: the disciplinary divide, geographic scale differences, and temporal disconnect. This section discusses how each of those challenges is addressed to achieve the aim of this thesis. I start with the easiest challenge to address (the temporal disconnect) and conclude with the most difficult (the disciplinary divide).

First, energy security and climate change need to be analyzed on a common time scale. This means energy security needs to be dealt with on a longer time scale than most of the existing assessments, i.e. when an energy system has undergone a transition which would mitigate climate change. There are three possible tools for evaluating energy security under low-carbon energy scenarios: qualitative scenarios, wedge analysis, and quantitative scenarios (from integrated assessment models). As discussed in subsection 2.2.4, the earliest qualitative scenarios were used by Royal Dutch Shell to help the company position itself during and after the oil crisis of the 1970s (Wack 1985b, 1985a). Thus, one approach to analyzing energy security under low-carbon futures would be to formulate different story lines for how a low-carbon transition would affect energy security. The advantage of this approach is that it could take into account different geopolitical configurations and possibly major technological advances. The disadvantage is that due to the complexity of such transformations it would be difficult to depict the major changes in energy systems which may have a bearing on energy security, especially to express them quantitatively.

A more quantitative approach would be to use a wedge analysis such as used in Pacala and Socolow's "stabilization wedges" (Pacala and Socolow 2004). However, while the wedge-type analysis provides a clear energy policy message for the scale of the climate problem, these studies fail to account for costs or interdependencies of different technologies and therefore do not give a comprehensive picture of the energy system under low-carbon transitions. For example, would the increase in wind power lead to a decrease in gas trade by alleviating demand or increase it due to a higher need for dispatch-able power? Thus, without an energy systems-analysis, answering this question is at best an educated guess and at worst pure conjecture. In contrast to wedge analysis, integrated assessment models (IAMs) provide details for energy extraction, conversion, transformation and use as well as details about how different futures could meet climate goals. Thus, IAMs are the most straightforward way to connect low carbon futures to energy security since they offer a detailed numerical description of an energy system, both with a climate constraint and without one.

The second challenge that needs to be resolved is the geographic difference. This means considering both the global and national energy security implications of an energy scenario in a future which meet global climate targets. In this thesis, I have used integrated assessment models with global coverage and regional resolution. This approach makes most sense for large countries which (almost) coincide with global regions or with highly integrated regions such as the European Union (E.U.). Thus, my study primarily focuses on "major economies" which are both nations and world regions: China, the E.U., India and the U.S. A smaller part of my study focuses on energy exporters, depicting them not as individual countries, but rather as a group of similar economies (OPEC or the former Soviet Union). Ideally, I would also evaluate the national-level implications of these scenarios for more countries: however, the uncertainty of national energy systems in a global model is too high.

The third challenge is to square the "policy-driven" nature of energy security with the "science-driven" nature of climate change. For the latter, this means spelling out policy concerns in quantitative terms and identifying concerns in a way which is consistent with the history of energy security policies. I approach this by linking policy concerns to the concept of vital energy systems and their vulnerabilities seen from three distinctly different policy perspectives. This process is explained in the next section.



## 3.3 Evaluating energy security in IAMs

As chapter 2 describes, the last several decades have seen an explosion of energy security assessments. At the same time, there has been little reflection or agreement in the literature on a *generic* energy security assessment framework. With each new paper on measuring energy security, new 'dimensions' of energy security and new indicators for measuring it are proposed. I argued in the Literature Review that the growing complexity in the literature reflects the underlying growing complexity in energy security itself. It also is a natural social progression through what the social psychologist William Schutz identified as a series of stages, from superficial simplicity through confusing complexity to profound simplicity (Schutz 1979). It is safe to say that over the first decade of the 21st century we have moved from superficial simplicity where energy security was only about oil to confusing complexity. The scholarly work for the next decade is to move from confusing complexity to profound simplicity. In other words, not to mirror the complexity of the energy system in one's analysis but rather to distill what is essential.

I do not claim that this thesis takes us to the next step—indeed it is one that will need to be taken by scholars and policy-makers collectively—but my aim is that the analysis presented here moves in that direction. The assessment framework I describe in this section is a generic one which could be adapted and applied to another study of energy security (either under decarbonization scenarios or a short-term business as usual energy development). The framework was developed over the last three years with Aleh Cherp in my role as a lead author of the *Global Energy Assessment* team on energy security. I refined and modified it in my role as leader of the IEA's project to develop a *Model of Short-term Energy Security*.[24] The framework is also published in a more didactic and pedagogic form in Cherp and Jewell (2013). The framework which I propose and used consists of four elements explained in the subsequent subsections:

- Defining energy security;
- Delineating vital energy systems;
- Identifying energy security concerns;
- Selecting, applying and interpreting indicators for the identified systems and concerns.

In this section I take this generic energy security assessment framework and answer each of the questions in it for the purposes of this study: ex-

24. The results of this work are published in (Jewell 2011b; IEA 2011c).

amining the energy security implications of a long-term low-carbon energy transformation.

### 3.3.1 Defining energy security

In order to evaluate energy security under decarbonization scenarios, the concept must be defined in a way that is generic enough to be relevant under energy systems which are radically different from current ones but at the same time specific enough to be policy relevant. Similar to the *Global Energy Assessment* (Cherp et al. 2012; Riahi et al. 2012), I define energy security as *low vulnerability of vital energy systems.* This definition builds upon Yergin's classic definition from 1988:

> The objective of energy security is to assure adequate, reliable supplies of energy at reasonable prices and in ways that do not jeopardize major national values and objectives. (Yergin 1988, 112).

The concept of 'low vulnerability' is a more generic expression of Yergin's reliability, reasonable prices and compatibility with major national values and objectives. The concept of a *vital energy system* (further elaborated in the next section) is a more generic expression of Yergin's 'supplies of energy'. On the one hand, it looks beyond purely supply since energy systems also encompass energy end-use and any other elements of energy supply chains. On the other hand, it stresses that the focus of energy security is normally not on some abstract 'energy', but rather on those systems which are essential for the society, i.e. the energy services which a country cannot live without.

The definition which I use may seem more narrow and conservative than some of the ideas proposed in the 'new energy security' literature reviewed in chapter 2, but as I explained there, I find this interpretation more policy relevant and rigorous. Energy security is not about each and every energy issue: it is about those energy concerns which are linked in policy discourses and in public opinion to survival, normal functioning and stability of societies. The climate impacts of energy systems also fall into this category, but I specifically exclude those from my definition of energy security. This is because my whole thesis is about the *relationship* between climate mitigation and energy security and it would not be helped by lumping these two issues into one definition. I will show in the next sections that it is both generic enough to be relevant through the last century of energy security policies and can be specifically operationalized for a quantitative assessment framework.

### 3.3.2 Delineating vital energy systems

I define a vital energy system as a system which is essential for supporting critical societal functions. A serious disruption of a vital energy system may lead to social, political or economic instability and thus is a matter of [energy] security. There are two ways to draw boundaries of vital energy systems (Table 3.1). First, they can be geographic. Thus, one could in principle speak of energy security of a nation, a sub-national region, a regional or political alliance (e.g. the OECD), or the world as a whole. Second, it is possible to focus on security of a primary energy source (crude oil, natural gas, coal, hydro energy, etc.), energy carrier (oil products, electricity, hydrogen, etc.) or energy end-use (transport, industry, etc.). Various combinations of geographic and sector choices define a number of energy systems: "the global oil market", "European electricity network", "transportation in China", etc. For assessing long-term energy security it is necessary to identify energy systems which will be vital for the functioning of societies in the future.

The current and historic focus of energy security policies is national. It almost goes without saying that a nation's energy security is affected by its regional and global context. Many contemporary energy security policies focus on regional or global energy systems rather than merely national ones. For example, the European Union energy security policies address electricity systems in the European Union and their integration with neighboring countries (European Parliament 2006) as well as the Eurasian and global natural gas markets (European Union Council 2004). Regional and global energy markets are also considered in energy security policies and policy-driven assessments in the U.K. (Wicks 2009), Japan (Pant 2006; Atsumi 2007; Mansoz 2010) and Australia (Australian Government Department of Resources Energy and Tourism 2011). Concerns about global oil markets are clear from the presence and policies of international organizations such as the IEA and OPEC.

**Table 3.1:** Vital energy systems at present and in future energy scenarios

| | Geographies | Sectors<br>Energy sources | Energy carriers | Energy end-uses |
|---|---|---|---|---|
| **Present** | Global<br>Regional<br>National<br>Subnational | oil, natural gas<br>hydroenergy,<br>nuclear,<br>biomass, RES | oil products<br>biofuels<br>electricity | transportation<br>industry<br>buildings<br>export<br>revenues |
| **Future** | Global<br>Regional<br>National[b] | oil, natural gas<br>hydroenergy,<br>biomass, RES | oil products<br>synthetic fuels<br>hydrogen,<br>biofuels,<br>electricity | transportation<br>industry, R&C[a]<br>export<br>revenues |

Notes:

[a] The residential & commercial sector was evaluated but the data from the IAMs in this thesis are too aggregated to distinguish these systems as vital energy systems. See the Limitations for more discussion (section 3.5).

[b] National energy security is only evaluated with respect to the major economies (Table 3.2).

National, regional and global energy systems are likely to remain relevant to energy security in the future although their relative importance may change depending on the dynamics of regional and global energy integration. The global IAMs which I use provide regional and global rather than national level data. However, some "regions" are actually composed of one big country. So for China, India, and the U.S., I conducted national analysis. I also analyze the E.U. region in these models. Though the E.U. includes almost 30 countries, in many aspects it acts as a single cohesive economy. The E.U. also has a common energy (including energy security) policy. These are four of the world's major economies, which together account for 60% of the world's GDP and 50% of the world's $CO_2$ emissions (Table 3.2). In addition to the major economies, I analyze the energy exports of two resource-rich regions: the Middle East and the "Reforming Economies" (which is dominated by Russia). Energy export revenue is a vital energy system unique for resource-rich countries. Thus, I analyze three types of regions: industrialized and net-importers (the U.S. and the E.U.); emerging economies and net-importers (China and India); and energy exporters (the Middle East and North Africa, and Russia).

**Table 3.2:** GDP and emissions of major economies

| | GDP 2010 (billion $) | | $CO_2$ emissions ($GtCO_2$/year) | |
|---|---|---|---|---|
| | 2010 | 2050 | 2010 | 2050 |
| **China** | 4 (7%) | 14–37 (14–18%) | 7 (20%) | 11–21 (21–31%) |
| **E.U.** | 15 (27%) | 20–37 (15–19%) | 4 (11%) | 4–6 (6–9%) |
| **India** | 1 (1%) | 6–22 (6–12%) | 1 (2%) | 6–10 (11–16%) |
| **U.S.** | 14 (25%) | 25–34 (14–24%) | 5 (14%) | 4–8 (8–14%) |
| **All four** | 34 (60%) | 65–130 (49–73%) | 17 (47%) | 25–45 (46–70%) |
| **World** | 54 (100%) | 103–203 (100%) | 35 (100%) | 54–73 (100%) |

Notes: Range represents the range across the different models. For 2010, the model averages were used.

Projecting energy sectors into the future is less straightforward than projecting geographic boundaries of vital energy systems. In particular, key primary energy sources and energy carriers can change under radical energy transitions. For example while oil lies at the heart of today's energy security agenda, over the long-term nuclear energy, natural gas, electricity, hydrogen or biomass production could become central to ensuring energy security. Liquid carriers which at present are primarily oil products may become dominated by biofuels, synthetic fuels[25], hydrogen or even abandoned all together for electricity. Thus, to evaluate future energy security I use generic categories of energy sources and energy carriers instead of looking only at today's predominant sources and carriers. At the same time, end-use sectors—transportation, industrial and residential and commercial[26]—are unlikely to change in nature although their relative size and importance could change in future societies. Thus I tried to use the same energy end-use sectors which are used for evaluating current energy security. Ultimately, I was only able to evaluate transportation due to the limited depiction of end-uses in IAMs as discussion in the Limitations (section 3.5).

There are two final remarks to be made about using the concept of vital energy systems for evaluating future energy security. First in relation to energy security, the concept of a vital energy system implies a set of interacting elements which can substituted for each other in the case of a

25. Refers to liquefied coal and natural gas.
26. Residential and commercial energy are typically lumped together in energy statistics.

disruption but cannot be easily substituted by elements from outside the system. For example, when we identify a national electricity system as a unit of evaluation we assume that increasing generation at one national power plant can substitute for a failure of another one, but that increasing power production in another country cannot make up for such a loss and neither can the disruption be remediated by, say, increasing oil imports or refinery output.

Such assumptions are only partially correct at present (consider for example electricity imports or disconnected regional grids within one and the same nation) and their validity in the future may be put into further question. For example, we do not know to which extent global fuel markets or regional energy systems will be integrated and thus how valid it is to think of them as 'systems'. Despite these uncertainties, for effective energy security policy making vital energy systems should be clearly delineated. The only available alternative is to lump all energy systems together which significantly obscures vulnerabilities and blurs policy choices. In other words it is better to have an imperfect representation of vital energy systems than to have no distinction at all.

The second point is that vital energy systems are not independent from each other. End-use sectors depend on carriers which in turn depend on fuels. Thus vulnerabilities "propagate" through energy systems. An example is today's transport system which almost exclusively relies on oil produced in an increasingly limited number of countries and thus is relatively insecure. There is an emerging literature on taking a systems-approach to energy security which can eventually be exploited in evaluating future energy security as well (Scheepers et al. 2007; Le Coq and Paltseva 2009; Jewell 2011b; Cherp et al. 2012; Hughes 2012). I did not identify any specific cases where energy vulnerabilities are likely to propagate through future energy systems as with oil and transport today but these connections are explored more in Chapter 4.



### 3.3.3 Vulnerabilities

The second step in constructing an energy security assessment framework is defining vulnerabilities of vital energy systems, i.e. characteristics determining their energy security. As in the case of vital energy systems, the

**Table 3.3:** Three perspectives on energy security

| | Perspective Sovereignty | Robustness | Resilience |
|---|---|---|---|
| **Historic roots** | War-time oil supplies and the 1970s oil crisis | Electricity blackouts and oil scarcity fears | Liberalization of energy systems |
| **Key risks for energy systems** | Intentional actions by malevolent agents | Predictable natural and technical factors | Diverse and partially unpredictable factors |
| **Primary protection mechanisms** | Control over energy systems and geopolitical arrangements | Upgrading infrastructure and switching to more abundant resources | Increasing the ability to withstand and recover from various disruptions |
| **Parent disciplines** | Security Studies, International Relations, Political Science | Engineering, Natural Science | Economics, Ecology, Complex Systems Analysis |

Notes: Modified from Cherp and Jewell 2011b.

vulnerabilities should be defined specifically enough to echo the current and historic energy security concerns and yet generically enough to be applicable to future energy systems potentially very different from the present ones. This thesis builds on a generic way of structuring vulnerabilities which is based on organizing the concerns over energy security which have emerged and evolved over the last 100 years into three distinct 'perspectives' (Cherp and Jewell 2011b). These perspectives have persisted over the 20th century despite radical changes in energy systems and thus may be considered sufficiently generic and 'timeless' to remain relevant under radical energy transitions of the future (Table 3.3).

The first perspective *sovereignty* views risks as hostile intentions of foreign actors and vulnerabilities as a misbalance of power. It is rooted in such historic events as energy embargoes and malevolent price manipulations by powerful market actors. It analyses energy security in terms of the power balance, the degree of sovereign control over energy systems and the space for maneuver. This perspective persisted through most of the last century as documented by Yergin (1991) culminating in the oil embargoes of the 1970s. It is still relevant with the present-day worries over the 'Russian gas weapon' (Baran 2007) or 'Chinese dash for resources' (Klare 2008).

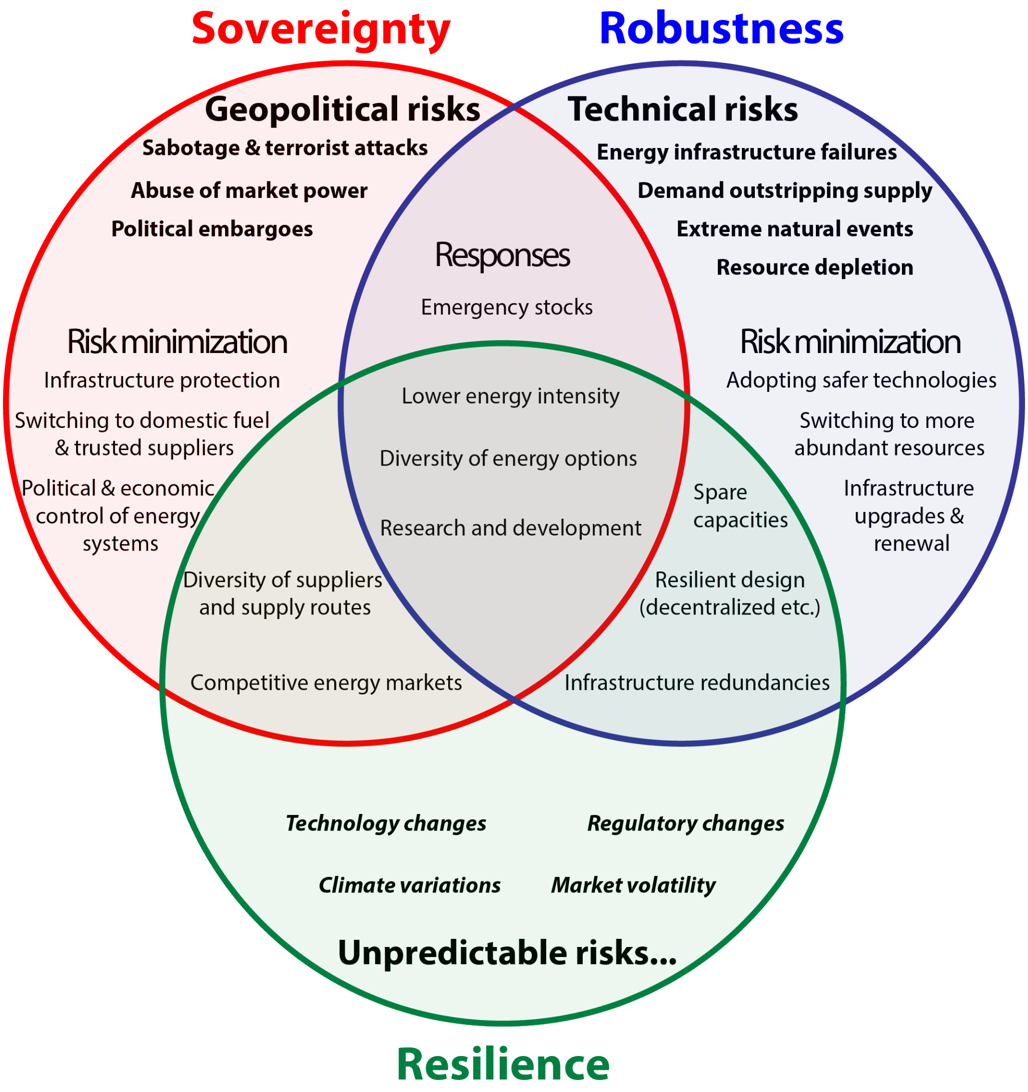
The sovereignty perspective has its disciplinary roots in security studies, international relations and political science. Although it has many aspects (e.g. related to technology dependencies and market arrangements), its main concern is dependence on imported energy and concentration of energy resources in a limited number of hands.

The second perspective *robustness* views risks as stemming from natural or technical events. It is rooted in concern over electricity blackouts, other infrastructure failures and resource scarcity. It analyses energy security in terms of probabilities of such disruptions as well as stresses such as resource scarcity and demand growth. This perspective has become especially prominent with increasing concerns over resource scarcity (Energy Watch Group 2007, 2006; Laherrère 2004; Aleklett et al. 2010; Heinberg and Fridley 2010; Campbell and Laherrère 1998) and the creation of technically complex critical energy infrastructure vulnerable to a wide range of natural and technical disruptions (Dobson et al. 2007; Farrell, Zerriffi, and Dowlatabadi 2006). The robustness perspective has its roots in natural sciences and engineering.

Finally, the *resilience* perspective views risks as largely uncertain and unpredictable and hence emphasizes the ability of energy systems to recover from potential disruptions of any nature. This perspective has its roots in the 'small is beautiful' resilience ideas of the 1970s and 1980s and was boosted with the studies of diversity of electricity generation portfolios in the U.K. in the 1990s. The resilience perspective has its roots in economics and complexity science and addresses the capacity of energy systems to deal with evolving and unpredictable risks as reflected in diversity, energy intensity and vitality of energy markets.

The generic nature of these perspectives and their rooting in political, epistemological and cognitive factors explains the fact that they have framed the energy security policy for the last century and are likely to be relevant for this century as well. These three perspectives encapsulate understanding of risk but also prioritization of response strategies. As shown in Figure 3.2, risk minimization or response strategies can be relevant for one or more perspectives. Within each of these generic perspectives, the nature of vulnerabilities can differ. Vulnerabilities of an energy system are a combination of its exposure to risks and its resilience, i.e. its capacity to respond to disruptions. In Figure 3.2 this is expressed as "risks" and "risk minimization"

**Figure 3.2:** Three perspectives on energy security




The three perspectives on energy security differ with respect to their focus on different energy security risks and response strategies. The 'no-regrets' responses situated in the center of the diagram address the concerns of all three perspectives

strategies.[27] Energy security risks differ with respect to their time-profile (shocks or stresses) and nature (physical or economic)—Figure 3.2 and Table 3.4 show how these distinctions relate to the three perspectives. Resilience can relate to specific risks (e.g. the presence of alternative pipelines

27. Some authors only look at risks (APERC 2007; Winzer 2012), others focus primarily on resilience (Stirling 1994, 1998) whereas others (Kendell 1998; Gupta 2008) look at both risks and resilience.

**Table 3.4:** Examples of vulnerabilities related to the three perspectives

| | Sovereignty | Perspective<br>Robustness | Resilience |
|---|---|---|---|
| **Risks vs** | Disputes with transit countries | Infrastructure failure | Technological surprises |
| **Resilience** | Diversification of supply routes | Infrastructure redundancies | High diversity of energy options |
| **Shocks vs** | Oil embargo | Natural disasters | Regulatory & political changes |
| **Stresses** | Growing oil demand from Asia | Aging power plants | Increasing droughts affecting hydro and thermal power plants |
| **Physical vs** | Sabotage of infrastructure or supplies | Resource depletion | Terrorist attack on domestic infrastructure |
| **Economic** | Price manipulations by suppliers | Underinvestment in production & exploration | Price volatility |

may help to reroute gas imports in case of problems in transit countries) or to more general risks (e.g. strategic storage can protect from shocks of supply caused by political, economic or technical factors).

Another distinction is in relation to disruptions of vital energy systems which can come in the form of shocks (rapidly unfolding short-term disruptions) and stresses (slowly approaching and longer-lasting phenomena) (Stirling 2013). Historically the energy security agenda was primarily shaped by shocks such as the oil crises of the 1970s, the coal miner strikes of the 1980s, and the disruptions of natural gas supply and electricity blackouts of the 2000s. Stresses include unrelenting demand growth, resource depletion and aging of infrastructure. The final distinction between physical and economic risks is drawn from the IEA's definition of energy security: "uninterrupted availability of energy sources at an affordable price" (IEA 2012b).[28] While "uninterrupted availability" is an intuitively clear concept referring to physical risks, "affordable price" is more of a widely debated political construct. As discussed in the section on the economic side of

28. This definition is from before 2012 but I was not able to find the original use of this definition.

energy security (subsection 2.1.5), policy rhetoric on this issue uses such colorful but unhelpful terms as “reasonable”, “true”, “fair”, “affordable”, “cost-effective” and “competitive” prices. Thus, the objective is not to minimize prices but to make sure they are at a balanced level where they ensure sufficient supply and upstream investment without hindering competitiveness of vital national industries or triggering social instability. One decidedly economic energy security problem is price volatility since it can lead to under-investment, swings in state and business revenues and other undesirable effects.

The bigger problem with the physical versus economic distinction is that it is very difficult to draw a boundary between the two because they are inextricably linked (Keppler 2007a). Sufficient supplies of energy can virtually always be obtained but at what price? Indeed over the last several decades the two have gone hand-in-hand: with abundant supplies so go low prices and vice-versa (Helm 2002). Thus while at first glance this may seem like one of the easiest distinctions to make, in actuality it is very difficult and in many cases impossible to disentangle the two. In the next section I will discuss how I deal with this ambiguity in my evaluation of future energy security and how I translate these vulnerabilities into indicators.

### 3.3.4 Indicators

One of the critiques which I levied against the existing literature on energy security in de-carbonization scenarios is that it typically projects current energy security concerns into the future and does not justify the indicators used to evaluate energy security (see section 2.3). The proposed framework, of exploring vulnerabilities of vital energy systems categorized into the three perspectives of energy security avoids this problem by systematically identifying future vital energy systems along with the main vulnerabilities which may emerge in a low-carbon energy system. These concerns can then be expressed with *indicators* or quantitative proxies for vulnerabilities of energy systems (Table 3.5).

Indicators of energy security are used to compare energy security of different countries (Gnansounou 2008; Gupta et al. 2002; Le Coq and Paltseva 2009; Jewell 2011b), plot the evolution of energy security over time (Lefèvre 2010; Löschel, Moslener, and Rübbelke 2010a) or to analyze aspects of future en-

**Table 3.5:** Energy security assessment framework with indicators

| | | | Perspective | |
|---|---|---|---|---|
| | | **Sovereignty** | **Robustness** | **Resilience** |
| **Primary energy sources** | **TPES (all fuels)** | Global energy trade volume & intensity | | Diversity of TPES & Energy intensity |
| | **globally-traded fuels** (oil, coal, gas & bioenergy[a]) | Volume of fuel trade & Regional diversity of exports | Cumulative fossil energy extraction | Predominance of energy source in TPES |
| **Carriers** | **globally-traded carriers** (hydrogen & electricity) | Global energy trade volume of carrier & Regional diversity of exports of carrier | | Diversity of sources used in carrier production |
| **End-use sectors** | **transport**[b] | | | Diversity of sources & carriers used in transport |
| **Regions** | **Four major economies** (China, India, E.U., U.S.) | Energy imports & exports | Cumulative regional fossil energy extraction | Diversity of TPES, electricity & transportation |
| | **Energy exporters** (Middle East and Reforming Economies) | Energy export revenues | | |

Notes:

[a] Bioenergy includes traded biomass in some models and biofuels in others see Table 3.4.1.

[b] I also looked at the diversity of the residential and commercial sector and the industrial sector in GEA. Both of these sectors have high diversity at the regional and global level. Thus, they were ultimately excluded from the analysis since the level of aggregation provided by the models means it is not possible to identify vital energy systems.

ergy security (Costantini et al. 2007; Turton and Barreto 2006; Kruyt et al. 2009). Hundreds of energy security indicators have been proposed in dozens of scholarly articles and policy papers, but only a small number of them are relevant to evaluating energy security under de-carbonization scenarios. During the course of this research I identified, selected and developed a large number of indicators, which are described in detail in Table 3.6. Data and time limitations prevented me from using all of them, but developing this comprehensive list of indicators for future energy security was a methodological contribution of this thesis.

A single indicator can be a measure of one or more concerns and a single concern can be expressed by one or more indicators (Table 3.6). For example, the diversity of exporting regions for a given fuel or carrier relates to the concern of an exporter instituting an embargo (sovereignty perspective) but also to the concern of an energy exporter experiencing a natural disaster or technical disruption such as when Hurricane Katrina disabled most of the U.S.' oil refining capacity (resilience perspective). The following five sections describe the main indicators I use in this thesis as well as the concerns to which they relate.

**Table 3.6:** Indicators of energy security in long-term energy scenarios (indicators used in this thesis are **bold**)

| Indicator | Concern(s) | Definition | Formula | Unit | Geography | Sector | References |
|---|---|---|---|---|---|---|---|
| | | | **Sovereignty Indicators** | | | | |
| **Energy trade volume (T)** | Disruption of trade flows by various factors | Total interregional trade | $T_i = \Sigma s_i$ where $s_i$ is the sum of fuel or carrier $i$ which is traded (it can also be the sum of all traded fuels and carriers for the total trade volume) | EJ/year | Global | **TPES, crude oil, oil products, natural gas, coal, hydrogen, bioenergy, synfuels, electricity**, uranium, other fuels & carriers | Kruyt et al. 2009; Riahi et al. 2012 |
| **Trade intensity (TI)** | same as above | Total interregional trade of a fuel or carrier divided by the total energy of that fuel or carrier | $TI_i = \frac{\Sigma s_i}{E_i}$ where $s_i$ is the sum of fuel or carrier $i$ & $E_i$ is the total of fuel $i$ in the energy system | Global | share | **TPES**, crude oil, oil products, natural gas, coal, hydrogen, bioenergy, synfuels, electricity, uranium, other fuels & carriers | Kruyt et al. 2009; Riahi et al. 2012 |
| **Geographic diversity of exports (GE)** | same as above | Diversity index of regions contributing to global exports of a traded fuel or carrier.[a] | $GE_i = -\Sigma(p_r * \ln(p_r))$ where $p_r$ is the proportion of exports for fuel $i$ from a given region $r$ | unit less | Global | TPES, **crude oil, oil products, natural gas, coal, hydrogen, bioenergy, synfuels, electricity**, uranium, other fuels & carriers | Lefèvre 2007; Costantini et al. 2007; Cherp et al. 2012; Neff 1997[b] |

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| Indicator | Concern(s) | Definition | Formula | Unit | Geography | Sector | References |
|---|---|---|---|---|---|---|---|
| **Net imports (NI)** | Regional vulnerability to trade disruptions by various factors | The sum of all imports minus the sum of all energy exports. | $NI_r = \Sigma f_i - \Sigma f_e$ where $f_i$ is the sum of all imported fuels and $f_e$ is the sum of all exported fuels for a given region $r$ | EJ/year | Regional | **TPES, crude oil, oil products, natural gas, coal, hydrogen, bioenergy, synfuels, electricity**, uranium, other fuels & carriers | |
| **Net import dependence (NID)** | same as above | The sum of all imports minus the sum of all energy exports divided by the region's TPES. | $NID_r = \frac{\Sigma f_i - \Sigma f_e}{E_i}$ where $f_i$ is the sum of all imported fuels and $f_e$ is the sum of all exported fuels & $E_i$ is the total value of energy source $i$ in the TPES for region $r$ | share | Regional | same as above | Costantini et al. 2007; Sovacool and Mukherjee 2011; Kendell 1998; Cherp et al. 2012 |
| Cost of energy imports in relation to GDP (CI) | Regional vulnerability to trade disruptions or price volatility by various factors | The value of all net energy imports in relation to the GDP. | $CI_r = \frac{\Sigma c_i - \Sigma c_e}{GDP_r}$ where $c_i$ is the value of all imported fuels and $c_e$ is the value of all exported fuels & $GDP_r$ is the gross domestic product for a given region $r$ | share | Regional | **TPES** | Costantini et al. 2007; Kendell 1998; Cherp et al. 2012; Vivoda 2009; von Hippel et al. 2011[c] |
| **Value of energy exports in relation to GDP (VE)** | Securing export revenues | The export value of all or certain fuels divided by the region's GDP. | $VE_r = \frac{\Sigma c_e}{GDP}$ where $c_e$ is the value of exported fuels & $GDP_r$ is the gross domestic product for a given region $r$ | share | Regional | TPES, **crude oil, oil products, natural gas, coal**, or a particularly important fuel for exports | Persson et al. 2007; Johansson et al. 2009; van Vuuren et al. 2003, and many others |

*continues on next page*

| Indicator | Concern(s) | Definition | Formula | Unit | Geography | Sector | References |
|---|---|---|---|---|---|---|---|
| Rate of decline of energy export revenue (RE) | Instability associated with rapid decline of energy export revenues | The annual change in energy export revenues | $RE_s = \frac{V_e^t - V_e^{t-1}}{V_e^{t-1}}$ where $V_e^t$ is the value of energy exports $e$ in year $t$. | %/year | Regional | crude oil, natural gas, coal, uranium | |
| Carriers dependence on imported fuels (CD) | Regional vulnerability to trade disruptions by various factors | The share of energy carriers produced from imported sources. | $CD_{cr} = \Sigma(p_i * d_i) + d_c$ where $p_i$ is the proportion of fuel $i$ in carrier $c$ in region $r$ and $d_i$ is the net import dependence of fuel $i$ in region $r$ (zero if fuel is exported) and $d_c$ is the net import dependence of carrier $c$. | share | Regional | oil products, electricity, hydrogen, gas (as a carrier) | Cherp et al. 2012; Gnansounou 2008; Bazilian et al. 2006; Jewell 2011b |
| End-use dependence on imported fuels (ED) | same as above | The share of end-use demand which depends on imported sources. | $ED_{sr} = \Sigma(p_i * d_i) + \Sigma(p_c * CD_c)$ where $p_i$ is the proportion of fuel $i$ in end-use sector $s$ in region $r$ and $d_i$ is the net import dependence of fuel $i$ in region $r$ (zero if fuel is exported) and $p_c$ is the proportion of carrier $c$ in sector $s$. | share | Regional | transportation, industry, residential (particularly the heating sector in certain countries) | Cherp et al. 2012 |
| | | | **Robustness Indicators** | | | | |
| **Cumulative resource extraction (E)** | Vulnerability to energy shocks | All extracted resources of an energy source. | $E_i = \Sigma e_t$ where $e_t$ is the resource extraction for each energy source in year $t$. | EJ | Global or Regional | **crude oil, natural gas, coal**, uranium | Kruyt et al. 2009 |



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| Indicator | Concern(s) | Definition | Formula | Unit | Geography | Sector | References |
|---|---|---|---|---|---|---|---|
| **Share of reserves and resources which are extracted (SR)** | same as above | Sum of all resources extracted for a given energy source divided by the reserves and resources estimate for that source. | $SR_i = \frac{E_i}{R\&R_i}$ where $E_i$ is the extraction for each non-renewable energy source $i$ (see cell above) and $R\&R_i$ is the estimated reserves and resource estimate for that source. | share | Global or Regional | **crude oil, natural gas, coal**, uranium | |
| Reserves to production ratio (RP) | same as above | Reserves or resources divided by annual production rates | $RP_i = \frac{R_i}{a_i}$ where $R_i$ is the reserves or resources for energy source $i$ and $a_i$ is the annual extraction of that source. | years | Global or Regional | crude oil, natural gas, coal, uranium | Turton and Barreto 2006; Wicks 2009; APERC 2007, and many others |
| Average age of infrastructure (IA) | Failure of energy infrastructure | The age of all infrastructural facilities in relation to the projected lifetime. | $IA_i = \frac{A_i}{P_i}$ where $A_i$ is the average age of infrastructure type $i$ and $P_i$ is the projected retirement age for that infrastructure. | share | Global or Regional | power plants, oil refineries or other types of infrastructure | Cherp et al. 2012; UK Conservative Party 2010 |
| Spare capacity for electricity generation(SC) | Electricity blackout | Installed capacity divided by the critical or average load. | $SC = \frac{C}{I}$ where $C$ is the critical or average load and $I$ is the installed capacity. | share | Global or Regional | electricity | Lilliestam and Ellenbeck 2010 |
| Rate of energy sector growth (RG) | Burden from rapid growth | The growth in energy supply, fuel, carrier, or end-use demand | $RG_s = \frac{E_s^t - E_s^{t-1}}{E_s^{t-1}}$ where $E_s^t$ is the energy supply or demand in energy sector $s$ in year $t$. | %/year | Global or Regional | primary energy sources, carriers, end-use demand | Cherp et al. 2012; Leung 2011 |

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| Indicator | Concern(s) | Definition | Formula | Unit | Geography | Sector | References |
|---|---|---|---|---|---|---|---|
| | | | **Resilience Indicators** | | | | |
| **Energy intensity (EI)** | Vulnerability to energy shocks | **Total primary energy supply** or total final energy consumption divided by GDP | $EI = \frac{TPES}{GDP}$ | MJ/$ | Global or Regional | **TPES** | Gnansounou 2008; Kruyt et al. 2009; Cherp et al. 2012, and many others |
| **Diversity of energy sources in TPES (DP)** | Overall vulnerability to various primary energy source disruptions | Diversity of total primary energy supply using either SWDI or HHI[d] | $DP = -\Sigma(p_i * \ln(p_i))$ where $p_i$ is the proportion of source $i$ in the $TPES$ | unit less | Global or Regional | **TPES** | APERC 2007; Jansen, van Arkel, and Boots 2004; Riahi et al. 2012 |
| **Diversity of energy sources in carrier (DC)** | Carrier vulnerability to various primary energy source disruptions | Diversity of energy sources used in carrier production | $DC_c = -\Sigma(p_i * \ln(p_i))$ where $p_i$ is the proportion of source $i$ in carrier $c$ | unit less | Global or Regional | **electricity, liquids**, gases, hydrogen | Stirling 1994[d] |
| **Diversity of energy sources in end-uses (DE)** | End-use sector vulnerability to various primary energy source disruptions | Diversity of energy sources used in end-uses | $DE_e = -\Sigma(p_i * \ln(p_i))$ where $p_i$ is the proportion of source $i$ in end-use $e$ with $p_i = u_i + p_c * c_i$ where $u_i$ is the is the proportion of use of source $i$ in end-use $e$ and $p_c$ is the proportion of carrier $c$ in end-use $e$ and $c_i$ is the proportion of source $i$ in carrier $c$ | unit less | Global or Regional | **transportation**, industrial sector, residential heating | |

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| Indicator | Concern(s) | Definition | Formula | Unit | Geography | Sector | References |
|---|---|---|---|---|---|---|---|
| **Diversity of energy carriers in end-uses (DCE)** | End-use sector vulnerability to various carrier disruptions | Diversity of energy carriers used in end-uses | $DE_e = -\Sigma(p_i * \ln(p_i))$ where $p_i$ is the proportion of carrier $i$ in end-use $e$ (also see figure Figure 4.3.2) | unit less | Global or Regional | **transportation**, industrial sector, residential heating | |

Notes: Indicators used in this thesis are marked in **bold**. Indicators which were not reported were left out either because they were not possible to calculate in the IAMs or they did not add information to the indicators which are covered. More explanation can be found in the main text.

[a] This thesis uses the Shannon Wiener diversity index (see page 83 for the equation used in all diversity calculations). See the following section on diversity for a discussion of the Herfindahl-Hirschmann index.

[b] Neff 1997 and Lefèvre 2007 use the Herfindahl-Hirschmann index. Costantini et al. 2007 use both the SWDI and HHI.

[c] Kendell 1998 uses value of oil imports as a measure for oil import dependence and Costantini et al. 2007 uses value of oil and gas imports as a vulnerability indicator. Neither of them presents this indicator in relation to GDP.

[d] Only uses diversity of energy sources in electricity production.

### Energy trade

*Global fuel trade* is the sum of all net exports for each globally-traded fuel or carrier and is a proxy for disruption of trade flows by various factors. This thesis analyzes trade in crude oil, oil products, natural gas, coal, electricity, hydrogen, bioenergy (including biofuels and biomass), electricity and fossil synfuels (produced from coal-to-liquids or natural gas-to-liquids). Global energy trade is the sum of all global fuel trade. This value only accounts for trade between regions and excludes trade within a region (such as electricity trade between France and Spain) but it accounts for the majority of global energy trade.[29] Two models (ReMIND and IMAGE) model uranium trade but I did not analyze it because trade in uranium is not the main energy security issue for nuclear energy. The geographic concentration of the nuclear industry (both enriched fuel and nuclear power plant construction) is more of an energy security issue (Cherp et al. 2012) which is not represented in any of the models analyzed.

*Trade intensity* is calculated by dividing the total volume of energy trade (or the volume of trade for a carrier or a fuel) by the total primary energy supply (or the total supply for a carrier or a fuel). For this indicator it is critical to use the same primary energy accounting method to compare different scenarios. In the thesis, I use the direct equivalent accounting method for the LIMITS and RoSE scenarios; for the GEA scenarios I use the substitution equivalent. This is because the study protocol for LIMITS and RoSE scenario exercises called for using the direct equivalent accounting method and the GEA scenario exercise called for using the substitution equivalent method.

The *geographic diversity of exports* for each globally-traded fuel or carrier reflects the current energy security concerns associated with fuels such as oil, which are only produced in a small number of countries and regions. The regional proportion for each globally-traded fuel or carrier is calculated by dividing a region's net-exports of a fuel or carrier by the total volume of global trade for this fuel or carrier. Then the Shannon-Wiener Diversity Index (SWDI) is calculated for the distribution between energy exporting regions. It would also be possible to calculate this using the Herfindahl-

29. Country-to-country oil trade in 2010 was about 110 EJ (British Petroleum 2012) while in the models in this thesis oil trade was between 68 EJ and 83 EJ. Thus, interregional trade currently accounts for about 60%–75% of all oil trade.

Hirschmann Index (HHI) (Hirschmann 1945, 157–162) but I chose the SWDI for reasons discussed in the next section.

On the regional level, *net energy imports* is the sum of all imports minus the sum of all exports for all fuels and carriers. The indicator relates to disruptions from imported fuels. I follow the IEA's convention and do not add a conversion factor for secondary fuels. For example, if a country imports 10 EJ of crude oil, 3 EJ of oil products and 0.5 EJ of biofuels with no other imports or exports, their import dependency is 13.5 EJ. *Net-import dependence* is calculated by dividing the net energy imports by the TPES. Energy imports are an indicator of exposure to both physical and price disruptions since imported energy represents energy which policy-makers have less influence over. While domestic energy can easily be heavily subsidized or even nationalized for energy security reasons, this is more difficult (or impossible) to do for imported energy.

For energy exporters, I calculate the total *energy export revenue* from oil and gas exports by summing the value of energy exports. I also compare it to a region's GDP to approximate the proportion of the economy which comes from energy exports. A similar calculation was done for energy importers using the value of energy imports divided by the GDP of the country or region but it did not tell a different story then the net energy import story so was excluded from this thesis.

Another regional trade indicator is the reliance on imported fuels in carrier production or end-use sectors. This can be calculated by decomposing the end-use sectors into their globally-traded fuels and carriers (similar to the primary energy source decomposition in Figure 4.3.2) and sum the net-imports for each globally-traded fuel or carrier. This indicator could capture concerns such as the high import dependence of the transportation sector in most countries today (Cherp et al. 2012). The indicator was tested in the LIMITS scenarios but was ultimately not included in the thesis because it did not show a different story from the net energy import one.



### *Diversity*

For diversity, I use the Shannon-Weiner diversity index (SWDI):

$$SWDI = -\Sigma p_i * \ln(p_i)$$

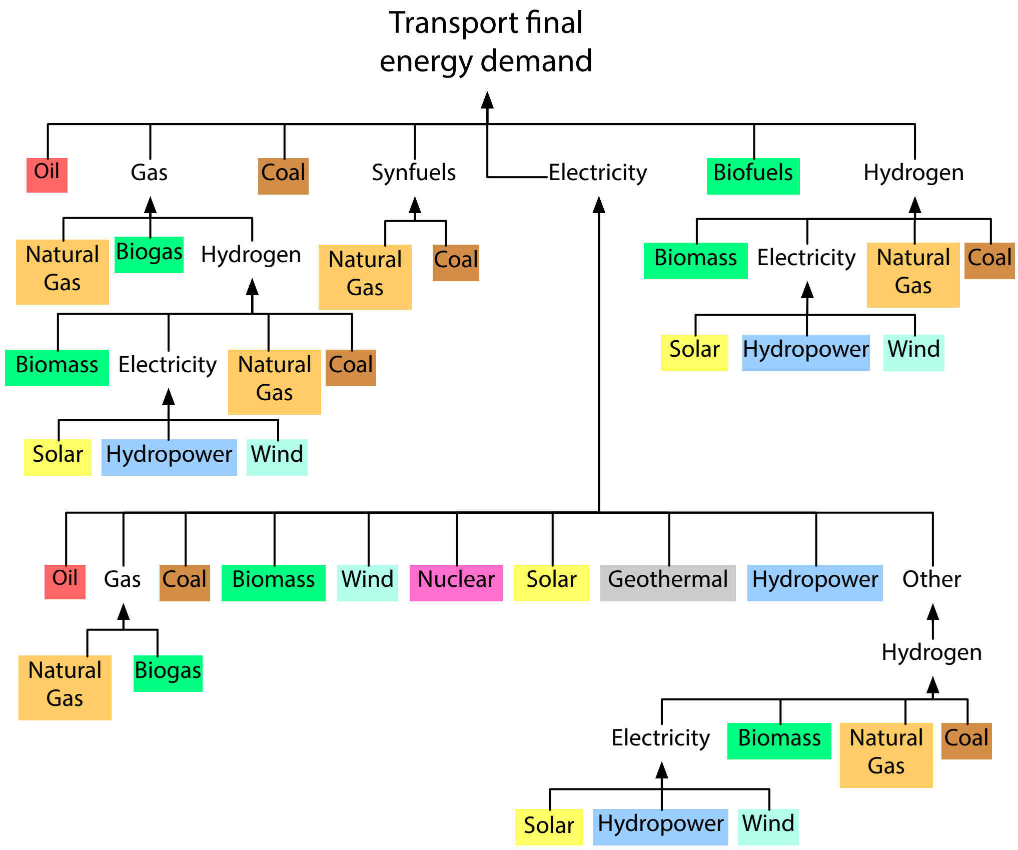
where $p_i$ is the share of the primary energy source $i$ in the TPES. This index has been widely used in the literature (Jansen, van Arkel, and Boots 2004; Costantini et al. 2007; Kruyt et al. 2009). The Herfindahl-Hirschmann index[30] (HHI) (Hirschmann 1945) has also been used in the literature as a measure of diversity (Grubb, Butler, and Twomey 2006; Jansen, Beurskens, and Tilburg 2006; Jewell 2011b; Neff 1997). Stirling argues that the SWDI is better than the HHI because the ordering of results are not influenced by the base of the logarithm or power) which is used (Stirling 1998, 53–54). However, the HHI comes from economics while the SWDI comes from biology so there are cases when it is simply easier to use the HHI because it is less of a stretch for one's audience to understand. For example, when I worked at the IEA on energy security indicators, I used the HHI because many of my colleagues were economists and thus took to the HHI easier then to the SWDI. (Yet another example of how one's disciplinary roots shape analysis even in interdisciplinary research).

Much more important than the question of which diversity index is the question of diversity of *what* is measured. The most useful analysis of diversity is one that measures the diversity of energy options within a vital energy system (subsection 3.3.2). Indeed diversity indices were first proposed to measure the diversity of sources in an electricity system (Stirling 1994). Electricity systems are both vital to modern economies and the various sources of electricity production are substitutable.

In this thesis, I present the diversity of TPES as well as the diversity of energy sources used for electricity generation, liquids (in the case of RoSE) and the transport sector (in LIMITS and GEA). The TPES diversity was calculated based on the proportion each primary energy source contributed to the TPES using the substitution equivalent PES accounting method for GEA and direct equivalent for RoSE and LIMITS as discussed on page 81. The SWDI is used for electricity and liquid fuels and reflects the diversity of fuel sources used for electricity generation or liquids. It is calculated for end-uses based on the diversity of primary energy sources by proportionally allocating different energy carriers to their respective sources (see Figure 4.3.2). This proportional allocation 'map' needs to be tailored for the specific configuration of an energy system, actual or modeled. In the LIMITS scenarios it was not possible to do such a detailed calculation for

30. Herfindahl-Hirschmann index = $\Sigma p_i^2$

**Figure 3.3:** Allocating primary energy sources for transportation in the GEA scenarios




all the models so the diversity is calculated between "fossil energy", "bioenergy", "non-biomass renewables", "nuclear" and "other". Thus the way we apply the end-use diversity index accounts for disruptions which would occur at the primary energy level. It is also possible to measure the diversity of carriers (e.g. electricity vs. liquid fuels) used in an end-use sector. I did not include that analysis in this thesis though I do highlight cases where the transport sector comes to be dominated by hydrogen.

### *Energy intensity*

Energy intensity is the amount of energy used per unit of GDP or value-added. It is a proxy for how vulnerable an energy system is to supply or price shocks and is a widely-used indicator for energy security (Gnansounou 2008; Hughes 2012; Jansen and Seebregts 2009). This is also an indicator of vulnerability to price volatility since the more energy intensive an economy is the more exposed to price swings it is. Energy intensity is also a proxy for the prices of energy services although the link between energy services and energy use in end-use sectors is not well represented in IAMs. Nevertheless, the decoupling of final energy use from GDP as reflected in decreasing energy intensity reflects, on the macro level, generally lower vulnerability of energy services to energy price fluctuations and thus gains in energy security.

In this study energy intensity is a unique indicator because, in Integrated Assessment Models, it is typically an endogenous variable. The GEA scenario set offered a unique opportunity to test the effect of an increase in energy intensity on other aspects of energy security such as energy trade and diversity since energy intensity was partially exogenous. Thus while I only calculated the other energy security indicators ex-post (except for resource scarcity discussed in the next section), I also tested the effect energy intensity has on other aspects of energy security.

### *Resource scarcity and robustness indicators*

The total resources extracted divided by the current estimated resources and reserves from Rogner et al. (2012) is a proxy for energy resource "scarcity". There are several who argue that resource scarcity is not a critical issue in energy security (Rogner et al. 2012). However, experience of many countries such as the U.S., U.K., China and Argentina demonstrates that projected depletion and scarcity of domestic resources becomes an energy security concern long before it translates into actual import dependency (for example, Kuzemko (2012) provides ample evidence that looming depletion of domestic resources shaped the U.K. energy policy). Resource scarcity (even only in perception) leads to speculation, price volatility and overall uncertainty. Similar to energy intensity, this indicator is used both as an endogenous variable and as an exogenous assumption to see how it impacts other aspects of energy security with and without climate policies.

A separate note should be made concerning other robustness indicators. Many such indicators have been proposed and used for the studies of present-day energy security. These include reserves or resources-to-production (R/P) ratio, rates of demand growth, reliability of electricity and heating supply, age of energy infrastructure, spare storage capacities and number of import entry points (Cherp et al. 2012; Winzer 2012; Jewell 2011b). Almost none of these indicators can be meaningfully estimated in IAMs. For example, the reliability of electricity supply and the age of power plants can be empirically observed at present but their behavior in the future is endogenously optimized meaning the replacement of power plants follows planned retirement ages and lifetime extensions are not represented.

*Summary of indicators*

In summary, this study uses indicators which can be grouped into three categories: (1) related to trade and reflecting the sovereignty perspective, (2) related to resource depletion and reflecting the robustness perspectives; (3) related to diversity of energy options and energy intensity and related to the resilience perspective. Each category contains one or several generic indicators. The novelty of my approach is that in line with the proposed energy security assessment framework that focuses on 'vital energy systems', I utilize these indicators in relation to multiple energy systems delimited by various geographic and sectoral boundaries. That means that all in all I use 21 global indicators and nine indicators for each of the four regions.

## 3.4 Study design

The bulk of this thesis is based on three sets of scenarios generated by six Integrated Assessment Models: GCAM (Calvin, last revision 21 August 2012), IMAGE (MNP 2006; van Vuuren 2007), MESSAGE (Riahi, Grubler, and Nakicenovic 2007), ReMIND (Bauer, Brecha, and Luderer 2012; Bauer, Baumstark, and Leimbach 2011; Luderer et al. 2011; Leimbach et al. 2010), TIAM-ECN (Keppo and van der Zwaan 2011; van der Zwaan, Keppo, and Johnson, *under review*) and WITCH (Bosetti, Galeotti, and Lanza 2006; Bosetti et al. 2009). This reflects the intellectual development from the initial stages of research in the *Global Energy Assessment* (Riahi et al. 2012; Jewell, Cherp, and Riahi, *under review*), which used MESSAGE, to using my approach in two multi-model comparison scenario exercises (Jewell et al., *under review*; Cherp et al., *under review*). Participating in these projects gave me access to large datasets which are needed to achieve my objective of evaluating energy security under low-carbon scenarios. In addition to the IAM scenario exercises, I used secondary data from published studies to analyze the impact of climate policies on energy export revenues.

Each IAM scenario exercise involved one or more models which generated several decarbonization and baseline scenarios designed to explore a specific research question. All of the scenario exercises include de-carbonization scenarios which stabilize the concentration of greenhouse gases in the atmosphere at 450 ppm $CO_2$-equivalent but each set was oriented to test different variables and uncertainties. The GEA scenarios were designed to explore different policy and technological options both on the supply and demand side. Thus, the scenario taxonomy emphasizes different technological constraints (ranging from no-nuclear development to rapid electrification of the transport sector) but does not vary GDP or population growth rates, resource availability or GHG limits. (All GEA scenarios meet a 450ppm $CO_2$-eq target which implies staying within the 2°C limit with a 50% probability). On the other hand, the RoSE scenarios explore the effect of different GDP and population growth rates, resource availability constraints and GHG limitations. Finally, the LIMITS scenarios were designed: (1) to test the feasibility of reaching 450 ppm $CO_2$-eq or 500 ppm $CO_2$-eq emissions targets based on when different climate policies are implemented and (2) the regional costs of different burden sharing regimes.

This study design (using multiple models with three different scenario sets) offers both an opportunity and a challenge. On the one hand it means that the effect of different variables and assumptions on future energy security can be explored. The GEA scenario set can be used to explore the effect different technological options would have on energy security. The RoSE scenarios can be used to explore the effect of different economic growth rates, resource constraints and stringency of climate targets on energy security. And the LIMITS scenarios can be used to test the energy security implications for major economies. By using multiple modeling frameworks I can triangulate my findings which allows me to test their robustness and identify where the most uncertainty exists. However, in this sort of study one should be prepared to deal with frequent disagreement between models. Such disagreements require careful interpretation as they may result from substantive uncertainties of the future or methodological artifacts of different modeling approaches. The rest of this section describes each of the modeling frameworks and scenario sets. I conclude by mapping the scenario exercises and their respective scenarios to my research questions.

### 3.4.1 Models

This thesis uses results from six Integrated Assessment Models (IAMs). Table 3.7 summarizes the aspects of each energy model relevant for the purpose of this thesis, especially with respect to energy trade which has direct relevance to energy security.

As discussed in the Literature Review (subsection 2.2.5), IAMs were constructed largely for the purpose of exploring different global futures and informing policy-makers about potential options to mitigate climate change. All IAMs used in my thesis are energy-economy models. This enables them to calculate the future energy demand and various options for meeting this demand with different combinations of energy resources and technologies. In order to link these future energy systems with the global climate, the IAMs use additional models related to emissions, atmospheric chemistry, atmosphere-ocean interaction, land-use, forestry and agriculture, and other models. The IAMs are different in both how they represent energy-economy interactions and how they connect to climate and other global systems. These differences are rooted in different histories of the models, different assumptions, calculation methods and data that they use.

With respect to the energy-economy interaction the IAMs use different algorithms to connect the representation of the energy system to the representation of the economy. The most notable divide is between the simulation and the optimization models. *Simulation* models (such as IMAGE) use deterministic algorithms to 'predict' investments in energy systems based on energy demand, modeling constraints and other assumptions (van Vuuren 2007). These models aim to "realistically" depict the behavior of energy markets under given conditions and constraints. Energy investments are not optimized over a long period of time but rather follow costs and prices at each time period so as to balance supply and demand within each time step; this solution mechanism is called 'recursive dynamic' (Stanton, Ackerman, and Kartha 2009). *Optimization* models, such as ReMIND, in contrast, seek the *optimal* (rather than the *realistic*) solution for a given set of constraints and thus optimize investments over a long period of time.

The optimization can be conducted with respect to 'welfare maximization' or 'cost minimization'. Many models can be run with different solution mechanisms in different parts of modeling experiments. For example, MESSAGE, ReMIND and WITCH, which are all typically run in intertemporal optimization with perfect foresight were run with myopic settings for the LIMITS experiments (i.e. with a linear recursive solution mechanism in certain time-steps).

Neither modeling approach is inherently superior to the other. Simulation models inevitably contain certain assumptions to constrain the energy system and investments in a 'realistic' path. On the other hand, optimization models contain the unrealistic assumption of a 'central planner' who optimally allocates resources; while less realistic, these models are actually more transparent and can be more didactic by normatively pointing to the optimal or cheapest way to reach a given set of energy goals. Additionally, neither modeling approach directly replicate how economic decisions are made since; in reality, decisions are neither made with complete disregard for the future (linear recursive) nor with perfect foresight (intertemporal optimization).

Another distinction between models is the degree of *market equilibrium* which is achieved. Market equilibrium can either achieved with a 'general equilibrium model', such as ReMIND, where economic growth is an endogenous (internally calculated) variable strongly linked to energy system developments and thus to climate policy or with 'partial equilibrium models' where economic growth is an exogenous (externally defined) variable which is not affected by developments in energy systems. General equilibrium models typically assume idealized interactions between economic sectors which are somewhat unrealistic; they also tend to be limited in technological detail (Krey, *under review*). On the other hand, partial economy models probably underestimate the interaction between different economic sectors and the impact which a climate policy would have on the overall economy.

All advanced IAMs evolve with time by incorporating new and more sophisticated modules for addressing various aspects of reality (ranging from fertility to biodiversity) and learning from each other. The models also evolve with respect to the number (and type) of regions that they analyze. For example, IMAGE was originally designed as a model with a single region and now it has 26. Since IAMs are constantly being improved, it is impossible to define a fixed categorization. In the '90s and early 2000s, IAMs were typically divided between 'top-down' (rooted in economics) and 'bottom-up' (rooted in engineering); these two types had vastly different cost estimates for decarbonization (Grubb et al. 1993). In recent years, this distinction has largely dissolved as virtually all IAMs today are hybrids (Hourcade et al. 2006; Clarke et al. 2009). Nevertheless, this history is useful to keep in mind since even as IAMs develop, they tend to retain their specific strengths rooted in their respective histories and the characteristics of the scientific communities that develop them.

For example, MESSAGE began as a tool for energy planning and is still very strong in depicting detailed energy systems and their various characteristics such as local air pollution from energy installations and energy access in developing countries (Riahi et al. 2012; McCollum et al. 2013). GCAM is a partial equilibrium model with the capacity to model interactions between land-use from different economic sectors and endogenous representations of land-use, land coverage as well as the terrestrial carbon stock and flows (Wise et al. 2009; Calvin, last revision 21 August 2012). WITCH has an advanced representation of innovation and research and development as well as the ability to represent 'non-cooperative' solutions where various regions pursue different goals (Bosetti et al. 2011). ReMIND is unique in that it is an economic growth model with high technological resolution and a high degree of flexibility (Leimbach et al. 2009). IMAGE, originally conceived as a global change model has an energy-economy simulation module (TIMER) and detailed representation of various global environmental parameters (MNP 2006). TIAM-ECN is a partial equilibrium model based on the widely used TIMES model (Loulou et al. 2005); the Energy Research Center of the Netherlands (ECN) is developing the model with a particular strength in depicting technological diffusion, both of supply and demand technologies (van der Zwaan, Keppo, and Johnson, *under review*; Keppo and van der Zwaan 2011; Rösler, Bruggink, and Keppo 2011).

**Table 3.7:** Key model characteristics

| Model | Time step (years) | no. of regions | Economic treatment | Solution mechanism | Key features | Trade: Primary oil | Primary gas | Primary coal | Primary U | Primary bio | Trade: Secondary oil | Secondary elec | Secondary bio | Secondary $H_2$ | Secondary syn | Key references |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GCAM | 10 | 14 | market equilibrium | recursive dynamic | energy economy model with an emphasis on interactions between energy, agriculture & land-use | - | - | - | - | - | - | - | - | - | - | Calvin, last revision 21 August 2012 |
| IMAGE | 1 | 26 | simulation | recursive dynamic | global change model with an energy-economy module | X | X | X | X | X | | | | X | | van Vuuren 2007; MNP 2006 |
| MESSAGE | 10 | 11 | cost minimization | intertemp. optimization | energy-economic model strong in system engineering supplemented by several modules (climate, access etc.) | X | X | X | | | X | X | X | X | X | Riahi, Grubler, and Nakicenovic 2007 |
| ReMIND | 5 | 11 | general equilibrium | intertemp. optimization | energy-economy model with detailed representation of energy technologies and simple CC module | X | X | X | X | X | | | | | | Luderer et al. 2011; Leimbach et al. 2010 |
| TIAM-ECN | 5 | 15 | welfare maximization | intertemp. optimization | bottom-up energy system model with emphasis on technological development | X | X | X | | X | X | X | X | | | Keppo and van der Zwaan 2011; van der Zwaan, Keppo, and Johnson, *under review* |
| WITCH | 5 | 12 | welfare maximization | intertemp. optimization | energy-economy model strong in representation of innovation supplemented by climate change & land-use modules | X | X | X | | | | | | | | Bosetti et al. 2009, 2006 |

Note: GCAM does model trade but they did not report it for this exercise. WITCH only reported oil trade in the RoSE project.

Integrated Assessment Models can be used for different purposes in designing and evaluating climate mitigation and other long-term energy policies. Most useful is their ability to explore how the global energy system responds to various constraints, such as: carbon taxes, access to electricity, resource extraction limits, efficiency or renewable energy targets. Models differ with respect to what types of constraints they can include. The constraints are typically set within a scenario exercise to answer certain questions (the constraints used in the scenario exercises which I use in this thesis are described below). Given these differences between models and their usage, the advantage of a multi-model comparison is that it is possible to look for robust findings across different modeling assumptions while the advantage of using a single model is that the scenario design can be more complex and the system boundaries can be wider.

### 3.4.2 Scenarios

This thesis is based on some 70 scenarios selected from three modeling exercises to answer the Research Questions. The scenarios are described in the following three sub-sections grouped by the modelling exercise. I give relatively more space to the description of the GEA scenarios because GEA provides 41 of all the explored scenarios arranged in a relatively complex taxonomy.

*LIMITS Scenarios*

The basic set of scenarios is from the Low climate IMpact scenarios and the Implications of required Tight emission control Strategies (LIMITS)[31] scenario exercise. I included three scenarios from the larger scenario set used in LIMITS: two climate policy scenarios and the Baseline-L scenario. The first climate policy scenario, the Stringent policy scenario or “StrPol-L”, projects the most ambitious interpretation of the Copenhagen emission reduction pledges. Thus, this scenario allows me to test the implication of nationally-implemented climate policies on energy security. The second climate policy scenario is identical to StrPol-L until 2020 with long-term stabilization policies (through a global carbon tax) implemented in 2020. While the latter is consistent with a 2°C target, the former is more likely

31. http://www.feem-project.net/limits/

to allow a temperature rise of around 3°C by the end of the century. More details on the scenarios are available in Kriegler et al. (*under review*).

For the energy exporter analysis, I use three scenarios: the Baseline-L scenario and two 450 scenarios. Both 450 scenarios assume the modest Copenhagen pledges until 2020 after which a global carbon tax is introduced to stabilize the climate at 450ppm $CO_2$-eq. One of the stabilization scenarios, only implements a global carbon tax (450r-L) while the other one is an "equal effort burden sharing scenario" (450rEE-L). The equal effort scenario, equalizes mitigation costs between all regions with financial flows through the global carbon market. Thus, this scenario allows me to analyze if a global carbon market could be used to compensate energy exporters for lost oil and gas revenues from global climate stabilization. More scenario details are available in Tavoni et al. (*under review*).

### *RoSE scenarios*

The RoSE scenarios[32] test the effect of: the nature of climate policies, different GDP growth rates and fossil fuel availability on future energy security (Table 3.8). The three different climate policies include: moderate policy or "MOD" which projects the lower end of the Copenhagen commitments; following the MOD trajectory until 2030 then adopting 550 ppm $CO_2$-eq stabilization; and following the MOD trajectory until 2020 followed by adoption of 450 ppm $CO_2$-eq stabilization. The GDP varies between "Slow", "Medium" and "Fast"[33]: at the global level, this means 1.9% over the 21st century in the "Slow" case, 2.4% in the "Medium" case and 2.9% in the "Fast" case. At the regional level the regions experience convergence (meaning that the relative GDP/capita difference decreases). The fossil availability assumptions vary between "Low", "Medium" and "High" availability of oil, gas and coal. Additionally, there is a "Low Oil" case with low oil availability.



32. http://www.rose-project.org/
33. An additional GDP scenario with slow growth and fast convergence (i.e. developing regions catching up very fast with the developed world) was tested, but it is not discussed in the Results because these assumptions did not have a discernible effect on energy security.

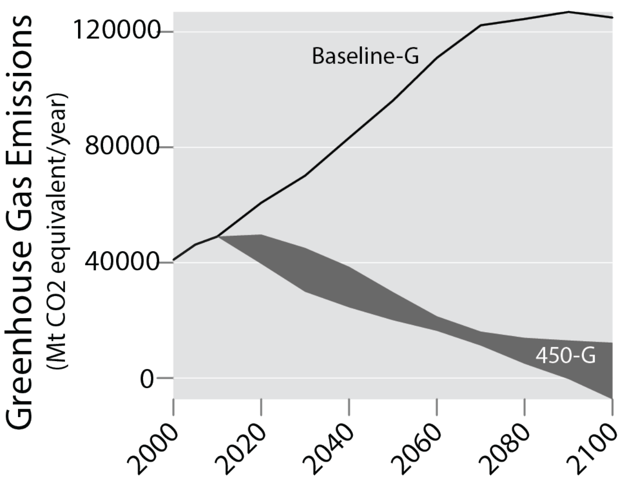
**Table 3.8:** Scenarios from the RoSE scenario exercise

| Climate Policies | GDP growth (medium fossil fuel availability) | | | Fossil Fuel availability (medium GDP growth) | | |
|---|---|---|---|---|---|---|
| | **Medium** | **Fast** | **Slow** | **High** | **Low** | **Low Oil** |
| Business as usual | BAU DEF-R | BAU FS Gr-R | BAU SL Gr-R | BAU HI Fs-R | BAU LO Fs-R | BAU LO oil-R |
| Moderate policy | MOD DEF-R | MOD FS Gr-R | MOD SL Gr-R | MOD HI Fs-R | MOD LO Fs-R | MOD LO oil-R |
| 550 ppme | 550 DEF-R | 550 FS Gr-R | 550 SL Gr-R | 550 HI Fs-R | 550 LO Fs-R | 550 LO oil-R |
| 450 ppme | 450 DEF-R | 450 FS Gr-R | 450 SL Gr-R | 450 HI Fs-R | 450 LO Fs-R | 450 LO oil-R |

### *GEA Scenarios*

The GEA scenarios stabilize atmospheric GHG concentration at 450 ppm $CO_2$-eq (which means that with 50% probability, global mean temperature does not rise more than 2°C above pre-industrial levels by 2100) under medium GDP and population assumptions (Figure 3.4).

**Figure 3.4:** Annual GHG emissions in the Baseline-G and 450-G scenarios



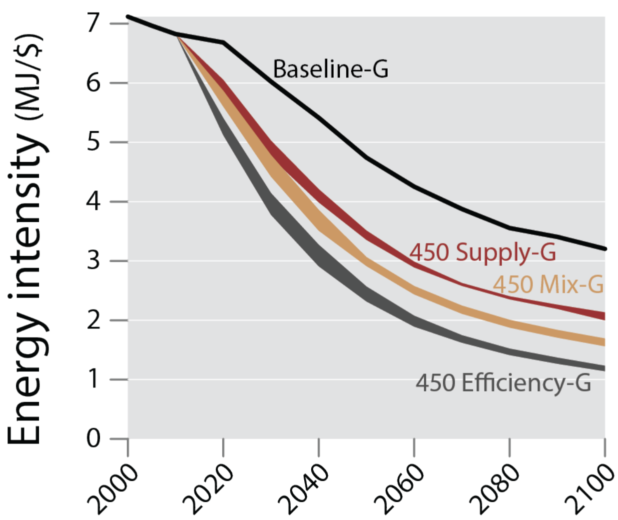

This scenario set[34] was designed to explore the possibility of stabilizing the climate with different technological options. There are three dimensions of technological and policy choices which potentially affect energy security in the low-carbon scenarios. The first dimension concerns energy demand, where the low-carbon scenarios fall into three groups:

34. More extensive documentation can be found in the GEA report (Riahi et al. 2012); additionally, quantitative results are publicly available at: http://www.iiasa.ac.at/web-apps/ene/geadb.

- **Efficiency** scenarios where the focus of policy and investment is on energy efficiency improvements resulting in significantly suppressed overall energy demand;
- **Supply** scenarios where policy and investments are focused on low-carbon energy supply technologies resulting in more rapid transformation of the energy mix and relatively fast growth in energy demand;
- **Mix** where equal focus is given to supply- and demand-side policies and investments.

Figure 3.5 shows energy intensity in the three groups of scenarios. Under a given GDP assumption, higher energy intensity translates into higher demand while lower intensity translates into lower demand.

**Figure 3.5:** Energy intensity in the Baseline-G and 450-G scenarios




The second dimension of choices potentially affecting energy security concerns constraints imposed on supply-side technologies in selected scenarios, namely:

- **Limited RES** scenarios where intermittent solar and wind energies make up no more than 20% of final energy consumption;
- **Limited BE** scenarios with bioenergy limited to no more than 50% of the estimated global potential;

- **No-NUC** scenarios where no additional nuclear capacity is built after 2020 and all nuclear power is phased out by 2060;[35]
- **No-CCS** scenarios with no development of carbon capture and storage (CCS).
- **No bioenergy CCS** scenarios where CCS technologies are not applied in conjunction with biomass combustion;
- **No carbon sinks beyond the baseline** scenarios where additional (non-energy) carbon sinks are not created.

The third dimension of choices within the GEA scenarios concerns the configuration of transport systems, namely:

- **CTR** scenarios with conventional transport systems relying primarily on liquid fuels;
- **ATR** scenarios with advanced transport systems increasingly relying on electric and hydrogen propulsion of vehicles.

Not all combinations of demand, supply and transport constraints are present among low-carbon scenarios. "Efficiency" scenarios allow for climate goals to be reached with a broader range of supply-side constraints (e.g. a combination of limited RES+limited BE or NoNUC + NoCCS). "Supply" scenarios allow only for selected supply-side constraints (e.g. NoNUC+NoCCS is not possible). The full list of scenarios is presented in Table 3.9.

The different levels of energy demand and alternative assumptions about possible restrictions for supply-side technologies have major implications for the future portfolio of energy options. The GEA scenarios depict many possible evolutions of the energy system, exploring alternative routes of low-carbon energy transitions. Some scenarios are for example characterized by a relatively high contribution of renewables while others emphasize carbon capture and storage or nuclear energy. For a more detailed discussion of the GEA scenarios, see Riahi et al. (2012).



35. This assumes a 40-year life-span for nuclear power plants.

**Table 3.9:** GEA 450 Scenarios (450-G)

| Supply limitations | Demand variations: Supply – Advanced transport (ATR) | Supply – Conventional transport (CTR) | Mix – Advanced transport (ATR) | Mix – Conventional transport (CTR) | Efficiency – Advanced transport (ATR) | Efficiency – Conventional transport (CTR) |
|---|---|---|---|---|---|---|
| **Full portfolio of supply options** | SupplyATR Full | SupplyCTR Full | MixATR Full | MixCTR Full | EfficiencyATR Full | EfficiencyCTR Full |
| **Limited renewable energy sources (RES)** | SupplyATR LimitRES | - | MixATR LimitRES | MixCTR LimitRES | EfficiencyATR LimitRES | EfficiencyCTR LimitRES |
| **Limited bioenergy (BE)** | SupplyATR LimitBE | - | MixATR LimitBE | MixCTR LimitBE | EfficiencyATR LimitBE | EfficiencyCTR LimitBE |
| **Limited RES & Limit bioenergy** | - | - | - | - | EfficiencyATR LimitRES & LimitBE | EfficiencyCTR LimitBE & LimitRES |
| **No nuclear (NoNUC)** | SupplyATR NoNUC | SupplyCTR NoNUC | MixATR NoNUC | MixCTR NoNUC | EfficiencyATR NoNUC | EfficiencyCTR NoNUC |
| **No carbon capture and storage (NoCCS)** | - | SupplyCTR NoCCS | MixATR NoCCS | MixCTR NoCCS | EfficiencyATR NoCCS | EfficiencyCTR NoCCS |
| **NoNUC & NoCCS** | - | - | - | - | EfficiencyATR NoNUC & NoCCS | EfficiencyCTR NoNUC & NoCCS |
| **No bioenergy CCS* (NoBCCS)** | SupplyATR NoBCCS | - | MixATR NoBCCS | - | EfficiencyATR NoBCCS | EfficiencyCTR NoBCCS |
| **No additional carbon sinks* (NoSinks)** | SupplyATR NoSinks | - | MixATR NoSinks | MixCTR NoSinks | EfficiencyATR NoSinks | EfficiencyCTR NoSinks |
| **No bioCCS & No sinks & Limited BE*** | - | - | - | - | EfficiencyATR NoBCCS & NoSink & LimitBE | EfficiencyCTR NoBCCS & NoSink & LimitBE |

Notes: *These constraints only had a small effect on energy security and for that reason are not specifically mentioned in the results (but they are included in the analysis). Cells marked with "-" denote scenarios which were infeasible.

### 3.4.3 Overall study design

My overarching research question: "How would climate change policies affect global energy security?" is broken into five sub questions: three which relate to different policy uncertainties (the nature of the climate regime (A), GDP growth & fossil fuel availability (B), and technological limitations(C)); one relates to the energy security of major economies (D); and one relates to energy exporters (E). Table 3.10 summarizes how each modeling exercise maps onto these research questions.

All of the modeling exercises are relevant to the each of the global concerns identified for the overarching research question (represented in the "climate stabilization policies" column). The one exception is the question of resource use and scarcity. I excluded GEA from this part of the analysis because in GEA, the resource use in the climate scenarios was restricted to conventional resources. The development of energy security of major economies (research question (D)) under climate stabilization policies (described in the bottom half of the table) was only explored in LIMITS which focused on the nature and timing of climate regimes. This is for two reasons: one conceptual and one practical. Conceptually, I chose to focus on the major economies in LIMITS because this scenario exercise focused on different burden sharing climate regimes. Thus it is an ideal scenario set to explore if the nature of the policy agreement effects the energy security of different countries and if the compensation delivered as part of the climate deal could potentially compensate "energy security losers" (such as energy exporters). Practically it was not feasible to explore the regional energy security implications of climate stabilization under different GDP and fossil fuel assumptions or technological limitations. Thus, research subquestions (B) and (C) are only analyzed to the extent different models in LIMITS have different assumptions related to GDP, fossil fuel availability, and technological limitations.

The "nature of the climate policies" (research subquestion (A)) was explored in RoSE in relation to stabilization at 450 ppm $CO_2$-eq, 550 ppm $CO_2$-eq, and the MOD policy scenario explained above and in LIMITS in relation to 450 ppm $CO_2$-eq and StrPol as well as in relation different burden sharing regimes. The GEA scenarios all stabilized atmospheric GHG concentration at 450 ppm $CO_2$-eq so this scenario set was not relevant to the "nature of climate policies" research question. RoSE was the only scenario set that specifically varied GDP growth rates and fossil fuel availability so research subquestion (B) focused on this scenario set. The RoSE analysis focused on the global level. The effect of different GDP and fossil fuel assumptions on the energy security of major economies would be interesting to explore (particularly in relation to the convergence rate of GDP/ capita) but the sheer volume of data included in this thesis prevented me from adding this analysis. The technological limitations (with the exception of resource scarcity) were explored primarily using the GEA scenarios (research subquestion (C)).

To address the last research subquestion (E), I use both scenarios from the LIMITS exercise and a systematic review and synthesis of existing studies to explore the effect of different techno-economic and political uncertainties on energy export revenues under climate policies. This is because the main scenarios included in this thesis do not cover the economic and political uncertainties which would influence the size and sign of export revenues under climate policies. As discussed in the Literature Review (section 2.3), in spite of the developed literature on energy (in particular oil) export revenues under climate policies, there is no comparative synthesis of these studies nor is there an exploration of if a global carbon market could be used to compensate energy exporters for their losses under climate policies. To close these gaps, I conduct a systematic analysis of oil export revenues under different techo-economic and political uncertainties and I compare the 'lost' oil and gas revenues for the Middle East and Reforming Economies to the financial flows from the carbon market to those regions in an "equal effort" burden sharing regime.

**Table 3.10:** Study design: Energy security geographies, perspectives, indicators and modeling exercises

| Geography | Perspectives of energy security | Indicators | Policy and policy-driver variables | | | |
|---|---|---|---|---|---|---|
| | | | **Climate policies** | **(A) Nature of climate policies** | **(B) GDP growth & fossil availability** | **(C)Technological limitations** |
| **Global** | **Sovereignty** | Trade volumes | LIMITS, RoSE, GEA | RoSE, LIMITS | RoSE | GEA |
| | | Geographic diversity of exports | GEA, RoSE, LIMITS | RoSE | RoSE | GEA |
| | **Robustness** | Resource use & depletion | LIMITS | LIMITS, RoSE | RoSE[a] | |
| | **Resilience** | TPES diversity | LIMITS, GEA, RoSE | RoSE, LIMITS | RoSE | GEA |
| | | Electricity diversity | LIMITS, GEA, RoSE | RoSE, LIMITS | RoSE | GEA |
| | | Transportation diversity[b] | LIMITS, GEA, RoSE[b] | LIMITS, RoSE[b] | RoSE[b] | GEA |
| | | Energy intensity[c] | LIMITS, GEA | | | GEA |
| **(D) Major economies** | **Sovereignty** | Import dependence | LIMITS | LIMITS | | |
| | | Energy exports | LIMITS | LIMITS | | |
| | **Robustness** | Resource use & depletion | LIMITS | LIMITS | | |
| | **Resilience** | TPES diversity | LIMITS | LIMITS | | |
| | | Electricity diversity | LIMITS | LIMITS | | |
| | | Transportation diversity | LIMITS | LIMITS | | |
| **(E) Energy exporters** | **Sovereignty** | Energy export revenues | LIMITS + Literature synthesis[d] | LIMITS + Literature[d] | | LIMITS + Literature[d] |

Notes: Letters (A), (B), (C), (D) and (E) refer to research sub-questions.

[a] In RoSE resource scarcity was used as an exogenous variable.

[b] In RoSE diversity of energy sources used in transport could not be calculated so liquid diversity was used instead.

[c] Energy intensity was used as an exogenous variable in GEA.

[d] The effect of political uncertainties on energy export revenues were also explored using the existing literature.

## 3.5 Limitations

Even though I have developed a novel and rigorous method for analyzing energy security and applied it to a large amount of recent data from IAMs, there are several limitations with my approach. These limitations can be grouped in two broad categories: those related to evaluating energy security in IAMs and more general limitations of IAMs as a tool for exploring the futures of energy systems. Any model is a simplification of the world and IAMs are no exception. IAMs focus on long-term global forces of the energy-economy-environment system. This is necessary when dealing with the magnitude and reach of the climate change problem but it means that their granularity is limited. It also means that institutions, actors, geo-political developments and even critical infrastructure, all of which are important for energy security, are largely excluded from these models.

Spatially, the IAMs which I use in this thesis have global coverage with regional granularity (ranging from 11 to 26 regions). There is too much uncertainty to represent national energy futures in global energy models (except for the largest economies). Nevertheless, energy security remains a driver at the *national* rather than on the regional level. In some regions there is consistency between regional and national energy security issues. Indeed, the regional definitions in models can approximate the biggest countries quite well (which is why I focus on "major economies" in my analysis). But some regions contain countries which are geopolitically (e.g. the Southeast Asia region in MESSAGE contains Pakistan and India) and sometimes even geographically far apart (e.g. ReMIND has a region called Rest of the World which contains Canada, Australia, South Africa and Turkey among others). This means that while IAMs can depict global energy security trends and forces in the largest countries, these models cannot represent the development of future energy security in small or medium-size countries.

Temporally, IAMs typically only deal with five or ten year (and occasionally one year) time steps. This means that they cannot incorporate hourly (or shorter) load-balancing in electricity systems or even oil supply-chain shocks which can last days to months. Related to this is the fact that IAMs contain long-term optimal prices, not market prices and as a result do not depict price volatility. By their very nature, "emissions scenarios for climate change research do not track 'short-term' fluctuations, such as business cycles or oil market price volatility" (Moss et al. 2010, 748). While these short-term issues are very important for energy security, I believe that the systemic macro-features of energy systems which I have analyzed are important in understanding their abilities to deal with both short and long-term 'surprises' be it economic downturns, changes of political regimes or sudden technological breakthroughs. For example, two of my 'systemic' indicators: energy intensity and import dependence, are both measures of an economy's vulnerability to disruptions, be they physical, economic or both.

In addition to their limited granularity relating to space and time, IAMs have a limited depiction of end-use sectors. While they include several key dynamics related to energy supply, energy transformation, energy trade, and economic trends, they have relatively simple depictions of energy demand and end-use sectors. In the *Global Energy Assessment* we identified a handful of countries which have particularly vulnerable residential sectors (for example several Central and Eastern European countries with cold climates and district heating dependent on imported Russian gas) or industrial sectors (for example Ukraine with an energy intensive steel industry dependent on Russian gas). Thus, when I started this project, I looked at all of the end-use sectors in all regions. Unfortunately, the regions are too aggregated to identify current vulnerabilities in either the residential or industrial sectors. Another end-use aspect which I had to exclude due to inadequate representation is the flexibility of energy services. IAMs do not adequately represent a link between final energy end-use and actual energy services. Arguably, energy security should be focused on the stability of vital energy *services* (such as sufficient light or maintaining comfortable temperature indoors) rather than on their crude proxy of 'residential energy use' as presented in IAMs.

Another short-coming of IAMs is that they have a limited representation of infrastructure and when it is represented it typically reflects exogenous assumptions. Protecting critical infrastructure is a key part of ensuring energy security and some argue the security of infrastructure is much more important than import dependence (Skea, Chaudry, and Wang 2012, 204). This concerns not only the existing but also emerging (and potentially very different) infrastructure, for example associated with renewable energy resources deployed on a very large scale. With a major increase in the share of renewables, new vulnerabilities ranging from technology dependence to intermittency and fragility of large-scale transmission systems or information and communication technologies involved in load adjustement (such as implied in the Desertec proposal (Düren 2011)) may emerge.[36]

There is also a question of how relevant the indicators I am using will be in the future. I have based the energy security framework and selection of indicators on an analysis of historical energy security concerns and present energy security analysis, but history does not predict the future. One example of this is how I measure the diversity of energy sources between oil, gas, coal, solar, hydropower, wind, bioenergy and nuclear. However, imagine the Hapsburg Empire a century ago, before World War I. What technological categories would we consider distinct for transport? Horses, bicycles, and trains? Thus, the farther the analysis stretches into the future, and the more different the energy system looks then today's, the greater the uncertainty is associated with these categories. Maybe there will be five different types of solar power, which are technologically distinct enough to become different "categories" for the purpose of diversity analysis.[37] Additionally, energy security is not only about objective realities but also about subjective perceptions. Thus while my study can depict the overarching development of how objective forces would impact energy security under climate policies, it cannot capture specific, contextual developments.

A broader limitation is that the scenarios which I have analyzed are essentially "surprise-free" scenarios without major discontinuities in policies, economies, technologies or societies. Since energy security is all about preparing for nasty surprises, the 'surprise-free' story-lines may not be particularly useful in this regard. The recent shale gas revolution is a perfect example of how a technological surprise can change the geography of energy trade and energy export power. But even in the scenarios which explore strategic uncertainties, the breadth of possible futures is fairly limited. For example, the RoSE scenario exercise explored GDP growth ranging from some 1.9% to 2.9% in line with the mainstream UN projections, but in no

36. See Farrell, Zerriffi, and Dowlatabadi (2006, 460) for a good overview.

37. This relates to Stirling's idea of disparity (Stirling 1998, 2010; Grubb, Butler, and Twomey 2006) which I have not used in this thesis because there is already enough uncertainty in considering the distinction between even the most basic categories, let alone evaluating *how* different they are.

scenario did the global economy contract or undergo another economic surprise (which after the recent crisis does not seem all that unlikely). This is a distinct departure from the early intellectual tradition of scenarios by Herbert Kahn who saw this tool as specifically equipped to deal with *surprises* and *nightmares*. It is also a shift from the Shell scenarios which were so useful for the company specifically because they considered *disruptive change* (Wack 1985b, 83).[38]

Finally, this thesis only deals with the technical energy system but not the institutions which support and influence it. While the import dependency to the E.U. has not substantially changed over the last decade, the region's energy security has radically improved with the Nord Stream, the construction of gas storage, bi-directional pipeline development, increased interconnections as well as the mechanism of 'solidarity' which provides for the Union to protect its most vulnerable member states. Institutions are crucial to shaping not only the perception of the level of energy security but also energy security itself. As Farrell, Zerriffi, and Dowlatabadi (2006, 458) observe: "[a]ll countries have electricity reliability institutions" and institutional arrangements will likely shape energy security as much as the technical details of the system itself. Thus this thesis depicts the energy and economic forces which may drive energy security policies and institutions, but not the institutions and policies themselves.



38. For example, they called one of their scenarios the 'three-miracles scenario' because it required the simultaneous occurrence of three extremely unlikely situations" (Wack 1985b, 82).

# Chapter 4

# Results

This chapter is organized by the three perspectives on energy security which are proposed as the theoretical framework (section 3.3). Within each perspective I first present the global results organized by the first three research sub-questions (nature of climate target, the effect of GDP and fossil fuel availability and the effect of technological constraints on energy security); secondly, I present the regional results of these global trends. As discussed in the previous chapter, this study is based on three scenario sets which are woven through the narrative in this chapter. Each section starts by naming the scenario modeling exercise which it uses. All scenarios have a letter at the end of its name which corresponds to the different scenario exercises ("L" for LIMITS, "R" for RoSE, "G" for GEA).

## 4.1 Sovereignty

Climate policies lead to lower energy trade and lower import dependency for most regions (as compared to business as usual development). At the same time, the energy exporters would likely suffer from lost energy export revenue but this would depend on several technological and political uncertainties. Climate stabilization scenarios leading to lower energy trade than national climate policies and the higher the stringency the lower the trade falls. However, as trade falls, so does the diversity of exporters for the fossil fuels which are phased out due to climate policies. At the same time under climate policies, new fuels such as hydrogen and bioenergy are supplied to the global market by many regions.

### 4.1.1 Global trade volumes

*Overarching trend of global trade and climate policies*

Climate policies would reduce energy trade modestly by 2050 and dramatically by 2100. Figure 4.1 displays global energy trade differentiated by fuel and carrier for 2010, 2050, and 2100. Both figures illustrate that the trade in the Baseline-L scenario would significantly grow as compared to the 2010 level. Climate policies decrease the total energy trade as well as the trade in each fossil fuel in all models: the decrease is more pronounced in the 450-L scenario than in the StrPol-L scenario.

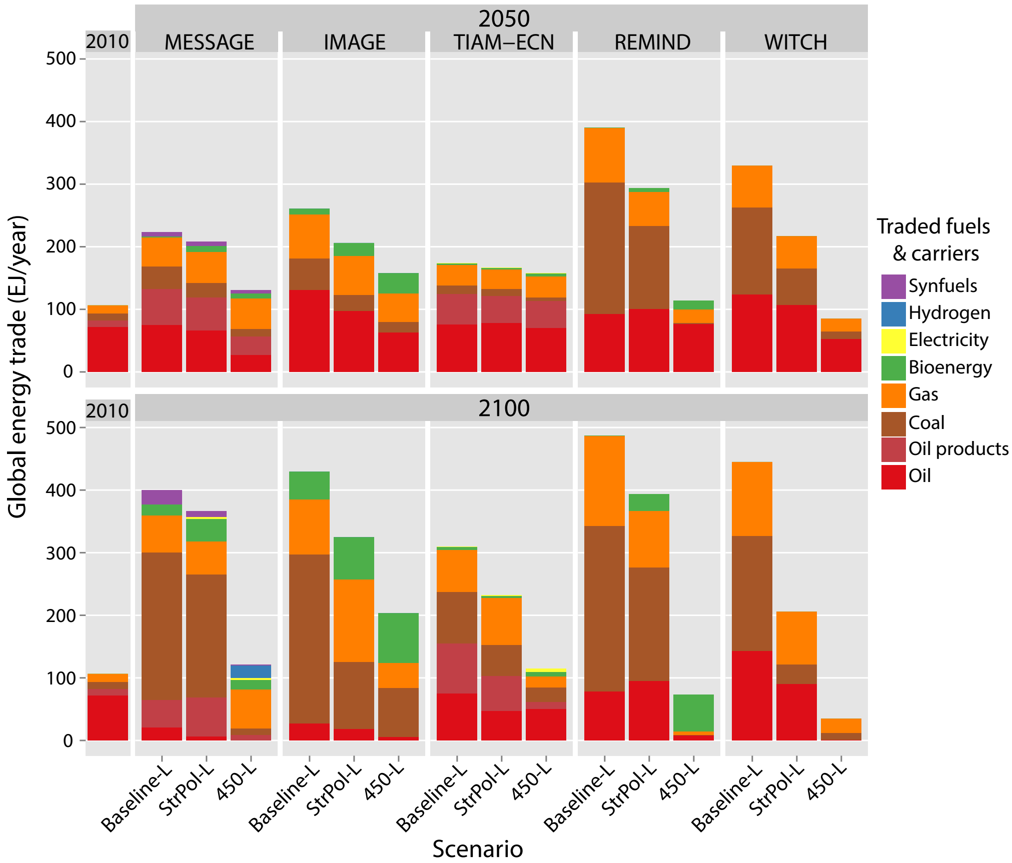
In most models, oil remains the most important traded fuel through 2050 but, oil trade is smaller in the 450 scenarios than in the Baseline scenarios, with this difference increasing by 2100.[39] With oil phased out in climate scenarios, most models show a shift to domestic energy carriers (electricity, hydrogen and domestically-produced biofuels) in the transport sector where most of today's oil is used.

By 2100, most models project coal as the dominant fuel in the Baseline-L scenario. Coal trade is especially high in ReMIND and WITCH in 2050 and in IMAGE, MESSAGE and ReMIND in 2100 due to their assumptions of regional endowments of coal and the demand (with cheaper coal being produced away from regions where the demand is the highest). The earlier development of the coal market in ReMIND means that coal trade over the 21st century is over 50% more in ReMIND than the model with the second largest trade, WITCH. Under climate policies all models show a drop in coal trade due to the decrease in coal use. Only in IMAGE does coal trade stay above 50 EJ per year in the 450-L scenario due to a higher penetration of CCS.

The decrease in natural gas trade under the 450-L scenario is lower than the other fossil fuels. Most models show a decrease in natural gas trade under climate policies, however in MESSAGE, it rises with the "Reforming

39. TIAM's later drop in oil trade is driven by the fact the transport sector only starts to transform after 2050 when hydrogen comes in to replace oil.

**Figure 4.1:** Global energy trade in five models and three scenarios in 2050 and 2100




Notes: Global trade for the year 2010 is taken from MESSAGE since this model trades the most fuels and carriers which are relevant to current data. Bioenergy in MESSAGE only includes biofuels.

economies" region (which is primarily Russia) coming to dominate the export market by the end of the century. At the same time, climate policies lead to increasing trade in bioenergy (MESSAGE, IMAGE, and ReMIND) and hydrogen (MESSAGE). These increases do not offset the overall decline in trade as a result of climate policies. The trade in gas reaches the current levels of oil trade in climate stabilization scenarios in MESSAGE (against the background of a much larger energy system). The rise in bioenergy trade is particularly pronounced in IMAGE and ReMIND because these models assume highly flexible bioenergy markets with trade of biomass (whereas in MESSAGE, only biofuels are traded).

*Sensitivity to the stringency of the climate target*

The drop in energy trade was tested under different climate policies (450 ppm $CO_2$-eq, 550 pm $CO_2$-eq and national climate policies following the Copenhagen pledges) in the RoSE scenario exercise in the WITCH and ReMIND models. The drop in energy trade was robust to varying the degree of stringency of climate targets: however, the reasons for this decrease were different between WITCH and ReMIND.

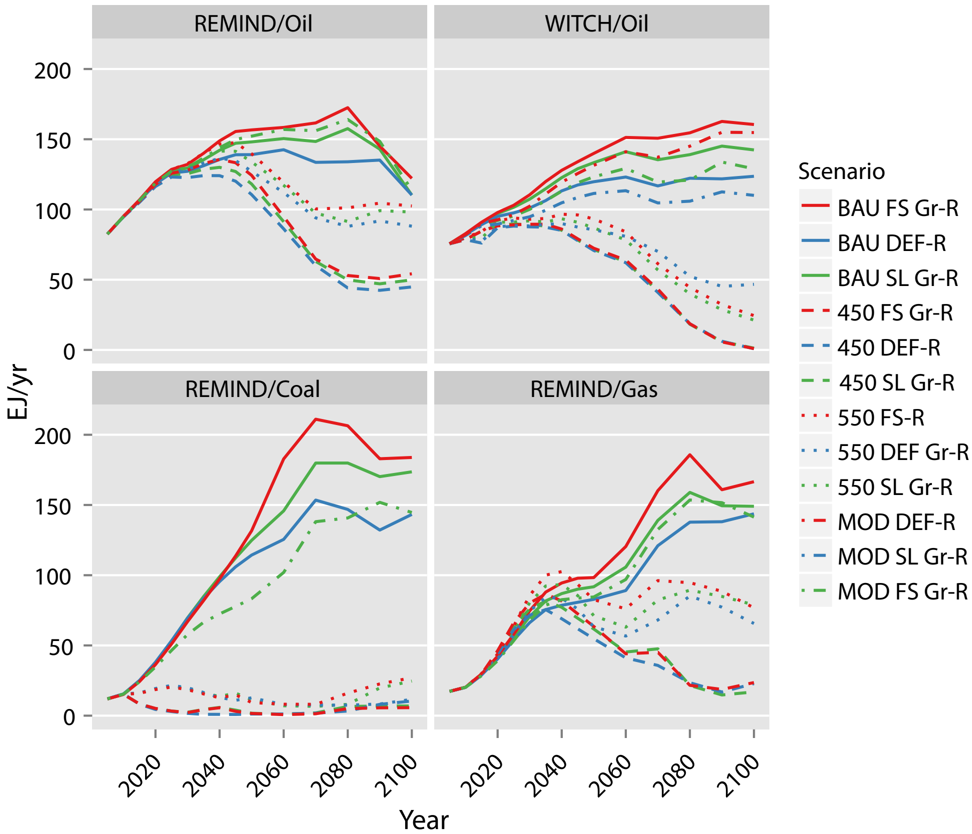
Figure 4.2 shows the volumes of global trade in oil, gas and coal throughout the 21st century in the Baseline-R and climate policy scenarios. In the Baseline-R scenario, ReMIND models an almost 5-fold rise in global energy trade as compared to the present level. This is primarily a result of expansion in gas and coal trade due to rising demand in developing countries, which adds to the existing demands from industrialized countries. The increase of oil trade (which at present constitutes the bulk of the interregional energy trade) is about 50% in both ReMIND and WITCH. However the rise in the overall energy trade volumes in WITCH is not as dramatic because WITCH does not report trade in gas and coal.[40]

Both models show radically lower energy trade under the 450-R scenarios: in ReMIND it is almost 4.5 times less compared to the Baseline-R, and in WITCH it declines to almost zero. The drop in energy trade in ReMIND is due to a decrease of coal and oil trade over the short-term and all fossil fuels over the long-term whereas in WITCH it is entirely explained by the phase-out of oil.

Stabilizing GHG concentration at 500 ppm $CO_2$-eq or implementing national climate policies (rather than meeting a global stabilization target) still leads to a reduction in energy trade, but to a lesser extent than the 450-R scenarios. Figure 4.2 shows the global energy trade level of the three fossil fuels in ReMIND and oil in WITCH under three different assumptions of climate policies: stabilization at 450 ppm $CO_2$-eq, stabilization at 500 ppm $CO_2$-eq and MOD policies (national Copenhagen pledges). While all are lower than the Baseline-R, the more stringent the climate policies are, the greater is the reduction in trade. This confirms the results presented

40. WITCH did not report gas and coal trade in the RoSE project, but they did report it in the LIMITS project.

**Figure 4.2:** Sensitivity of fossil fuel trade to climate policies and economic assumptions




Notes: For definition of scenarios see Table 3.8. Only oil trade is modeled in WITCH. ReMIND only models medium GDP growth assumptions for the moderate policy scenario and did not run the MOD SL Gr-R or the MOD DEF-R.

in the last section that StrPol-L still models lower trade than the Baseline, but higher than the 450-L scenario.

### *Sensitivity to GDP assumptions*

This section describes the effect of GDP assumptions on energy trade from the RoSE exercise in two models: ReMIND and WITCH. Higher economic growth results in higher global energy trade in the Baseline-R. But regardless of the GDP growth assumptions all climate policies lead to lower energy trade than in the Baseline-R (Figure 4.2). At the same time, the global energy trade under climate policy scenarios is less sensitive to GDP growth assumptions because economic growth is primarily fueled by non-tradable fuels (e.g. solar in ReMIND) or does not even translate into significantly increased energy consumption (in WITCH) due to radical efficiency gains. The sensitivity of trade in climate policy scenarios to economic growth is smaller for stricter climate policies.

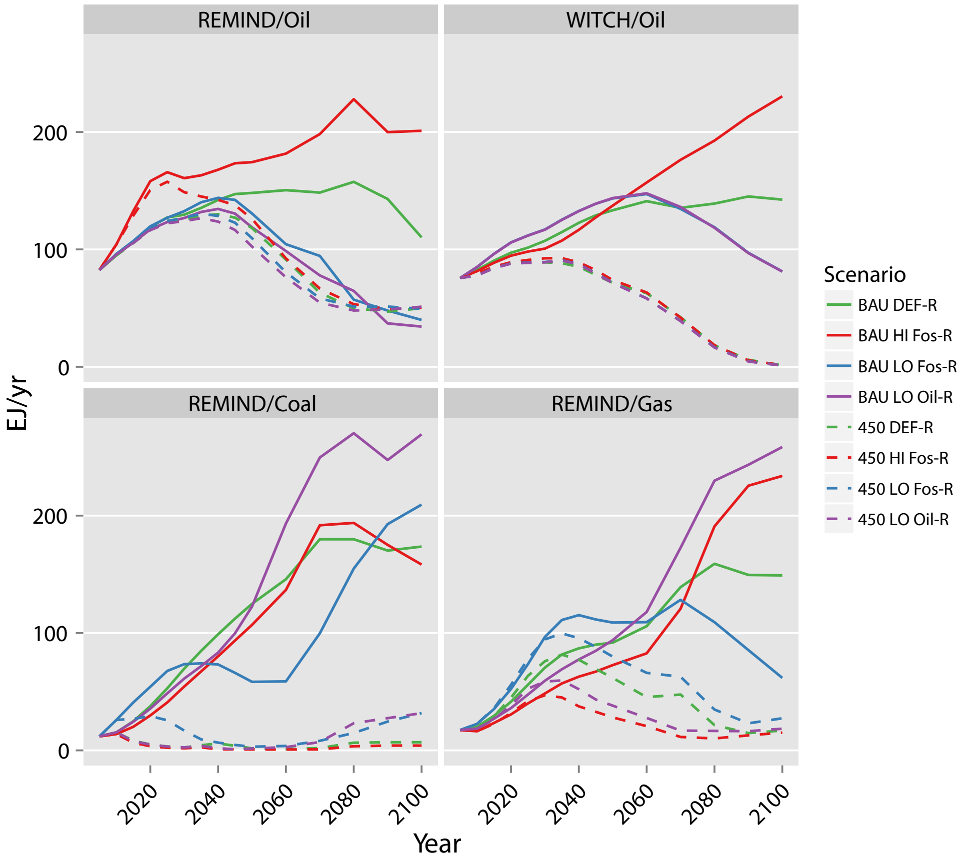
While there is a dramatic decrease in energy trade in both ReMIND and WITCH, the underlying dynamics which are driving this decrease are different. In both models, higher GDP growth means higher total energy use in the Baseline-R scenarios. This higher energy consumption in WITCH is primarily fueled by gas and coal whereas in ReMIND renewable energy sources also become an important source in the second half of the 21st century. There is also a difference between the two models in how GDP growth assumptions affect energy consumption in the climate policy scenarios. In ReMIND, energy consumption responds to higher growth much stronger since additional GDP growth is served by solar and other low-carbon sources. Nevertheless, at the end of the century primary energy consumption in each of the four Baseline scenarios in ReMIND is some 1.4–1.6 times higher than in the 450-R scenarios with the same economic assumptions. In contrast in WITCH higher GDP growth means even higher energy efficiency gains under climate policies so that the overall energy consumption is virtually not affected.

*Sensitivity to fossil fuel availability*

This section describes the effect of fossil fuel availability assumptions on energy trade as tested in the RoSE exercise in ReMIND and WITCH. In both models, the Baseline-R scenarios are dominated by fossil fuels and feature higher energy consumption under higher fossil fuel availability. However, lower availability results in a higher share of bioenergy in WITCH (up to 30% in 2100 under low fossil fuel availability as compared to negligible amounts under high fossil fuel availability) and a higher share of all renewable energy sources in ReMIND (up to 40% in 2100 as compared to some 16% under high fossil fuel availability). Under the climate policy scenarios the total energy consumption and the energy mix are much less affected by fossil fuel availability assumptions.

In the Baseline-R scenarios, higher availability of fossil fuels generally results in higher volumes of trade in these fuels, especially in the longer term. Lower

**Figure 4.3:** Sensitivity of fossil fuel trade to fossil resource availability




Notes: Trade in all fuels is significantly affected by resource availability assumptions in the Baseline, but not under CPs. Trade in coal and oil under CPs is not sensitive to resource availability assumptions. Trade in gas under CPs is higher in case of low availability, but still lower than in the Baseline.

availability of oil results in lower oil trade in both models in the longer term (Figure 4.3). Lower availability of oil also results in higher trade in coal and gas, which substitute for oil in ReMIND. Trade in coal and gas is less sensitive to resource availability assumptions except that, in the case of low resource availability, gas trade becomes lower in the longer term but higher in the short term. This dynamic happens because gas infrastructure is not invested in for the long-term but the short-term demand already in place must be met with traded gas.

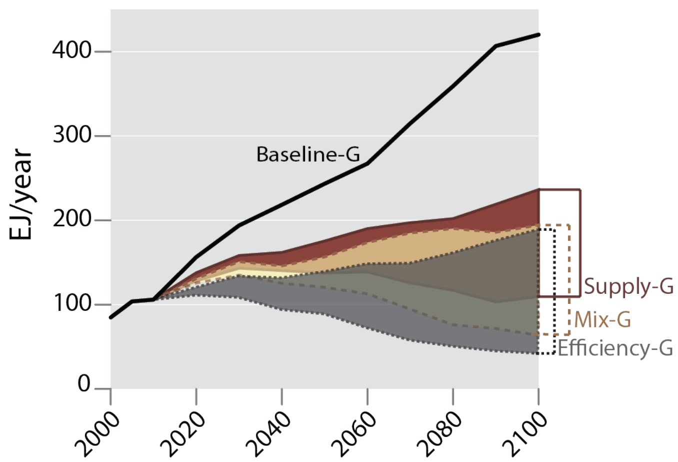
In climate policy scenarios, the availability of fossil fuels does not generally affect the global oil and coal trade. However, low fossil fuel availability results in higher gas trade under climate policies. This occurs because the low gas assumption lowers the endowments of import regions disproportionally more than of export regions. Even under the lowest resource assumption the trade in any fuel in the Baseline-R is higher, in absolute terms than the trade under any of the climate policy scenarios.

*Sensitivity to technological constraints*

I tested the robustness of the trade results to assumptions about energy intensity and energy supply choices in the GEA scenarios with the MESSAGE model. The GEA scenarios are divided in three groups: Supply (with lowest gains in energy intensity), Efficiency (with highest gains in energy efficiency) and Mix (with medium gains in energy intensity). Since the GDP growth is the same in all GEA scenarios, energy intensity assumptions directly translate into the level of energy demand. In turn, the volume of energy trade correlates with the overall level of energy demand. In other words, under other equal assumptions, the trade in Supply scenarios is higher than in Mix scenarios which is in turn higher than in Efficiency scenarios since higher overall demand increases the demand for tradable fuels (Figure 4.4 and Figure 4.5). Thus gains in energy intensity translate into reductions in energy trade.

In the Baseline-G scenario, with the higher level of demand and a high reliance on fossil fuels (which are easy to trade), the global energy trade

**Figure 4.4:** Global energy trade in the Baseline-G and 450-G scenarios under different demand assumptions



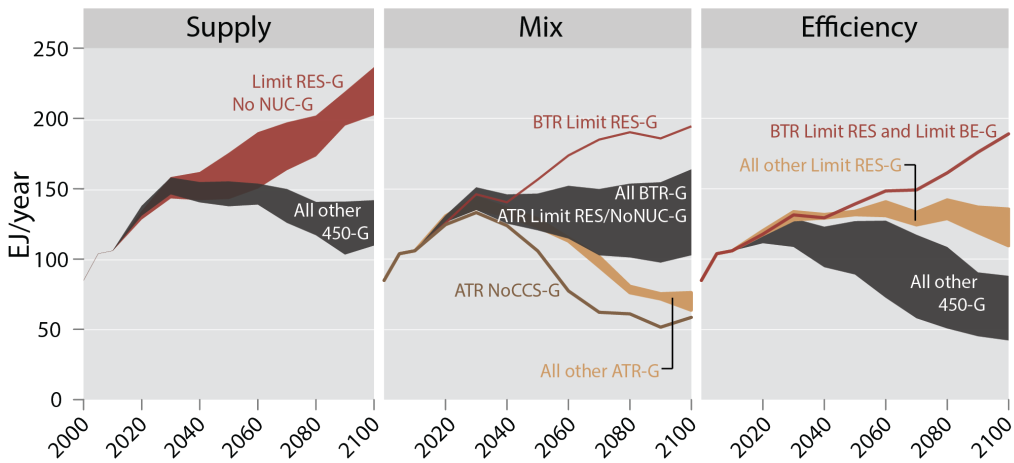
rises dramatically from the current 80EJ/year to over 400 EJ/year by 2100. The levels of trade in the low-carbon scenarios are much lower, ranging from 40 EJ/year to 240 EJ/year by 2100. The trade initially rises in all 450-G scenarios, and declines in the second half of the century in certain Efficiency and Mix scenarios Figure 4.5. The lower level of trade in the 450-G scenarios is explained by (a) generally lower energy supply and use (especially in the Efficiency scenarios) and (b) a higher share of non-tradable energies (renewables and nuclear) in the energy mix.

There are certain technological constraints that lead to higher energy trade. Under equivalent assumptions, limiting RES and phasing out nuclear, particularly when combined with conventional transport assumptions, leads to higher trade volumes (Figure 4.5). The higher the demand, the more easily the rise of energy trade is triggered by technological constraints:

- In Supply scenarios, higher trade is triggered by limitations on renewables or nuclear energy;
- In Mix scenarios, higher trade is triggered by limitations on renewables combined with conventional transport;
- In Efficiency scenarios, higher trade is triggered by limitations on RES and bioenergy combined with conventional transport.

Since technological limitations have the largest effect on the overall global trade volumes, I did a detailed analysis of the individual fuel trade for the 42

**Figure 4.5:** Sensitivity of global energy trade to technological constraints



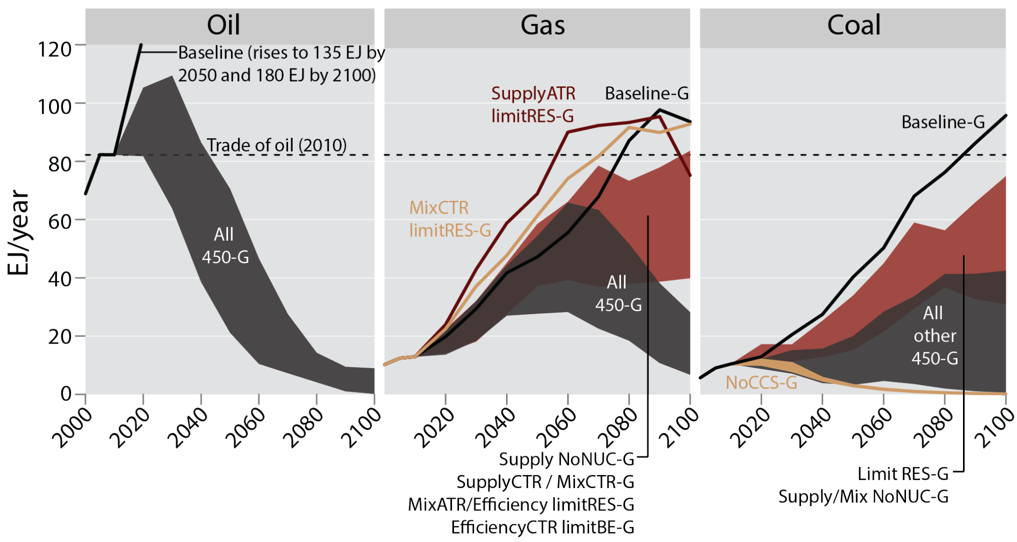
scenarios with technological limitations in MESSAGE. Figure 4.6 illustrates the trade in fossil fuels, which currently make up the bulk of the global energy trade. The most striking difference between the Baseline-G and 450-G scenarios is in relation to **oil** trade. Whereas in the Baseline scenario, oil trade steadily rises and more than doubles by the end of the century, in the 450-G scenarios it peaks around 2030 and then rapidly declines as oil is phased out of the energy system.

**Natural gas** trade rises in both the Baseline-G and 450-G scenarios in the first half of the century. In the second half of the century, the trade in the Baseline-G continues to rise reaching over 100 EJ/year (more than oil trade at present). At the same time the 450-G scenarios diverge falling roughly into three groups:

1. In one Supply-G and one Mix-G scenario with limitations on RES, gas trade increases to levels comparable to the Baseline-G and exceeding present-day oil trade volumes. In these scenarios, natural gas continues to be a critical part of the energy system until the end of the century. (Marked with the red and orange lines in Figure 4.6).

2. In several scenarios, gas trade plateaus (with some gradual growth or decline) at levels below the present volumes of oil trade and below the Baseline-G. These scenarios are: Supply-G combined with no nuclear

**Figure 4.6:** Sensitivity of fossil fuel trade to technological constraints



development (leading to gas being used in electricity); Supply-G or Mix-G combined with conventional transport (leading to the use of liquified gas in transportation); Mix-G or Efficiency-G combined with limited RES (leading to a lack of alternatives to gas); and Efficiency combined with conventional transport and limited bioenergy (leading to liquified gas being used in transportation instead of biofuels).

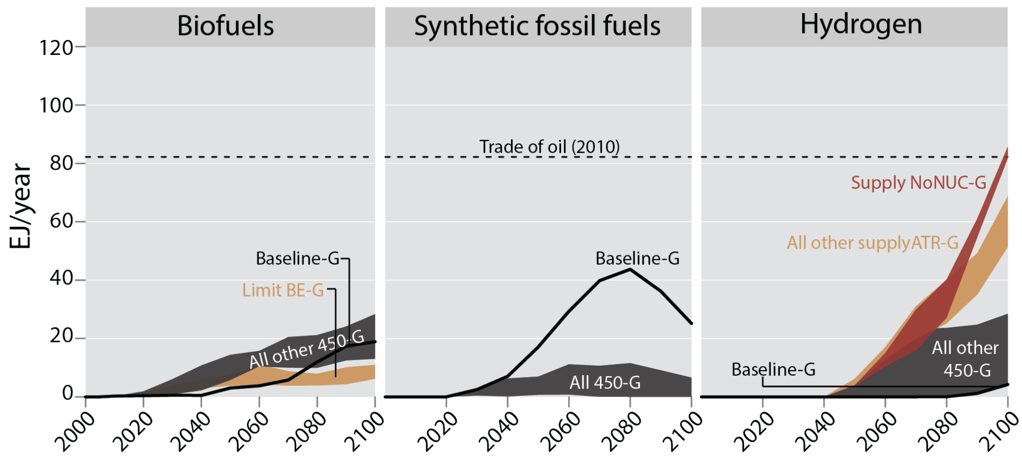
3. In other scenarios gas trade significantly declines in the latter half of the century. These include: the most advanced transport scenarios (where there is not a limitation on renewables or nuclear energy); and Efficiency scenarios with conventional transport and no limitations on bioenergy. In these scenarios, gas serves as a bridge fuel, being gradually replaced by other energy sources towards the end of the century.

In the Baseline-G scenario global **coal** trade rises from its current 10 EJ/year to over 90 EJ/year by 2100. Coal trade in 450-G scenarios varies depending on supply and demand constraints. In scenarios with limited CCS the use of coal is not compatible with GHG limitations so coal trade virtually disappears. Coal trade is higher in scenarios with limited renewables and nuclear (when combined with Mix or Supply) where it is used in combination with CCS to in electricity generation.

In addition to traditionally traded fossil fuels, some scenarios include significant trade in "new" fuels and carriers: biofuels, synthetic fossil fuels, and hydrogen (Figure 4.7). In the Baseline-G scenario the trade in **biofuels** after 2040 rises to ca 20 EJ/year by the end of the century. In the 450-G scenarios, the trade in biofuels increases to comparable levels (quicker), but less so in scenarios where the production of bioenergy is limited since this in turn limits the extent of biofuel use. In all scenarios the levels of trade in biofuels are 2–10 times lower than the volumes of oil trade at present. The trade in **synthetic fuels** (liquids produced from coal or gas) in the Baseline-G scenario rises to over 40 EJ/year but stays below 12 EJ/year in all 450-G scenarios.

In contrast to synthetic fuels, **hydrogen** trade is present in some 450-G scenarios, but not in the Baseline-G scenario. Towards the end of the century, trade in hydrogen rises to levels comparable to oil trade today in Supply scenarios with advanced transport or with no nuclear energy. For the Supply

**Figure 4.7:** Sensitivity of trade in "new" fuels to technological constraints

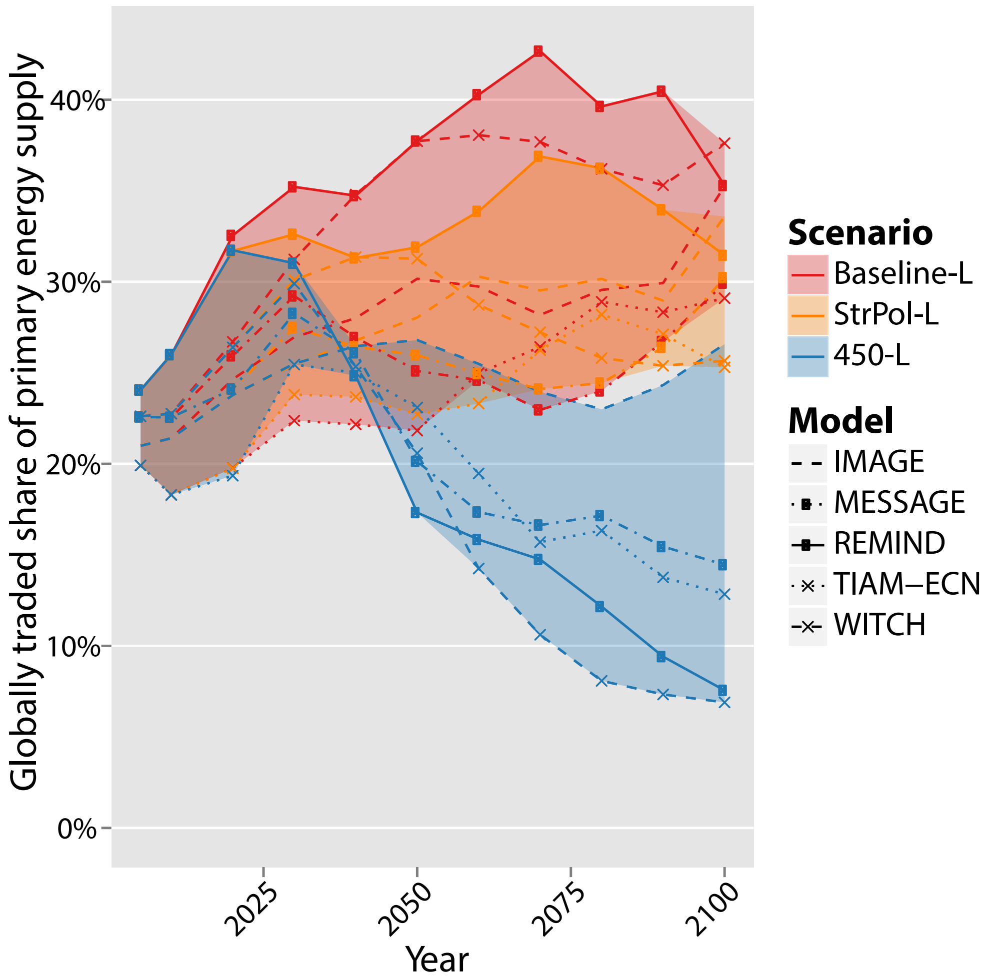



scenarios with advanced transport this is because of high demand combined with high potential for fuel cell technologies. For the Supply scenarios with No Nuclear, this is because the limitations on nuclear energy limit the number of regions where it is economically feasible to produce hydrogen but at the same time there is high demand for it.

## 4.1.2 Global trade intensity

Under the LIMITS scenarios, the share of tradable energy in TPES ('trade intensity') declines to lower levels in the 450-L scenarios than in Baseline-L scenarios in all models (Figure 4.8). Trade intensity of the Baseline-L and 450-L scenarios follow the same trajectory over the short term (through 2040); in 2040, trade intensity falls in 450-L scenarios while in the Baseline-L scenarios it typically plateaus in all models between 20% and 40%. The fall in trade intensity under the 450-L scenario is most pronounced in WITCH and ReMIND: in WITCH this is because of the rapid rise in energy efficiency while in ReMIND it is due to the rapid penetration of non-tradable renewable sources, particularly solar energy. The StrPol-L scenario has little effect on trade intensity, since the StrPol-L scenario only leads to a modest decrease in the overall energy trade.

**Figure 4.8:** Trade intensity in four models under the LIMITS scenarios




*Trade intensity and stringency of climate targets*

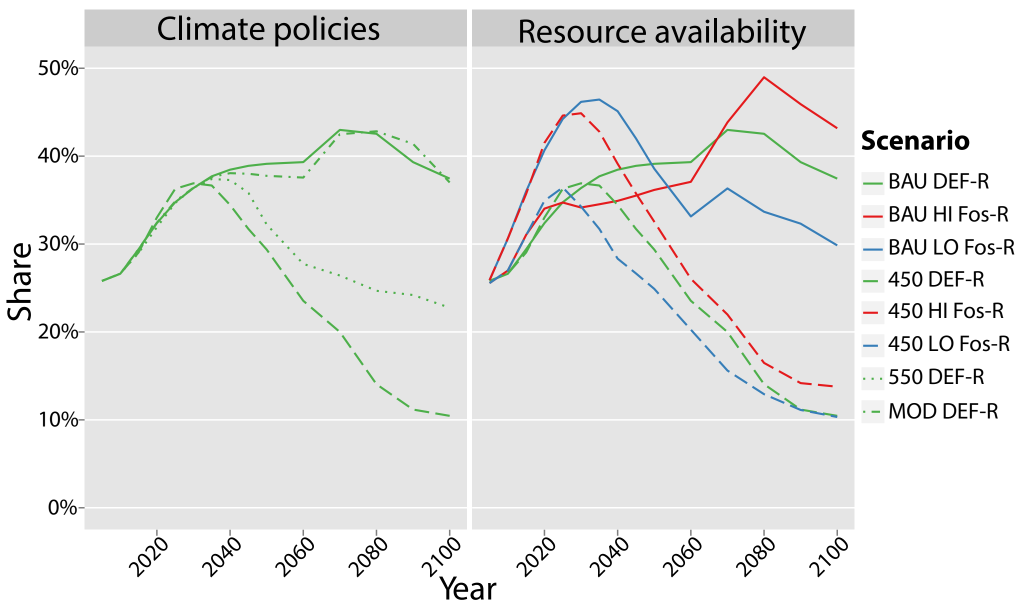
The more stringent the climate target, the earlier the decrease in trade intensity begins and the lower it ultimately falls (Figure 4.9). For example, in ReMIND, the present trade intensity of some 25% increases to 40% in the Baseline-R, but drops to some 10–15% in the 450-R scenario or stays at approximately the same level of 25% in the 550-R scenario. In WITCH, where only oil is traded, the present global trade intensity of some 20% declines to 10–15% in the Baseline-R scenario and drops to zero under the climate stabilization scenarios. This occurs due to declining shares of tradable fuels (oil, coal and gas) in the energy mix under climate policies. Consistent with the findings from LIMITS (and the StrPol-L scenario), the

MOD-R scenario does not lead to a decrease in trade intensity from the Baseline-R. All of the scenarios have comparable trade intensity until 2035 rising from the present 25% to 40%. In 2035, the trade intensity of the 450-R scenario begins to fall, and ten years later the trade intensity in the 550-R scenario begins to fall.

### *Trade intensity and fossil fuel availability*

Fossil fuel availability has an interesting impact on the trade intensity (Figure 4.9). Under an assumption of low fossil fuel availability, trade intensity in the Baseline-R (BAU LO Fos-R) is higher than in the 450-R scenario (450 LO Fos-R) over the short-term (till 2050). This occurs because the low fossil assumption lowers the endowments of regions heterogeneously: more so in the importing regions. However, over the same time span, under high fossil fuel availability, trade intensity in the 450-R scenario (450 HI Fos-R) is higher than in the Baseline-R (BAU HI Fos-R). In the second half of the century, an assumption of low fossil fuel availability leads to *lower* trade intensity in the Baseline-R scenario as the whole system is forced

**Figure 4.9:** Sensitivity of trade intensity to climate policies and resource availability in ReMIND




Note: This trade intensity only includes trade in oil, gas, and coal.

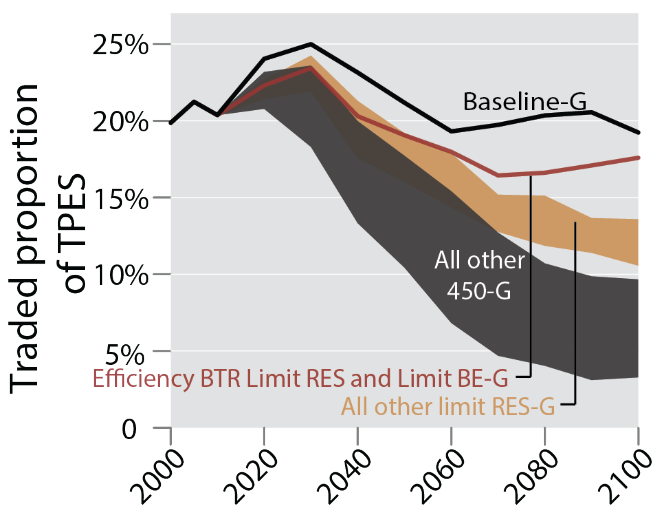
to shift away from tradable fossil fuels to non-tradable renewable energy sources. In contrast, under a high fossil assumption, the trade intensity for the 450-R scenario converges with the trade intensity of the other 450-R scenarios as the climate stabilization policies drive the energy system away from tradable fossils, i.e. in the same direction as resource scarcity.

### *Trade intensity and technological constraints*

Unlike trade volumes, trade intensity does not notably vary across Supply, Mix and Efficiency GEA scenarios. Even though Efficiency scenarios are generally associated with lower trade volumes the overall energy demand is also lower which results in similar trade intensity. The trade intensity rises in the Baseline-G scenario from the current 20% to 25% by 2030 before returning to ∼20% and leveling off. In contrast, in all 450-G scenarios, trade intensity peaks at a lower level and declines after 2030 (Figure 4.10).

At the same time, trade intensity is affected by supply-side constraints. In scenarios with no limitations on RES, trade intensity declines to 1–10% by the end of the century. When RES are limited, this decline is less pronounced (11–15% by the end of the century) since the world is pushed to using more tradable fuels. Interestingly, the Efficiency scenario with limited RES combined with conventional transport and limited bioenergy has a trade intensity which is only marginally lower than in the Baseline-G. Although the overall energy demand of this scenario is lower, the transport

**Figure 4.10:** Sensitivity of trade intensity to technological constraints



system continues to be dominated by liquids but is unable to take full advantage of domestic biofuels due to the limitations on bioenergy.

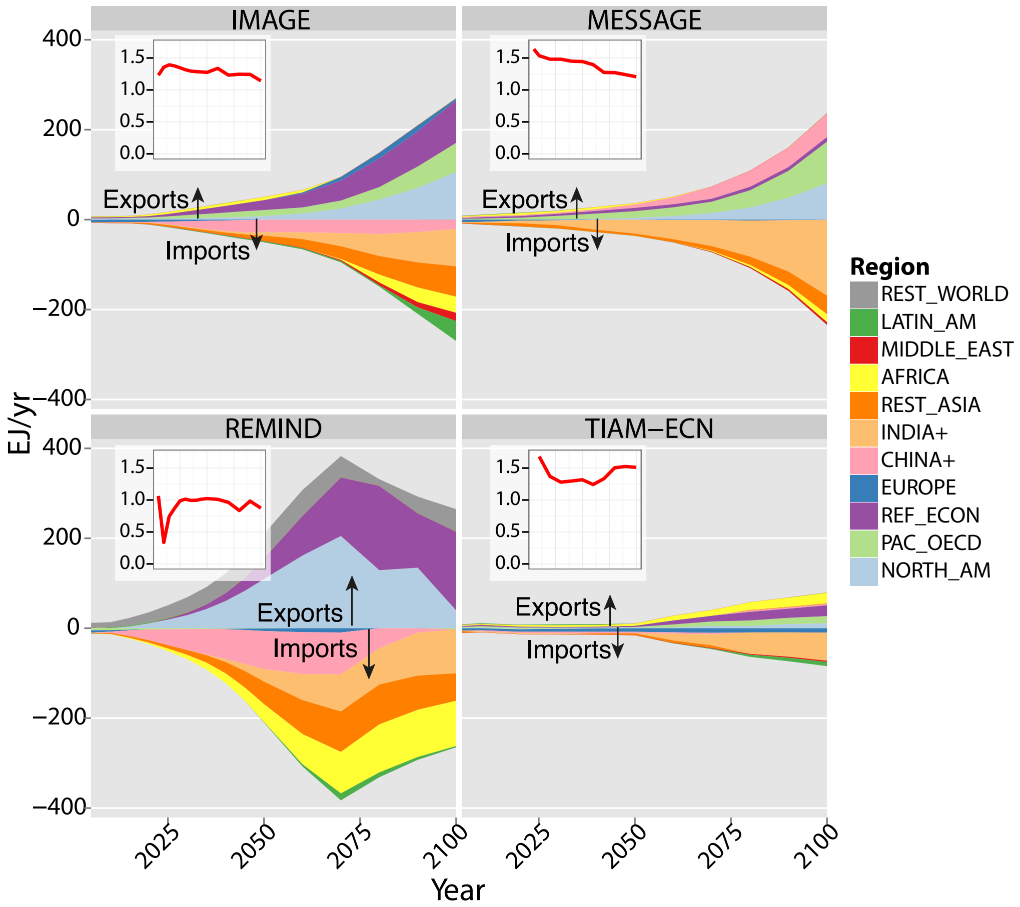
### 4.1.3 Geography of global trade

It is not only the volume and intensity of energy trade but also the regional pattern of supply and demand which affect global energy security of traded fuels. High volumes of trade may be especially risky if the fuel in question is primarily produced in a small number of regions. Under the Baseline scenario, coal trade is the most intensely traded of all energy sources by the end of the century in three of the four models which provide detailed tracking of trade in several fuels. Under climate scenarios a fuel can either be phased out (e.g. oil), act as a bridge fuel to a low-carbon energy system (such as gas in many models), or be introduced due to climate policies (such as hydrogen). What happens to any given fuel depends on each model's technological assumptions. In general fuels which are phased out have lower exporter diversity under climate policies; fuels which act as bridge fuels have comparable exporter diversity under climate policies and in the Baseline; and new fuels typically have high exporter diversity of production. This section gives several examples of each type of fuel and its geographic diversity of exports in different models.

*Baseline concentration of exports*

In the LIMITS scenarios under the Baseline-L, coal becomes the most intensely traded fuel by the end of the century in four of the five models (IMAGE, MESSAGE, ReMIND, WITCH). While the trade volumes are comparable among these four models, the geographic distribution of exports is vastly different (Figure 4.11). North America is a major coal exporter under all models, the Reforming economies under IMAGE and ReMIND, and Pacific OECD under IMAGE and MESSAGE. This means that there is a high degree of uncertainty over which countries would be the main coal buyers and which the main sellers (which could imply price volatility and geopolitical tensions). Interestingly, the geographic diversity of coal exports is lowest in ReMIND which has both the highest coal trade and the least constraints on the types and volume of interregional energy trade.

**Figure 4.11:** Coal trade patterns and diversity of exporters (inset) in four models under the Baseline-L scenario

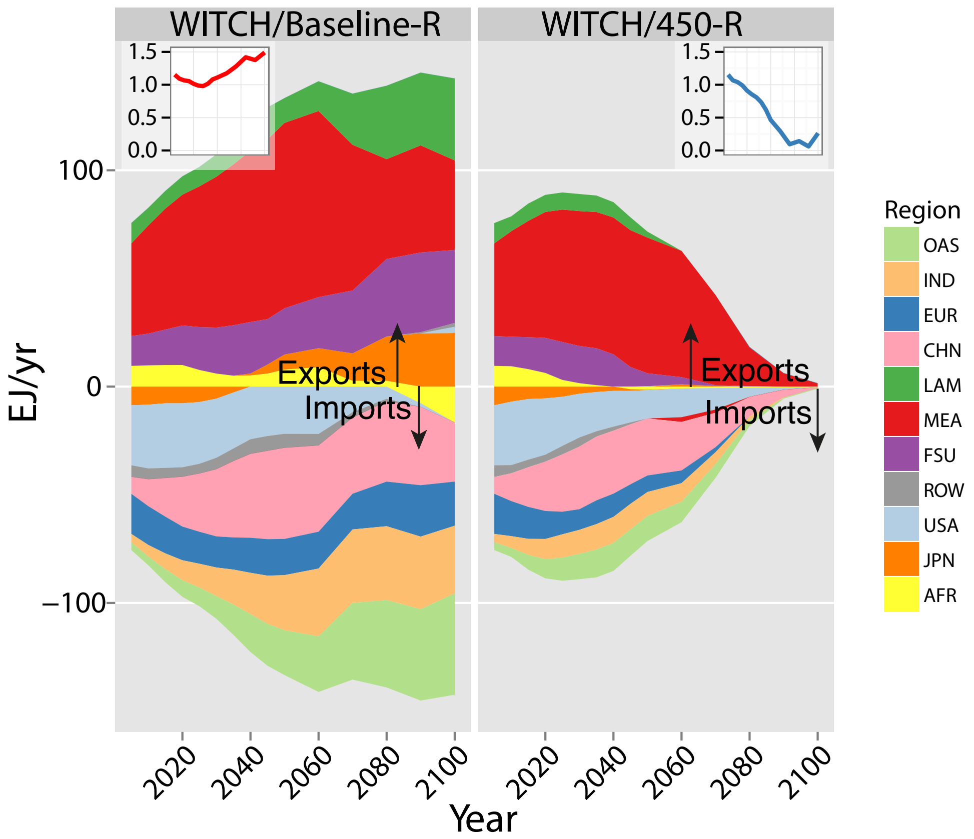



Note: The definition of the regions is provided in the Appendix.

*Fuels which are phased out*

Oil is generally phased out under climate policies and coal is phased out under certain technological assumptions. The geographic diversity of exports for both of these fuels is lower under climate policies. This is because as oil and coal are phased out of the energy system, the resource base is restricted as unconventional and carbon-intensive resources are not exploited. In WITCH, under the RoSE scenarios climate stabilization constrains exploitation of non-conventional oil, which results in oil being produced only in a small number of regions with conventional oil resources. Thus, under the 450-R scenario only the Former Soviet Union (FSU also known as

**Figure 4.12:** Oil trade patterns and diversity of exporters (inset) in WITCH model under the Baseline-R scenario and the 450-R scenario




Note: The definition of the regions is provided in the Appendix on regional mapping. In particular, FSU stands for former Soviet Union, JPN includes Canada and New Zealand in addition to Japan, OAS stands for East and South Asia (except Japan, South Korea and China) and ROW stands for South Korea, South Africa and Australia.

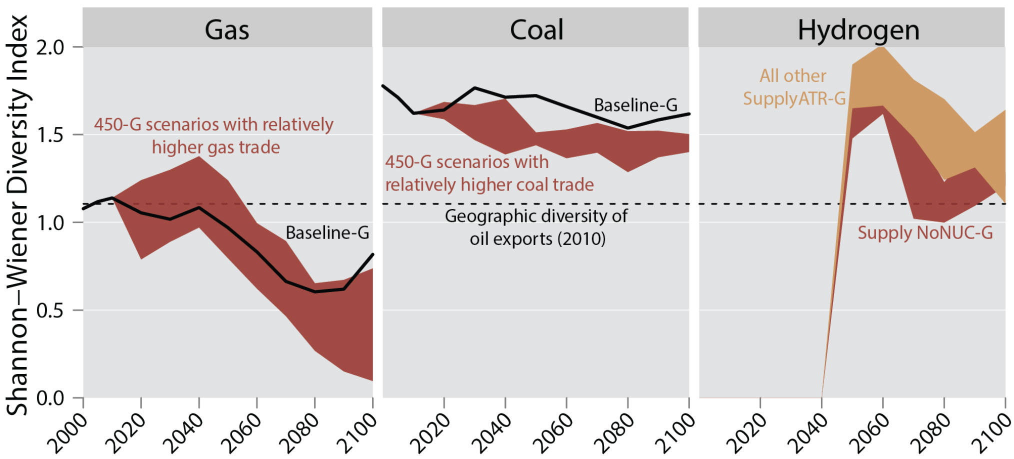
Reforming Economies) and the Middle East and Africa (MEA) export oil in the 2nd half of the century with rapidly declining volumes of exports for both regions (see Figure 4.12). In the Baseline, Latin America (LAM), the "Rest of the World" (ROW) and increasingly Canada, Australia and New Zealand (which are included in the region named JPN) also become exporters.

In other words, climate policies increase the geographic concentration of oil production, the share of tradable oil in the overall oil consumption, and import dependencies on oil of certain regions. Additionally, Figure 4.12 shows how the imports of oil shift from being concentrated in Europe and North America to India, China, other Asia and eventually Africa. At the same time, the overall importance of oil in the energy systems declines so these developments become progressively less important for energy security.

*Bridge fuels*

Many models feature natural gas and even coal as bridge fuels. As shown in Figure 4.1.1, under certain technological assumptions, trade in gas and coal increases. Thus in these scenarios, the importance of each of the fossil fuels rises into the future which means the geographic diversity of exports of these fuels is crucial to understanding the global energy security landscape under a low-carbon energy system. In the case of limited renewables and other scenarios associated with higher gas trade (groups (1) and (2) in the explanation to Figure 4.6) natural gas is produced in an increasingly smaller number of regions. This is because natural gas resources are not evenly distributed and large volumes of extraction inevitably lead to increasing geographic concentration of production. In fact, in these scenarios (as well as to some extent in the Baseline-G) the production of gas may become far more geographically concentrated than the production of oil today (Figure 4.13). Figure 4.13 also illustrates that geographic diversity of coal remains high even in scenarios with high coal trade. This is because coal

**Figure 4.13:** Geographic diversity of exports of gas, coal, and biofuels under 450-G scenarios



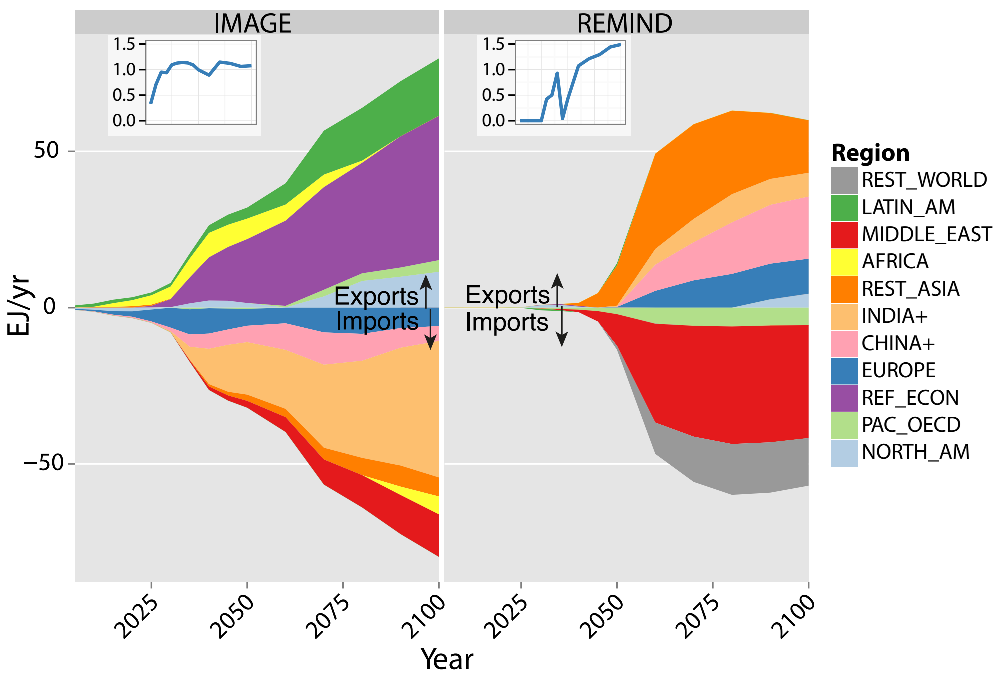
resources are more evenly distributed around the planet than natural gas or oil.

### *"New Fuels"*

There are two main "new fuels" which are highly traded under 450 scenarios in some models: hydrogen and bioenergy. Hydrogen only reaches very high trade volumes in MESSAGE under certain technological assumptions (see Figure 4.7). Under these scenarios, the diversity of hydrogen production is high under most but not all scenarios (Figure 4.13). Under supply scenarios with no nuclear energy, the geographic diversity of exports dips to that of oil's today. This is because the limitations on nuclear energy limit where it is economically-feasible to produce hydrogen.

Bioenergy trade reaches some 80 EJ in IMAGE and 60 EJ ReMIND, however which countries are exporting it and which are importing it are very different under the two models (Figure 4.14). The bioenergy market in

**Figure 4.14:** Bioenergy trade patterns and diversity of exporters (inset) in two models under the 450-L scenario




Note: The definition of the regions is provided in the Appendix.

IMAGE is supplied by the Reforming Economies and the Americas while the major importers are India and China; in contrast, ReMIND's bioenergy market is supplied by Asia and Europe with the main importer being the Middle East. The difference in these trade patterns are explained by different assumptions about regional population dynamics, yields, and transport infrastructure. While the diversity of exporters of bioenergy in ReMIND climbs through the century to 1.5, in IMAGE this diversity plateaus at about 1.0, which would make it similar to the diversity of today's oil exports. This lower diversity in IMAGE is driven by sustainability restrictions related to the food-versus-fuel tension.

### 4.1.4 Regional imports and exports

The decrease in global energy trade leads to lower energy imports (and exports) under climate policies than under business as usual development. Thus, for regions which face growing energy imports climate policies could alleviate energy security concerns, however, for resource rich regions this could mean lost energy export revenue. I examine three types of regions: industrialized and net-importers (the U.S. and the E.U.); emerging economies and net-importers (China and India); and energy exporters (Russia and the Middle East and North Africa). All regional results in this section are from the LIMITS scenario exercise except for energy exporters which also contains secondary data.

*Major economies*

For the most part climate policies do not notably affect energy interregional trade in the near term (to 2030). This is because while climate policies foster the growth of non-traded energy sources (renewables, nuclear energy,[41] some forms of biomass) they also limit the use of domestic coal, so in the short term there is only a small impact on the import dependence between the Baseline-L and climate policy scenarios. Over the long-term, however, climate policies have a significant impact on net import dependence of the

41. While "nuclear energy" is not traded, uranium resources and the enriched fuel are. The geographic concentration of the nuclear industry (both enriched fuel and nuclear power plant construction) is more of an energy security issue than uranium but only uranium trade is modeled in IMAGE and ReMIND.

major economies. The results for China, India, the E.U. and the U.S. are different between models, indicating significant uncertainties concerning climate policy impacts on future energy trade patterns.

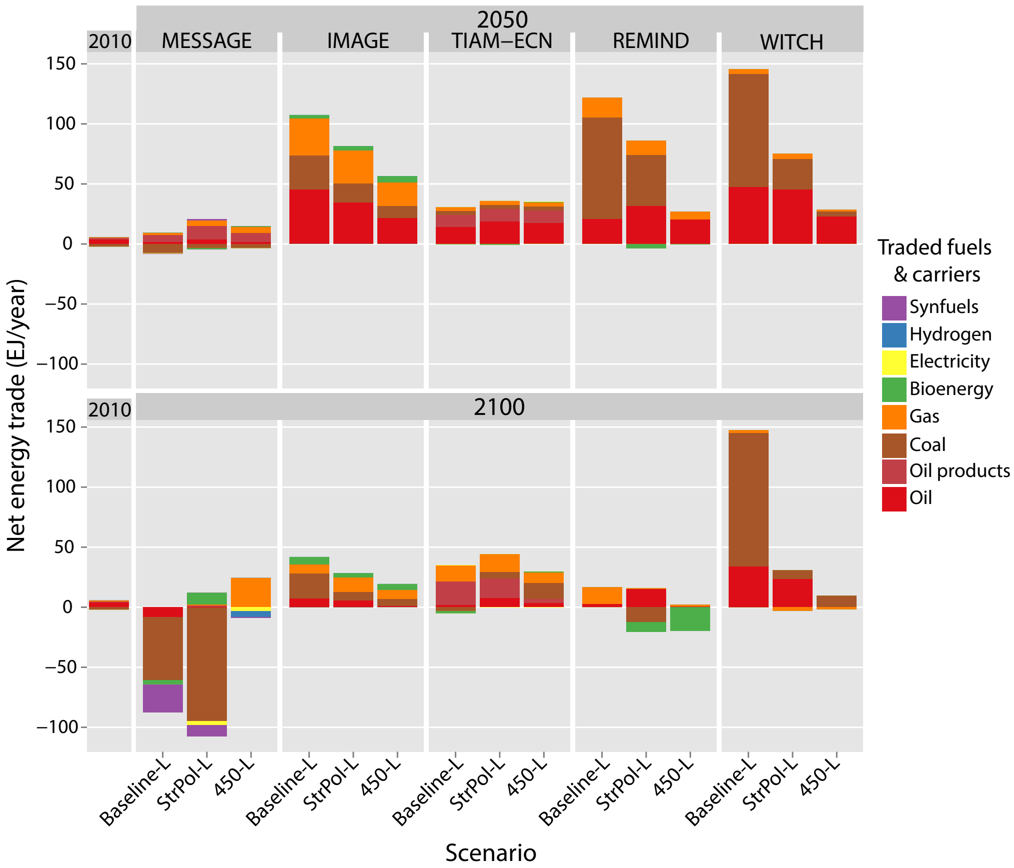
**China.** China had been a net exporter of energy until the 21st century and a net coal exporter until 2009 (British Petroleum 2012; World Bank 2012), but most models depict China's net imports growing from virtually nothing in 2010 to over 100 EJ in IMAGE, ReMIND and WITCH and about 30 EJ in TIAM-ECN by 2050 (Figure 4.15). The exception is the Baseline-L and StrPol-L scenarios in MESSAGE where China's imports do not change significantly by 2050 and, by 2100, the country exports almost 50 EJ per year. This amounts to between 1,300–1,700 EJ of coal or ∼6 trillion dollars worth over the twenty-first century which is about 0.2% of the country's GDP over that time (Figure 4.15). These massive coal exports are driven by China's cheap coal along with the high demand and limited domestic supply outside of the country.

In IMAGE, ReMIND and WITCH China's cumulative energy imports are significantly lower (by 2,500–8,800 EJ or by over 60%) in the 450-L scenario than under the Baseline-L (Figure 5.3). These import reductions occur primarily in the 2nd half of the century. In ReMIND, this decline is primarily due to a drop in coal imports; for IMAGE, the drop is distributed between all three fossil fuels and for WITCH it is due to a drop of imports of oil and coal trade. This reduction of cumulative imports translates into up to 50% lower import dependence, depending on the model and the year.[42] All of these trends are in line with the composition of global energy trade in each of these models.

In MESSAGE, under the 450-L scenario China foregoes the opportunity to export coal: its coal exports drop to 200 EJ over the entire century and China becomes a net energy importer. In contrast, in ReMIND under the climate policy scenarios China exports 500–600 EJ of bioenergy over the second half of the century because of a decrease in population (after peaking) and the large availability of cropland. This trend in bioenergy exports contrasts with IMAGE where China imports approximately the same

42. In WITCH declining absolute trade is actually accompanied by higher import dependency because reduction in domestic energy use occurs even faster than reduction of trade.

**Figure 4.15:** China's energy imports (positive) and exports (negative)

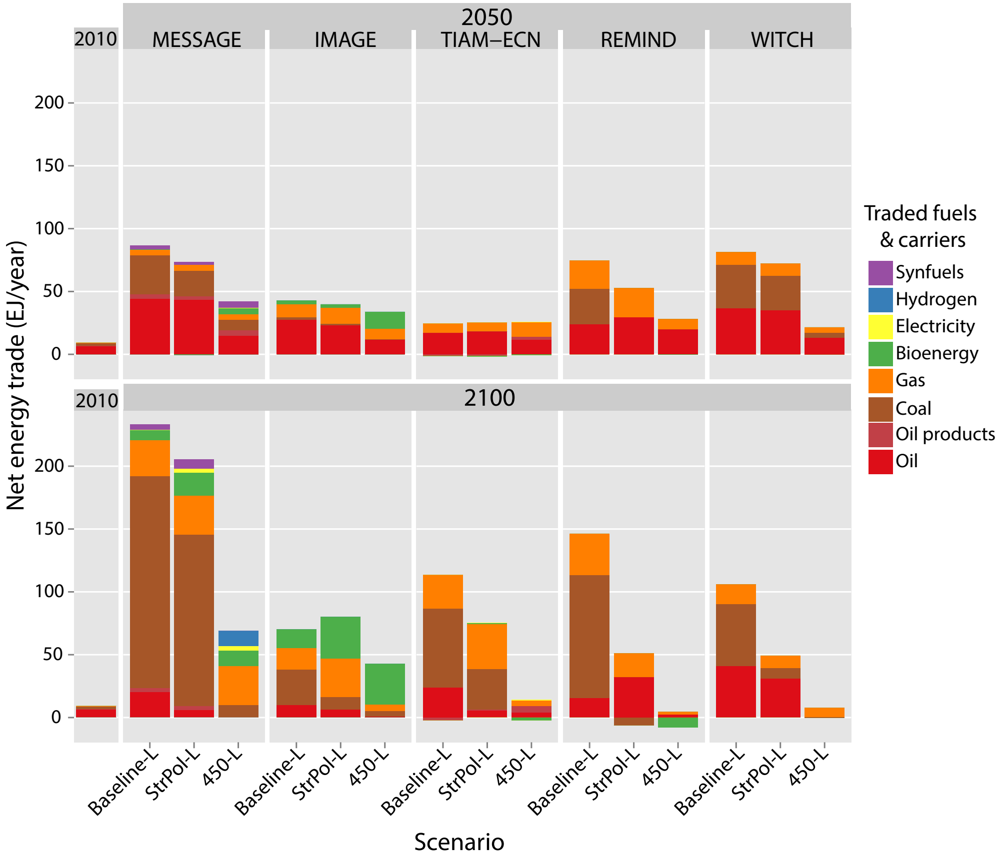



amount of bioenergy due to IMAGE's stricter constraints on the production of bioenergy. There is thus an uncertainty of whether China will export or import bioenergy.

In summary, most models project significant reduction of China's import dependence as a result of climate policies. A notable exception to this result is the reduction in Chinese exports of coal as a result of climate policies in MESSAGE. Both findings are in line with the global trends of reduction of global energy trade and interdependence. These global trends are less pronounced in TIAM-ECN which shows a smaller impact of climate policies on China's energy trade.

**India.** Among the major economies, India has the least energy resources: almost no oil or gas and very little coal resources. At the same time, India has the fastest growing population and economy and thus energy demand.

**Figure 4.16:** India's energy imports (positive) and exports (negative)




As a result, India is an energy importer under all models and scenarios, however, in most models import dependence would be lower under climate policies than under the Baseline-L scenario (Figure 4.16).

The lower annual energy imports result in a significant difference in cumulative energy imports over the 21st century between the Baseline-L scenario and the 450-L scenario (Figure 5.4). In MESSAGE, ReMIND, WITCH and TIAM-ECN, in the Baseline-L scenario India imports between 4,500 and 9,800 EJ over the century (or between 40%–70% of its TPES). Its imports drop in the 450-L scenario to between 1,600 and 4,500 EJ (or 20%–50% of TPES).[43] A large part of this drop is due to the phase out of coal imports in TIAM-ECN and ReMIND. Coal imports are also reduced in MESSAGE's

43. In WITCH the absolute imports decline but the import dependency actually increases because of the more rapid decline in overall energy use.

climate policy scenarios, but the region continues to import about 20 EJ/year to produce hydrogen (with CCS).

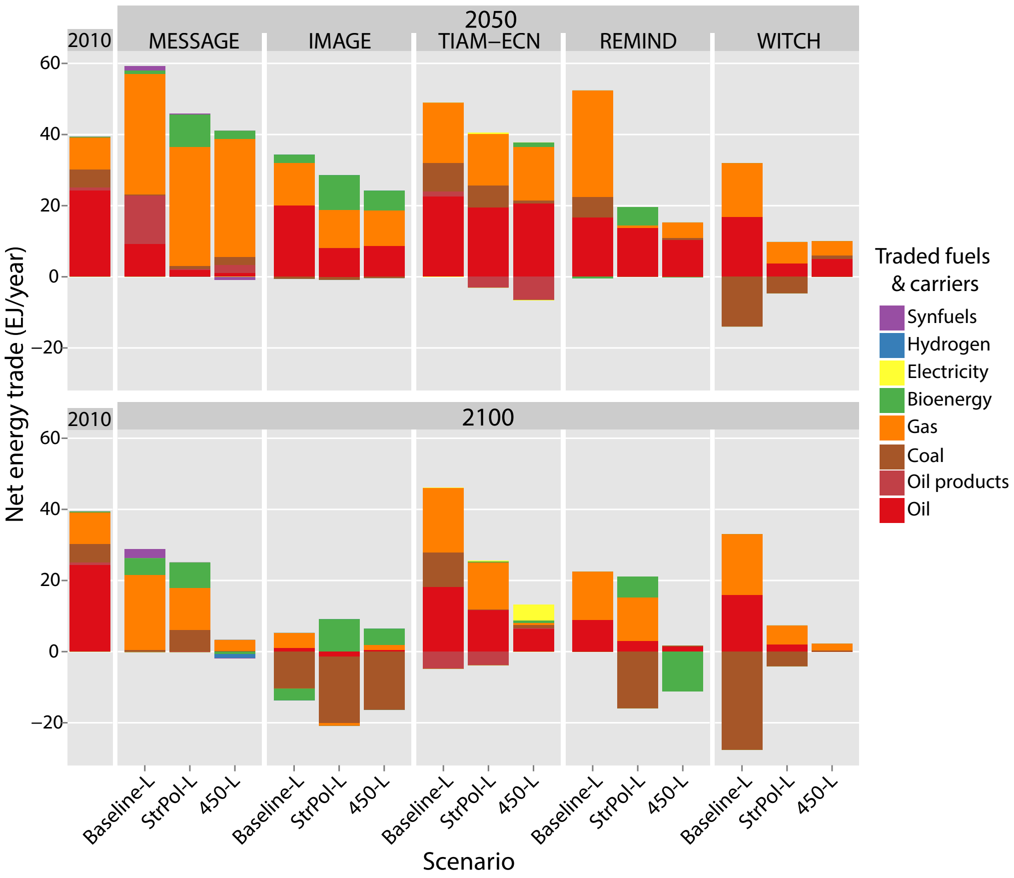
In IMAGE climate policies have a smaller impact on energy imports in India because, while fossil imports halve in the 450-L scenario, bioenergy imports grow to about 40 EJ/year. However, whether India becomes a net-exporter or importer of bioenergy under climate policies will partly depend on the bioenergy production restrictions—ReMIND, which has fewer restrictions on bioenergy production and which assumes both peaking population and high agricultural yields depicts the country as a net-exporter of bioenergy (∼8 EJ/year in the second half of the 21st century) but IMAGE with stricter restrictions on bioenergy production depict it as an importer of bioenergy.

**E.U.** In 2010 the E.U. imported about 50% of its TPES (World Bank, 2012). MESSAGE, ReMIND and TIAM-ECN show continuous import dependency over the 21st century in the Baseline-L scenario (Figure 4.17); IMAGE and WITCH depict the region as a net-exporter of coal. In these two models, the E.U. exports modest amounts of coal after 2050 in the Baseline-L scenario. These exports of lower-quality and more expensive coal are triggered in IMAGE by the depletion of cheaper coal reserves Worldwide and driven by Chinese coal demand.

In contrast, MESSAGE, ReMIND, and TIAM-ECN depict the E.U. as a net-importing region: between 4,000 and 4,600 EJ in the Baseline-L (or about 50% of its TPES) over the 21st century (Figure 5.5). Climate scenarios (both the StrPol-L and the 450-L) decrease net imports over the 21st century in these four models by between 20% and 55% (to between 20% and 40% of the E.U.'s TPES).

Climate policy scenarios generally reduce import dependence modestly by 2050 and dramatically by 2100. In IMAGE and WITCH, similar to other models, climate policies lead to a decrease in net energy imports in the E.U. in the first half of the century, however the composition of net-energy trade over the second half of the century differs from the other models. Additionally, similar to India and China, the the models differ in their depiction of bioenergy trade under the 450-L scenario. In ReMIND under the 450-L scenario, the E.U. exports ca 400 EJ of bioenergy (due to peaking popu-

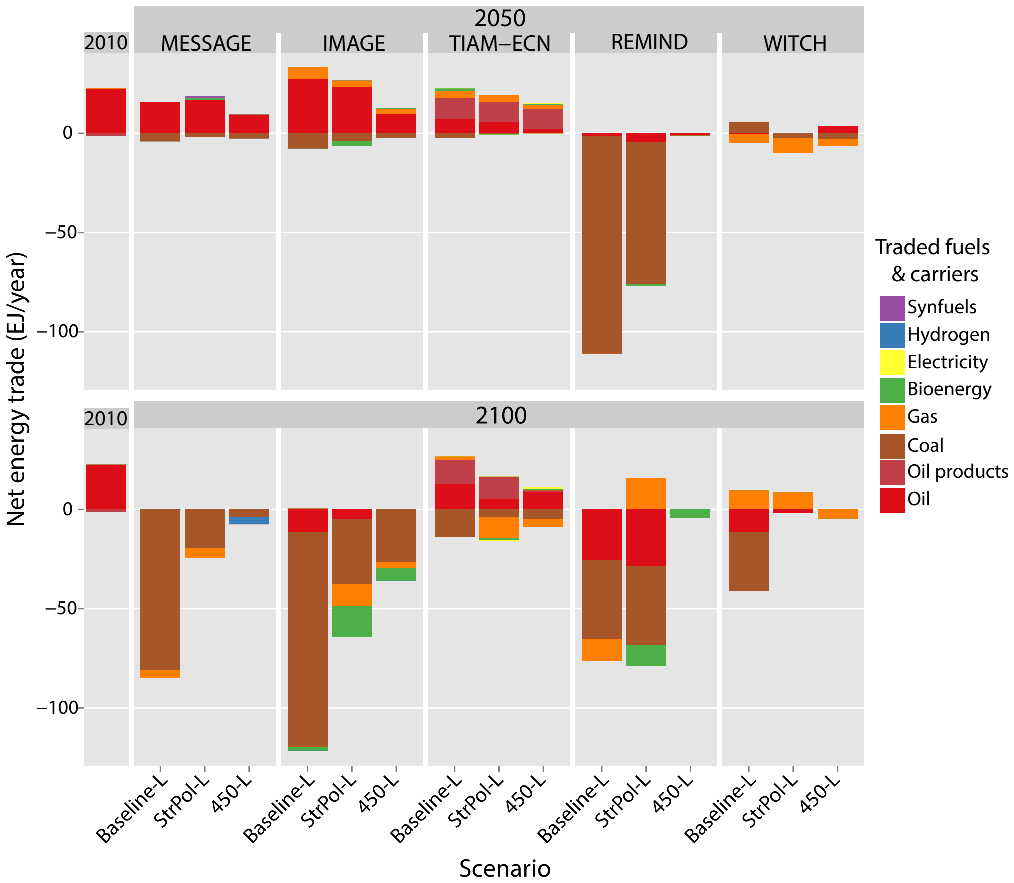
**Figure 4.17:** The E.U.'s imports (positive) and exports (negative)




lation, high yields and good transport infrastructure) whereas in IMAGE and MESSAGE the E.U. imports about 500 EJ of bioenergy over the second half of the 21st century.

**U.S.** The U.S. has been a net energy importer since the mid 1940s and over the last five years has imported about a fifth of its TPES (World Bank 2012). Under the Baseline-L and StrPol-L scenarios, the U.S. dependence levels shift such that by mid-century it becomes self-sufficient in 3 models and by the end of the century it is self-sufficient in all models (Table 5.5). In ReMIND the country actually becomes a net exporter in ReMIND by 2050 (Figure 4.18). There is little effect on net imports in MESSAGE, IMAGE, TIAM-ECN, or WITCH from climate policies by 2050. However, MESSAGE, IMAGE, and ReMIND models depict the U.S. as a net coal

**Figure 4.18:** The U.S.' energy imports (positive) and exports (negative)




exporter by 2100. The 450-L scenario significantly decreases the country's annual energy exports in most models.

These shifting import dependencies mean that in most models, the U.S. is a cumulative net-exporter over the 21st century for the region. Climate policies do not change this pattern but generally reduce the amount of energy exports in the latter half of the century (Figure 5.6). The effect of climate policies is the largest in ReMIND which models the largest amounts of exports for the U.S. (8,500 EJ of coal in the Baseline) which drops 30% in StrPol-L and virtually disappears in the 450-L scenario. In IMAGE, the export volumes (2,300 EJ in the Baseline-L) are lower but the drop in coal exports is 60% and 75% respectively in StrPol-L and the 450-L scenarios. TIAM-ECN models more stable long-term production of low-cost oil in the Middle East which means that the U.S. only becomes a net energy exporter at the end of the 21st century. This is in contrast to other models which indicate a rapid peak and decline of conventional oil production.

*Energy exporters*

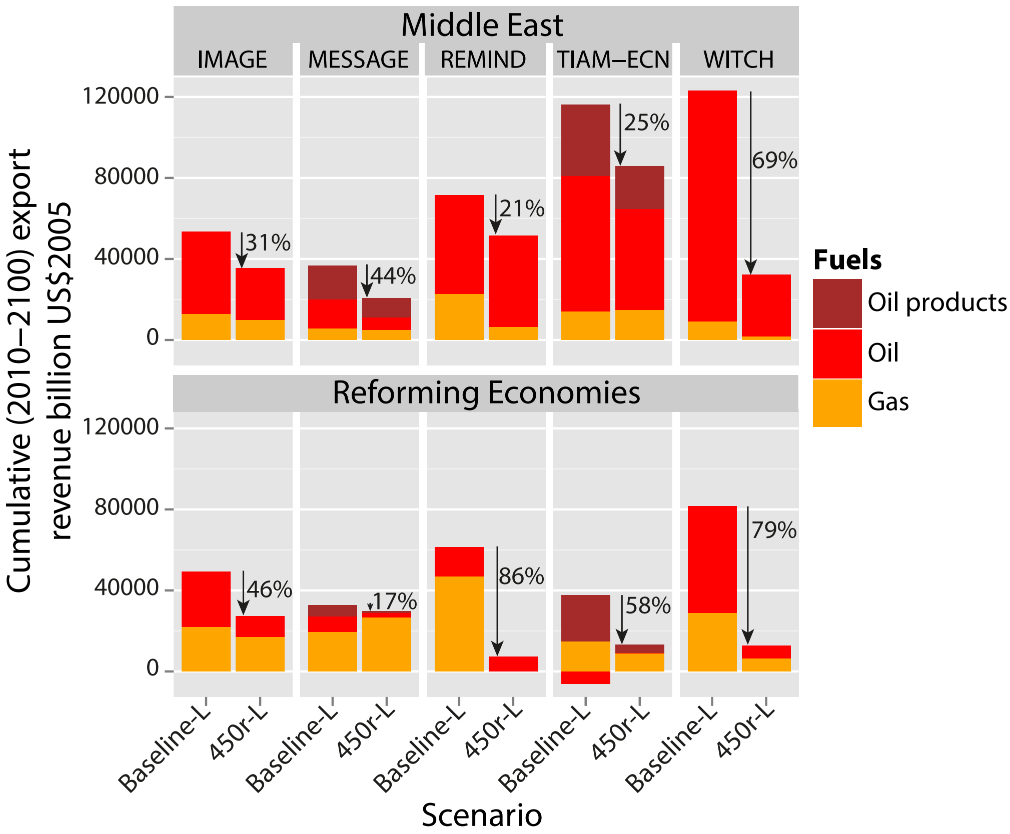
While lower energy imports are usually welcome from an energy security point of view, decline of energy exports leads to revenue losses. In this thesis, I include some calculations of what happens to oil export revenues for the two main energy exporting regions: the Middle East and North Africa (MENA) and the Reforming Economies (REF), which is dominated by Russia. However, since the scenarios included in this thesis do not cover the technological and political uncertainties which will impact energy export revenues, I also synthesize the existing literature on energy export revenues under climate policies in order to identify the main technological and political uncertainties which would impact energy export revenues under a climate regime.

**Oil and gas export revenues under climate stabilization.** All models show that the 450r-L scenario leads to a decrease in energy export revenues for the Middle East and Reforming Economies. For the Middle East this drop ranges from 21% in MESSAGE to 69% in WITCH (Figure 4.19). For IMAGE, MESSAGE, TIAM-ECN and WITCH, most of the drop in total export revenues comes from the drop in oil demand. However, in ReMIND, the drop is driven by a decrease in gas demand since in this model, unlike the others, gas is not used a bridge fuel and as a result the demand is dramatically lower in the 450r-L scenario than the Baseline-L.

The models show a wider range (and therefore higher uncertainty) for the effect that the 450-L scenario would have on the in total export revenues for the Reforming Economies region. The decrease in export revenues ranges between 17% and 86%. The wider range is because the export revenues for this region are primarily from natural gas, rather than oil which, as discussed above, ranges from being phased out in ReMIND under 450-L to increasing in MESSAGE to be used as a bridge fuel.

While the models show a decrease in the cumulative export revenues for both regions, the decrease in export revenues is actually concentrated in the latter half of the 21st century. The models do not show much impact

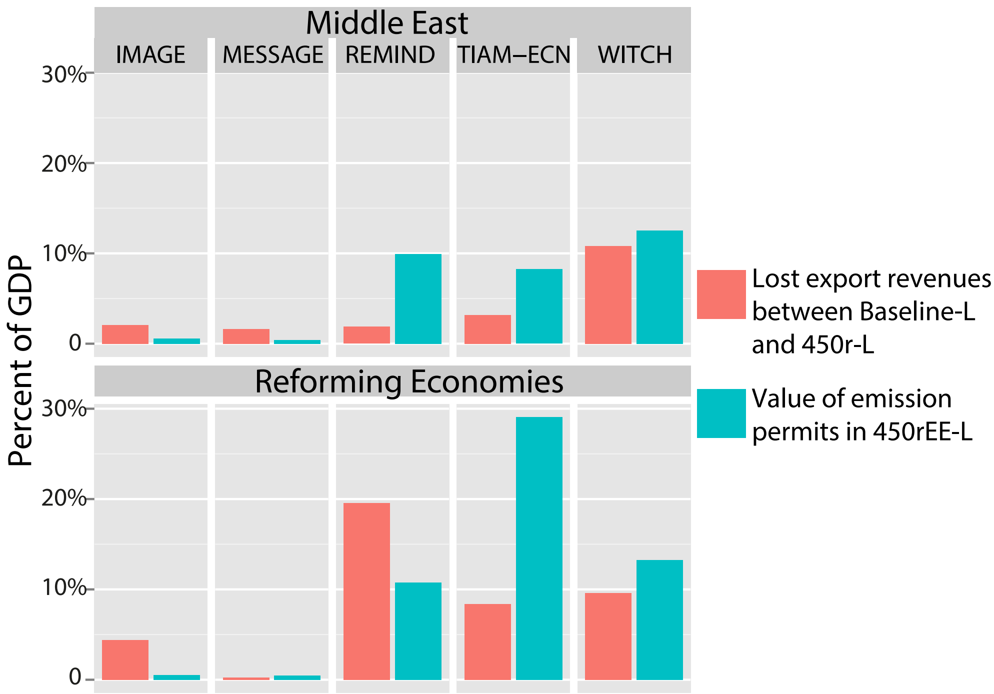
**Figure 4.19:** Oil & gas export revenue in the Middle East and Reforming Economies in the Baseline-L and 450-L




Note: The Reforming Economies region is a region dominated by Russia.

over the short-term (up till 2030) since the demand for conventional oil and gas is not elastic in the next several decades. Indeed for oil, in the RoSE scenarios, since the number of oil exporting regions is lower under climate policies (Figure 4.12), under stricter climate policies both the Middle East and Reforming Economies (called the Former Soviet Union in RoSE) experience larger oil exports in the first half of the century in the 450-R than in the Baseline-R. This is because in the Baseline-R scenario energy exports from these regions face strong competition from highly carbon intensive unconventional fossil fuels and coal- or gas-to-liquids technologies. The most strict climate policy would lead to smaller export revenues in the last third of the century, but the relative importance of energy exports for the economy in the Middle East may have already declined by this time even in the Baseline-R scenario.

**Figure 4.20:** Compensating 'lost' export revenues through the carbon market




**Compensating energy export losses through the carbon market.** One possible solution to lost energy export revenues would be to compensate energy exporting countries for their losses through a global carbon market. This was a scenario modeled in the LIMITS project (RefPolrEE–450-L). In this "equal-effort" burden sharing regime all regions incur the same mitigation costs in relation to their GDP. Implementing this regime leads to the formation of a global carbon market through which countries where GHG mitigation is relatively more expensive compensate countries where GHG mitigation is relatively less expensive.

Under this regime do financial transfers compensate for lost energy export revenues? Figure 4.20 shows the lost oil (both crude and products) and gas export revenues in 450rEE-L (which is almost identical to the lost revenues in 450r-L in Figure 4.19) relative to the financial flow to the regions through emissions permits. The results are different between models. In WITCH and TIAM-ECN, the financial transfers are larger than the lost oil export revenues for both regions. In contrast, IMAGE shows that emissions transfers are far less than lost oil and gas export revenues. MESSAGE and ReMIND show opposite results for each region.

**A synthesis of the key uncertainties for energy exporters.** The existing literature on oil export revenues shows an even wider degree of uncertainty in what would happen to oil export revenues under climate policies. This section synthesizes the existing literature and highlights the strategic uncertainties which will impact the oil export revenues of oil exporters. I restrict this discussion to oil export revenues since that is the focus of the existing literature.

There are three main drivers of oil export revenues under climate policies:

1. the development of the energy system: What is the demand for and price of oil and how do other energy technologies impact that demand and price?
2. the development of the economy: How does oil demand and other economic factors affect the demand for and price of oil?
3. the political interests and influence of oil exporters and importers: Are oil exporters trying to manipulate production and prices? Are oil importers coordinating to impact oil demand?

There is a modeling community which grew out of each of the above dynamics. Models dealing with oil export revenues under climate regimes (Table 4.1) can be broadly grouped into energy-economic models (either emphasizing energy system development or economic forces) and oil market models which simulate cartel behavior for OPEC versus a competitive oil market. The first two drivers of oil export revenues are addressed in the energy-economy literature while the third is explored using oil market simulations.



**Table 4.1:** Previous studies on oil export revenues under climate policies

| Study & Model Type | Time horizon | Climate policies | Uncertainties tested | Impact on oil revenue | |
|---|---|---|---|---|---|
| van Vuuren et al. 2003 energy-economic | Results: 2025, 2050; Model: 2100 | GHG stabilization at 550 ppm & 650 ppm[a] | **Middle East & Turkey region versus Baseline** | | |
| | | | | *2025* | *2050* |
| | | | *550 ppm* | -10% | -20% |
| | | | *650 ppm* | -25% | -35% |

*continues on next page*

| Study & Model Type | Time horizon | Climate policies | Uncertainties tested | Impact on oil revenue | |
|---|---|---|---|---|---|
| Haurie and Vielle 2011 general equilibrium | 2030 | Global $CO_2$ tax | **OPEC wealth versus no carbon tax** | | |
| | | | Carbon tax ($50/TC – $2500/TC) | -3%– -63% | |
| Berg, Kverndokk, and Rosendahl 1997b oil cartel | 2100 | Global $CO_2$ tax | **Reduction in OPEC's oil wealth from carbon tax** | | |
| | | | | *OPEC* | *fringe* |
| | | | *OPEC acts as a cartel* | -23% | -25% |
| | | | *competitive oil market* | -8% | -39% |
| Johansson et al. 2009 oil cartel | 2100 | Global $CO_2$ tax | **Reduction in OPEC's oil wealth from carbon tax** | | |
| | | | | *OPEC* | *fringe* |
| | | | *base case* | +4% | +5% |
| | | | *demand elasticity (+/- 0.3)* | +12%/-3% | +10% |
| | | | *synthetic fuel cost (+/-30%)* | -1%/18% | -/+29% |
| | | | *hydrogen cost (+/-$15/GJ)* | +9%-5% | +10%/-2% |
| Persson et al. 2007 energy-economic | 2100 | GHG stabilization at 450 ppm | **OPEC through 2100 versus baseline** | | |
| | | | *450 ppm base case* | +3% | |
| | | | *stabilization (+/-100ppm)* | -10%/+4% | |
| | | | *hydrogen cost ($50–$300/kW)* | +2%/+6% | |
| | | | *demand elasticity (-0.3/-0.8)* | -/+2% | |
| Bartsch and Müller 2000 energy-economic | 2020 | Kyoto Protocol | **Middle East revenues versus baseline** | | |
| | | | | *2010* | *2020* |
| | | | *Kyoto base case* | -14% | -10% |
| | | | *supply elasticity (2–0.15)* | -2% | -7% |
| | | | *demand elasticity (0.2 for transport and 5 for electricity)*[b] | -17% | -13% |
| McKibbin et al. 1999 energy-economic | Results: 2010; Model: 2050 | Kyoto Protocol | **OPEC oil revenue through 2010 versus baseline** | | |
| | | | *no GHG permit trading* | -25% | |
| | | | *trading within Annex I* | -13% | |
| | | | *full global trading* | -7% | |
| Ghanem, Lounnas, and Brennand 1999 energy-economic | Results: 2010; Model: 2050 | Kyoto Protocol | **Annualized OPEC revenue**[c] | | |
| | | | *no GHG permit trading* | -16% | |
| | | | *trading within Annex I* | -10% | |
| | | | *full global trading* | -8% | |

Notes:

[a] This study also includes different participation regimes but does not report the oil export revenues of these scenarios.

[b] This is a simplification. The elasticities in the base case are: 1 for agriculture; 1 between non-electric energy inputs; 0.2 for energy commodities, transport, private and government demand; 5 for electricity generation, energy intensive and other manufactured goods.

[c] These results are reported in dollar amounts.

The strength of energy-economic models is that they can test the impact of different techno-economic developments on export revenues. The weakness is that they assume perfect markets which pursue optimal least-cost and/or maximum profit solutions thus they generally do not incorporate oil cartel behavior. Additionally, oil prices in these models are generally the marginal price of production or the shadow price (the marginal utility of oil use) and exclude the retail markup and profit margin: thus, they may underestimate the actual export revenues.

Oil market models have been used to examine the effect of oil exporter behavior on energy markets. The strength of this approach is that it considers how actor behavior influences the oil market. Thus these models can consider how OPEC's coordination could impact the price of oil (and in turn export revenues). The weakness of the oil market simulation models is that they rarely have extensive technological detail. Recently, a few studies have also found that oil export revenues are not only impacted by OPEC's coordination but also by the coordination of oil importers (Dong and Whalley 2012).

While techno-economic and game-theoretic models emphasize different dynamics, in reality neither of these forces happens in isolation. No model can ever capture all of the dynamics from the real world at once. Nevertheless, synthesizing the literature which looks at each of these forces in isolation with the emerging literature which takes multiple perspectives simultaneously yields useful insight into the key techno-economic and political factors which could shape the development of oil export revenues in MENA and OPEC countries under climate policies.

*Techno-economic uncertainties:* The main techno-economic factors and uncertainties which could impact the development of oil export revenues in a low-carbon scenario are:

1. the responsiveness of oil demand and production to changes in prices and
2. the development of oil alternatives (ranging from synthetic fuels produced gas and coal in the near-to-medium term to hydrogen in the long-term).

Oil demand and production elasticity have a large impact on what happens to oil export revenues under climate regimes. Not surprisingly, the higher the demand price elasticity (i.e. the easier it is for consumers to curtail their oil use in response to price increases), the lower are OPEC's oil revenues under stabilization scenarios. When price elasticity for liquid fuels is increased from −0.3 to −0.8, OPEC's rents decrease by between 1.6% (Persson et al. 2007) and 2.4% (Johansson et al. 2009). This finding is consistent with an earlier top-down modeling exercise that both oil export volumes and prices are lower with more flexible demand (i.e. lower elasticity) (Bartsch and Müller 2000, 288–289). Additionally, Bartsch and Müller found that some flexibility in oil supply reduces the impact of the Kyoto protocol on oil revenues (282 and 290). The easier it is for oil producers to control global oil supply, the smaller the drop in oil export revenues will be from climate policies.

Related to oil demand elasticity is the cost of oil alternatives. Thus rapid innovation and price falls in alternatives to conventional oil-powered transport would shift demand away from oil and would likely decrease oil export revenues. On the other side, a lack of transportation alternatives would, even under climate scenarios likely lead to an increase in revenues.[44] The most immediate substitute to oil products in the transport sector is biofuels. While biofuels can be an important alternative to unconventional oil and other fossil liquids in the near-to-medium term (Riahi et al. 2012), the few studies that look into conventional oil exports proceeded from the assumption that biofuels are not competitive and thus are inconclusive with respect to biofuel impacts on OPEC export revenues.[45]

The transportation alternative which has been found to have an impact on export revenues is fuel-cell and hydrogen-production cost. Persson et al. (2007) found that decreasing the fuel cell cost from US$300/kW to US$50/kW decreased the net present value of OPEC's oil revenue by 0.9%. In another study, Johansson et al. (2009) find that varying the cost of production and distribution of H2 by +/- 15 U.S.$/GJ affects OPEC's oil revenue by

44. Transport is such an important sector for the development of oil export revenues because over 60% of oil product demand comes from that sector (calculated from IEA (2012a)).

45. One study on the current impact of biofuels on the oil market finds that the introduction of biofuels in 2007 led to a ∼1% reduction in fuel prices (gasoline, diesel, and biofuels), <1% reduction in oil consumption in oil-importing countries, but a global increase in fuel consumption by ∼1.5% (Hochman, Rajagopal, and Zilberman 2010).

+9% and –4.6% respectively. While none of the studies looked at the effect rapid electrification of transport would have on export revenues, it would likely be similar to the impact fuel cell development has.

Unconventional oil and synthetic liquid fuels from coal or gas could also compete with conventional oil produced in MENA.[46] Conventional oil reserves are fully depleted in scenarios designed to simulate implementation of the Kyoto protocol (Brack, Grubb, and Windram 2000, 39) and almost all long-term climate stabilization scenarios (Grubb 2001; Persson et al. 2007).[47]

The impact of the cost of other fossil alternatives[48] on MENA oil export revenues under climate policies is opposite to the impact of cost of 'climate-friendly' alternatives such as fuel cells. While under a business as usual scenario, a decrease in the price of fossil fuel alternatives to conventional oil might reduce oil export revenues in MENA, under climate stabilization scenarios, the opposite is the case. This is because low-cost fossil fuel alternatives are taxed under climate regimes in order to 'force them out' of the market. The lower the cost of these high-carbon fuels, the higher is the carbon tax and thus the higher is the price of conventional oil on the market, leading to higher export revenues (Persson et al. 2007).[49]

*Political uncertainties:* Political factors will also impact how MENA would fare under a climate deal. The most obvious political factor is the degree to which OPEC behaves as a cartel. There is disagreement in the literature as to what extent OPEC is a cartel. Early studies find evidence of cartel behavior (Gulen 1996; Youhanna 1994) while more recent ones come to the conclusion that OPEC may not be such a strong cartel after all (Robert K Kaufmann et al. 2008; Smith 2005; Alhajji and Huettner 2000). Even though OPEC is not a perfect cartel, there is evidence that its behavior

46. MENA accounts for less than 10% of unconventional oil reserves (Rogner et al. 2012) so it would be unlikely to play a large role in the region's production.

47. Nevertheless, if conventional oil reserves ended up being lower than previously thought (which is unlikely), oil price rises due to increasing scarcity would significantly off-set a decrease in oil export revenues due to lower export volumes (Barnett, Dessai, and Webber 2004). This finding was reported under a scenario simulating the Kyoto Protocol but would likely hold up under any climate stabilization scenarios as well.

48. This includes synthetic coal-to-liquid and gas-to-liquid fuels.

49. Note that this dynamic only happens in the latter half of the 21st century thus is not observed in shorter-term scenarios (e.g. till 2020 or 2030).

influences oil prices (R K Kaufmann et al. 2004) and that OPEC members do gain from coordinated behavior. In the 1970s, the gain of cartelization for OPEC was estimated to be some 50–100% of the overall rent (Pindyck 1978). Two decades later in the 1990s, with lower oil prices and a lower share of the global oil market, the estimated gain from cartelization was estimated to be much lower at some 18%–25% (Berg, Kverndokk, and Rosendahl 1997a) even under imperfect coordination (Griffin and Xiong 1997). Recent work on OPEC indicate that it is an imperfect cartel which moves towards a perfect cartel with increased demand elasticity (Okulloa and Reynèsa 2012). This finding emphasizes the interrelated nature of techno-economic and political factors.

But how will OPEC behave under global climate change policies? On the one hand, cartelization allows OPEC to better coordinate and adjust production capacity to manipulate prices which has been argued would prevent climate policies from depressing oil prices (Radetzki 2002). However some more recent analysis implies that OPEC does not have sufficient market power to manipulate world oil prices in the face of a global carbon tax (Haurie and Vielle 2011). Another consideration is that cartelization may put OPEC producers at a disadvantage to non-OPEC ones since OPEC producers would be obligated to curb production in the face of falling demand. In fact, two papers have found that OPEC would indeed suffer more than non-OPEC producers under a global carbon tax since: under a global carbon tax equivalent to $10 per barrel, OPEC's wealth drops 20% while non-OPEC producers lose a mere 8% (Berg, Kverndokk, and Rosendahl 1997b). In a similar scenario, by another group, OPEC's resource rents actually increase by about 5% under a global carbon tax; though non-OPEC oil producers experience a slightly higher increase in their oil revenues (Johansson et al. 2009). While the two papers use similar modeling frameworks, the oil price in (Johansson et al. 2009) is three times Berg et al.'s (1997) price (since the decade between the two papers saw a substantial increase in oil prices) which likely explains the divergent results. It seems unlikely that if the cost for cartel-like behavior really were as extreme as Berg suggests OPEC members would maintain their cartel behavior. On the other hand, climate policies would likely increase the technological options consumers would have to curb their oil production and could lead to higher demand elasticity which might increase the incentives for cartelization.

The reach of a climate regime also impacts oil export revenues. In fact Dong and Whalley (2012) find that a coordinated non-OPEC carbon tax would effectively lower oil prices (relative to a scenario without any carbon tax) and transfer monopoly rents from OPEC to oil-importing countries. This finding is consistent with earlier findings: the wider the reach of the climate regime, the less oil-export revenues drop under climate policies. For example, McKibbin found that implementing the Kyoto Protocol with no international greenhouse gas permit trading led to a $\sim$25% decrease in oil export revenues for OPEC by 2010 compared to the baseline versus a $\sim$13% decrease in revenues with trading between Annex I countries or a $\sim$7% decrease with full global trading of permits (McKibbin et al. 1999). Thus, there is an incentive for major oil importers to come to a climate deal without oil-exporting countries; at the same time OPEC must maintain its position at the climate talk table because a climate deal excluding OPEC would likely be far worse for oil-exporting countries.

## 4.2 Robustness

Climate policies almost universally lead to lower resource extraction. The only exception is gas extraction, which in some models, climate policies lead to slightly higher extraction. In this section I first describe the global results and then the regional ones. All results are from the LIMITS scenarios and include all six models.

### 4.2.1 Global resource extraction

Table 4.2 shows the global cumulative extraction of fossil fuels in the 21st century. Climate policies result in a notable decrease in the oil, coal and gas extraction volumes in all models. The exception is TIAM-ECN where where gas extraction in Str-Pol-L is the highest followed by the 450-L scenario and finally the Baseline-L. This is because in TIAM-ECN's StrPol-L scenario coal is substituted by natural gas leading to an increase in gas extraction. However, the emissions of natural gas technologies (even with CCS) are too high to support the 450-L scenario in this model and therefore the cumulative gas extraction is relatively lower as compared to the StrPol-L scenario.

**Table 4.2:** Global fossil fuel extraction

| | Extraction ZJ | | | | | | Reserves + |
|---|---|---|---|---|---|---|---|
| | Baseline-L | | StrPol-L | | 450-L | | Resources ZJ |
| Oil | 16–25 | *47%–106%* | 14–20 | *41%–82%* | 8–15 | *23%–61%* | *24–34* |
| Gas | 16–27 | *8%–37%* | 15–21 | *7%–29%* | 7–15 | *3%–21%* | *72–205* |
| Coal | 26–35 | *6%–11%* | 11–23 | *2%–8%* | 3–12 | *1%–4%* | *308–456* |

Notes: Figures in italics show the ratios of the projected extraction volumes to the last column: Reserves and Resources estimates from the *Global Energy Assessment* (Rogner et al. 2012). These estimates exclude gas hydrates and additional occurrences which are highly uncertain technologically and economically.

From an energy security perspective, the implication of these different extraction volumes is most obvious for oil. In the Baseline-L scenario, between 47% and 106% of available resources are extracted, which would inevitably result in anxiety over scarcity and price volatility. In the 450-L scenario, only between 23% and 61% of oil resources are extracted which would arguably lead to less concerns. Neither gas nor coal experience the same scarcity levels at the global level.

In general, the less stringent the climate target is, the higher the cumulative extraction. Results from other parts of the RoSE scenario exercise indicate that higher GDP growth leads to slightly higher cumulative extraction (at least in ReMIND) where cumulative fossil extraction is about 25% higher in the fast growth scenario (BAU SL Gr-R) than the slow growth one (BAU SL Gr-R). Neither supply nor demand technologies, from the GEA scenarios have a large impact on oil extraction. Gas and coal extraction do vary slightly based on supply constraints but never exceed the extraction rate in the Baseline-G. Similar to trade, limitedRES-G and the noNuc-G scenarios (particularly when combined with conventional transport) lead to higher cumulative extraction.



### 4.2.2 Regional resource extraction

Domestic resource scarcity leads to more energy imports and greater exposure to sovereignty concerns. At the same time, leaving resources in the ground (which CPs lead to) is a lost opportunity for a nation's economy. Cumulative extraction volumes for coal, gas and oil for the four major

**Table 4.3:** Fossil fuel extraction in the major economies

| | | Extraction EJ | | | | | | Reserves + |
|---|---|---|---|---|---|---|---|---|
| | | Baseline-L | | StrPol-L | | 450-L | | Resources EJ |
| China | Oil | 130–2200 | *20%–560%* | 130–1000 | *22%–260%* | 120–620 | *21%–160%* | *390–580* |
| | Gas | 560–1500 | *17%–50%* | 730–1300 | *22%–45%* | 350–1700 | *11%–55%* | *3000–3300* |
| | Coal | 4900–13400 | *4%–10%* | 3200–8200 | *2%–6%* | 1200–2900 | *1%–2%* | *129000* |
| India | Oil | 40–1200 | *66%–2300%* | 40–1100 | *66%–2200%* | 40–400 | *62%–805%* | *50–60* |
| | Gas | 140–800 | *3%–18%* | 110–750 | *2%–17%* | 92–590 | *2%–13%* | *4400–4600* |
| | Coal | 1000–5800 | *17%–94%* | 640–2600 | *10%–43%* | 380–1800 | *6%–30%* | *6200* |
| EU | Oil | 140–1200 | *15%–340%* | 160–820 | *17%–240%* | 120–570 | *13%–140%* | *340–915* |
| | Gas | 600–1400 | *34%–78%* | 600–1400 | *33%–76%* | 380–1160 | *21%–64%* | *1800* |
| | Coal | 500–3400 | *3%–20%* | 150–1700 | *1%–10%* | 90–1100 | *1%–6%* | *16605* |
| USA | Oil | 610–3400 | *3%–65%* | 600–3000 | *3%–57%* | 150–1300 | *1%–25%* | *5200–19000* |
| | Gas | 1100–3500 | *8%–25%* | 1500–3100 | *10%–22%* | 880–2100 | *6%–15%* | *14300–14500* |
| | Coal | 2600–10000 | *1%–5%* | 1300–7100 | *1%–4%* | 480–2400 | *1%* | *190000* |

Notes: Figures in parentheses represent the ratios of extraction volumes to reserve and resources estimates in the last column. Reserves and resource estimates are from the *Global Energy Assessment* (Rogner et al. 2012). The range represents resource plus reserve estimates from different sources. These estimates exclude gas hydrates and "additional occurrences" which are highly uncertain both technologically and economically. Models have their own resource availability and cost curves which in some cases depart from these R&R estimates. This is also why some regions exceed the R&R estimates used for this analysis.

economies and the two main energy exporters are shown in Table 4.3 with the estimates of reserves and resources as summarized from the literature in Rogner et al. (2012).

### *China*

The upper estimates for China's oil resource extraction (by WITCH and ReMIND) indicates the extracted volumes close to or over 2000 EJ (over five times the lower estimate for R&R) in the Baseline-L scenario which declines to some 900 EJ (still over two times the lowest estimate of R&R) in the StrPol-L scenario and to ca 670 EJ (up to one and a half times the lowest estimate of R&R) in the 450-L scenario. The other three models project more modest depletion levels ranging from just over 300 EJ (Baseline-L in IMAGE) to just under 100 EJ (450-L scenario in TIAM-ECN) which are well within the R&R estimates and decline less drastically in response to climate policies. Irrespective of the difference between models, these results indicate that there is a significant danger of China completely or nearly fully depleting its oil resources which will eliminate a buffer against potential disruption of imports under the Baseline-L scenario and that this danger is significantly lower in the case of climate policies.

For gas, the results are more consistent between four of the five models. In IMAGE, MESSAGE, ReMIND, and WITCH, gas extraction is between 1200 and 1500 EJ and slightly drops to between 870 and 1300 EJ in StrPol-L (staying within the 30%–50% of the estimated R&R) and 350 EJ–760 EJ in the 450-L scenario. In contrast, in TIAM-ECN China's gas extraction is lower in the Baseline-L but higher in the 450-L scenario. This is because in TIAM-ECN China's energy sector is heavily dependent on coal in the Baseline-L, leaving only a minor role for natural gas. Since natural gas substitutes coal under climate stabilization its extraction increases in the second half of the century. With respect to coal, climate policies result in the largest reduction of extraction volumes (by about four times in all the models), which in all scenarios stay well below 10% of its estimated coal reserves. In MESSAGE a large part of the coal extracted in the Baseline-L scenario is used for exports.

### *India*

India is the most resource-poor of the major economies without significant oil or gas resources and with low coal resources compared to the country's demand. With such low oil R&R, the modeled oil extraction is essentially moot since the country faces extreme oil scarcity no matter what it does. The country exploits between 40 and 90 EJ in the Baseline-L and StrPol-L scenarios (or between two-thirds and twice its estimated R&R). The 450-L scenario has almost no impact on oil extraction: only the upper estimate drops to 70 EJ (or one and a half times its estimated R&R).

India's gas results show that, for the most part, climate policies have little impact on cumulative extraction. In the Baseline-L, all models except WITCH suggest that India extracts between 200 and 470 EJ (or 11% to 27% of its estimated R&R). While the effect of climate policies is small in all four of these models, IMAGE and TIAM-ECN indicate that climate policies slightly increase cumulative gas extraction in India while MESSAGE and ReMIND show the opposite. The lack of significant gas resources or extraction in India is consistent with the fact that the country imports gas in all models. WITCH shows a significantly higher gas extraction in the Baseline-L: 1100 EJ or over 60% of the country's estimated R&R. This extraction drops to 970 EJ under StrPol-L and 470 EJ under the 450-L scenario.

India extracts about 2,000 and 2,500 EJ of coal (or 35%–40% of its R&R) in the Baseline in MESSAGE, ReMIND, and TIAM-ECN and 4,300 to 5,800 EJ in IMAGE and WITCH (or 70%–95%). In the first three models, StrPol-L has virtually no effect on extraction but in IMAGE and WITCH, in StrPol-L, coal extraction halves. In the 450-L scenario, coal extraction further drops by between 24% and 82%. Thus under the Baseline-L scenario, the country faces scarcity concerns in some models. Climate policies prevent India from facing these scarcity issues.

*E.U.*

Similar to India, the E.U.'s oil resources are so low compared to its demand that the region inevitably faces scarcity issues and imports most of its oil consumption in all models and scenarios. Nevertheless, climate policies lead to lower extraction (a drop from a maximum of 1200 to 510 EJ). The E.U. faces a similar situation with gas: scarce domestic resources and high import dependence. For most models, climate policies lead to a drop in gas extraction. But for TIAM-ECN they lead to a slight increase because natural gas technologies are an important part of climate mitigation in this model, so gas extraction is slightly higher in the climate stabilization scenarios (but as a result the region's import dependence on gas is slightly lower). For coal, the models depict two different realities. MESSAGE, ReMIND and TIAM-ECN depict E.U. coal extraction as <1300 EJ in the Baseline-L scenario. IMAGE and WITCH depict E.U. coal extraction as 2400–2600 EJ in the Baseline-L and the region becomes a net exporter of coal in the latter half of the century after the world's cheaper coal resources are depleted. Overall, climate policies lead to between a two- and ten-fold decrease in coal extraction.

*U.S.*

Among the major economies, the U.S. has the largest fossil resource endowments. Thus, it not only faces fewer scarcity issues than the other major economies, but is also the one which would be most likely to forgo significant export revenues as a result of global climate policies. The U.S. extracts between 1,100 EJ and 3,400 EJ of oil (or between 6% and 65% of its estimated R&R) in all models except TIAM-ECN. In ReMIND the country even becomes a minor net exporter of oil in the second half of the century in the Baseline-L through the exploitation of oil shale. In general, climate policies lead to a drop in oil extraction by at least 50% (but do not impact oil imports). TIAM-ECN is an exception: oil extraction in the Baseline-L is 600 EJ (3% of estimated R&R), which is relatively lower than the other models due to higher transport efficiency improvements and as a result, extraction does not change significantly under climate policies.

For gas, the country extracts between 2,300 and 3,500 EJ (16% to 25% of its estimated R&R) in the Baseline-L in all models except TIAM-ECN. In IMAGE, ReMIND and MESSAGE, the country even is a modest gas exporter in the second half of the century. The StrPol-L scenario leads to a small drop in gas extraction (highest of 22%) in all models. Under the 450-L scenario, the U.S. extracts less gas and exports virtually no gas. In TIAM-ECN, like other regions, gas extraction increases in StrPol-L and the 450-L scenario since the Baseline-L scenario is coal-intensive and climate policies lead to gas displacing coal.

In all models except ReMIND the U.S. extracts between 2,400 and 5,400 EJ of coal in the Baseline-L (<3% of the estimated R&R). This drops sixfold under climate policies which also leads to a drop in coal exports. In ReMIND, U.S. coal extraction drops from 10,000 EJ in the Baseline-L to less than 1,000 EJ in the 450-L scenario.

## 4.3 Resilience

The diversity of energy systems significantly rises in all scenarios, models, regions and sectors under climate policies in comparison to the Baseline. In general, the more stringent the climate policies, the earlier the diversity improvements occur, though this varies to some extent by region. Neither the GDP growth rate nor the energy intensity improvement rate impacts the development of diversity under de-carbonization scenarios but the fossil availability and supply-side technological limitations do.

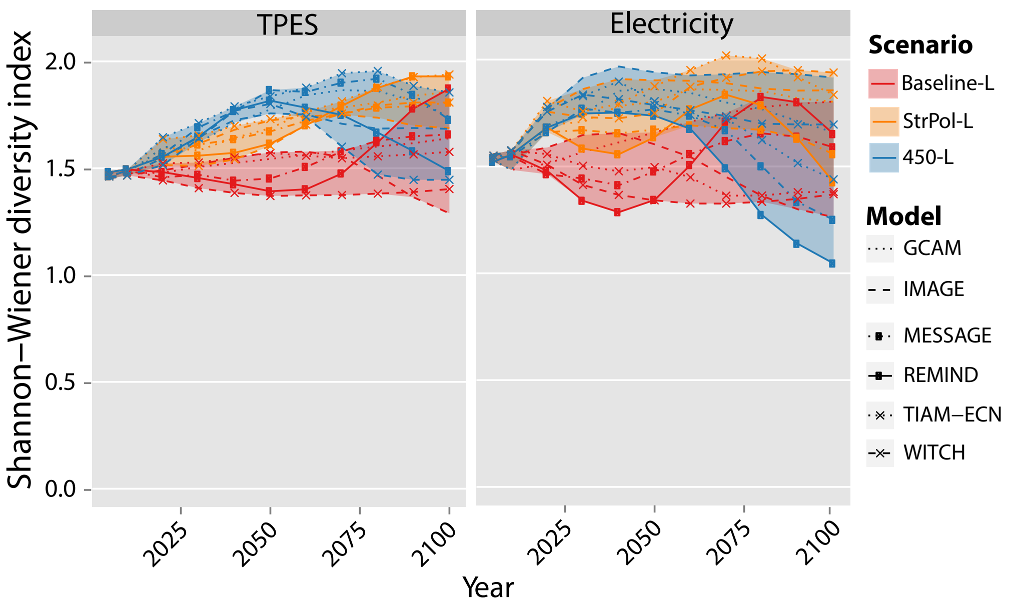
### 4.3.1 Global diversity of energy options

*Overarching diversity trends*

Figure 4.21 shows the global diversity of total primary energy sources (TPES). The diversity of TPES in the Baseline-L scenario varies between 1.4 and 1.6 staying close to the current level of about 1.5. In contrast, under climate policies the diversity of PES rises through 2050 to between 1.7 and 1.8 in the case of the 450-L scenario or 1.6–1.8 in the case of StrPol-L. This occurs because low-carbon technologies are rapidly introduced in energy systems and start balancing traditional technologies.

This pattern is even more pronounced in the diversity of electricity systems (Figure 4.21). While there is no global electricity system, the analysis of global electricity diversity shows the global context for the regional developments which are explored more in the next section on regional diversity. In the Baseline-L scenario, electricity diversity either slightly rises from its current 1.5 to 1.6 to a maximum of 1.6 or falls to 1.3. In contrast, under

**Figure 4.21:** Diversity of TPES and electricity in six models under three scenarios



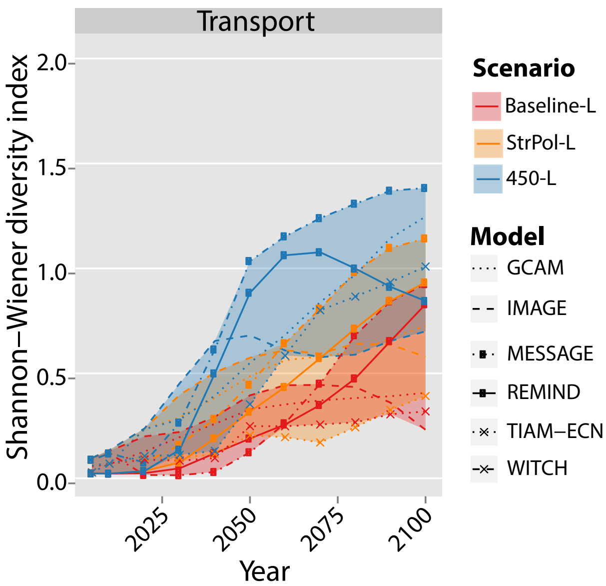

Notes: Diversity is calculated using Shannon Wiener diversity index as described on page 83. The TPES and electricity diversity is between the following sources: coal, oil, gas, bioenergy, nuclear energy, hydropower, wind, solar, and geothermal.

the 450-L scenario, electricity diversity rises to between 1.7 and 2.0 by 2050 and in the 450-L scenario to between 1.6 and 1.9.

Figure 4.22 shows the diversity of energy used in the transportation sector. At present, the low diversity of transport energy use (which almost entirely comes from oil) together with highly concentrated global oil production (which results in high energy imports in most countries) constitute one of the most significant energy security concerns (Cherp et al. 2012). Under climate policies, the diversity of energy sources in transport rises but models differ in their depiction of when and how this would happen.

In MESSAGE and ReMIND, diversity stays low in the Baseline-L through 2050 as the sector continues to be dominated by fossil fuels (oil in MESSAGE and oil plus liquefied coal in ReMIND). This domination of fossil fuels is fed by their continued economic competitiveness: in general, fossil fuels remain less expensive than alternative fuels in the absence of a carbon price. In contrast, the Baseline-L in IMAGE and GCAM has rising diversity from the penetration of biofuels in IMAGE and biofuels plus electrification in

**Figure 4.22:** Diversity of energy sources in transport in six models under three scenarios




Notes: Diversity is calculated using Shannon Wiener diversity index as described on page 83. The transport diversity represents diversity between: fossil energy, bioenergy, nuclear power, non-biomass renewables, and other because of how the models represent final energy use in the transport sector. The transport diversity excludes WITCH.

GCAM. These models depict a more competitive biofuels industry. Under climate policies, MESSAGE and ReMIND depict the largest diversity gains in the transportation sector with penetration of electricity and biofuels by 2050. While IMAGE and GCAM also depict penetration of electricity and biofuels into the transportation sector by 2050, the difference between the climate policy scenarios and Baseline-L scenario is less pronounced.

In contrast to IMAGE, GCAM, MESSAGE and ReMIND, TIAM-ECN models almost no change in the diversity of transport under any scenario before 2050. Most of the GHG efforts in TIAM-ECN during the first half of the century are related to efficiency increases rather than to changes in the energy mix. In the second half of the century energy diversity of the transport sector in TIAM-ECN rises reflecting a transformation to hydrogen-based systems; this is driven by long-term optimisitc cost assumptions of large-scale fuel cell production versus large-scale battery production.

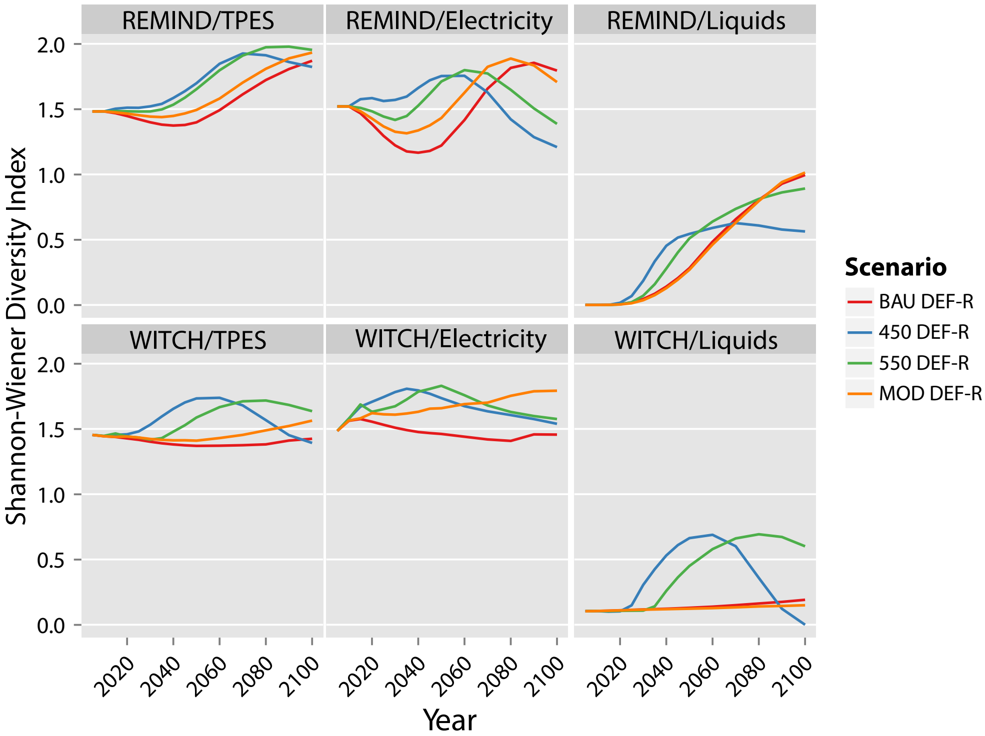
*Long-term global diversity trends*

In the second half of the century, the uncertainty of these diversity figures increases since the uncertainty of technologies rises (see the Limitations discussed in section 3.5). Nevertheless, there are a few trends which should be noted. In mid-century, aspects of the old and the new system coexist so in many cases the diversity dips slightly or significantly in the latter half of the century. In electricity, ReMIND (in the RoSE and LIMITS scenarios), shows the biggest dip as the electricity system comes to be dominated by solar electricity (both photovoltaic and concentrated solar power). Diversity of liquid fuels (primarily used in transportation) most significantly dips in WITCH in the RoSE scenarios where they are dominated by biofuels.

*Diversity and stringency of climate targets*

The nature of climate policies does impact the way diversity develops. For the TPES and electricity, as shown in Figure 4.21, the StrPol-L scenario typically has a diversity trajectory between the Baseline-L and the 450-L case over the first half of the century. However, by the end of the century (when admittedly the uncertainty is higher) the diversity of the 450-L scenario typically dips below that of the StrPol-L case. Similarly, the diversity of TPES and electricity in the MOD-R scenario is between the diversity

**Figure 4.23:** Sensitivity of diversity to the nature of climate policies

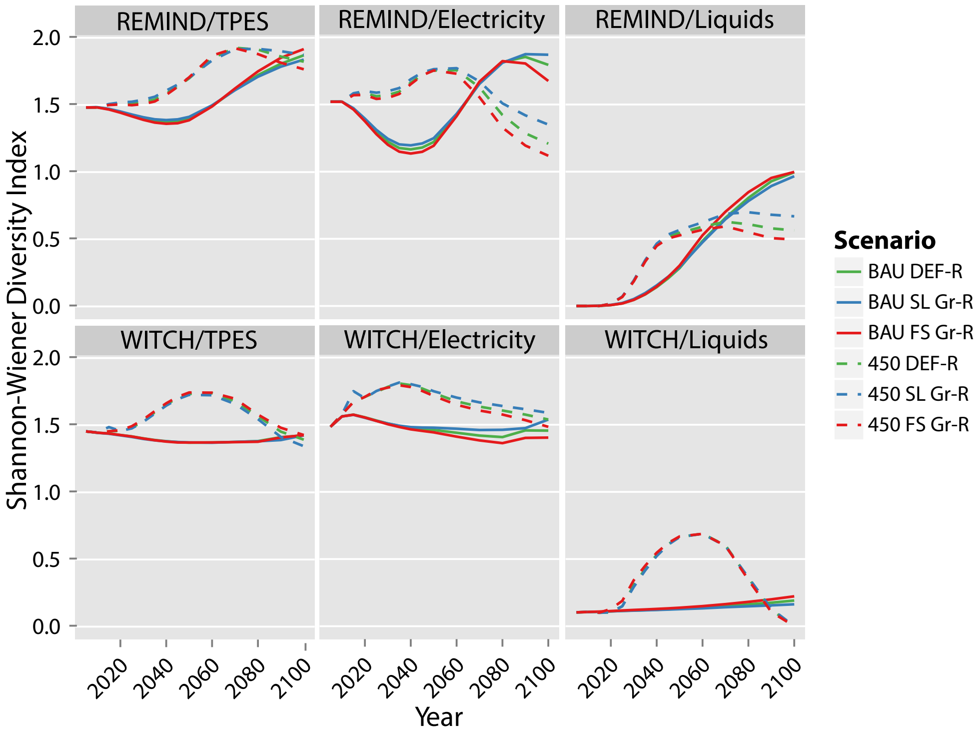



of the Baseline-R and 450-R scenarios (Figure 4.23). This is because in the 450-R case, a few low-carbon sources come to dominate the systems. The diversity trajectory of the 550-R scenarios, follows that of the 450-R scenarios with a one to three decade lag-time.

### *Diversity and GDP growth assumptions*

Figure 4.24 shows that the diversity of energy options is not significantly affected by GDP growth assumptions in either the Baseline-R or the climate policy (RoSE) scenarios. One exception is the diversity of electricity and liquids under strict climate policies in ReMIND in the 2nd half of the century, when faster economic growth leads to a greater decline in diversity. This occurs because faster growth forces more rapid penetration of solar energy (in electricity) and biofuels (in liquids), further accelerating the pattern already induced by climate policies.

**Figure 4.24:** Sensitivity of diversity to economic growth

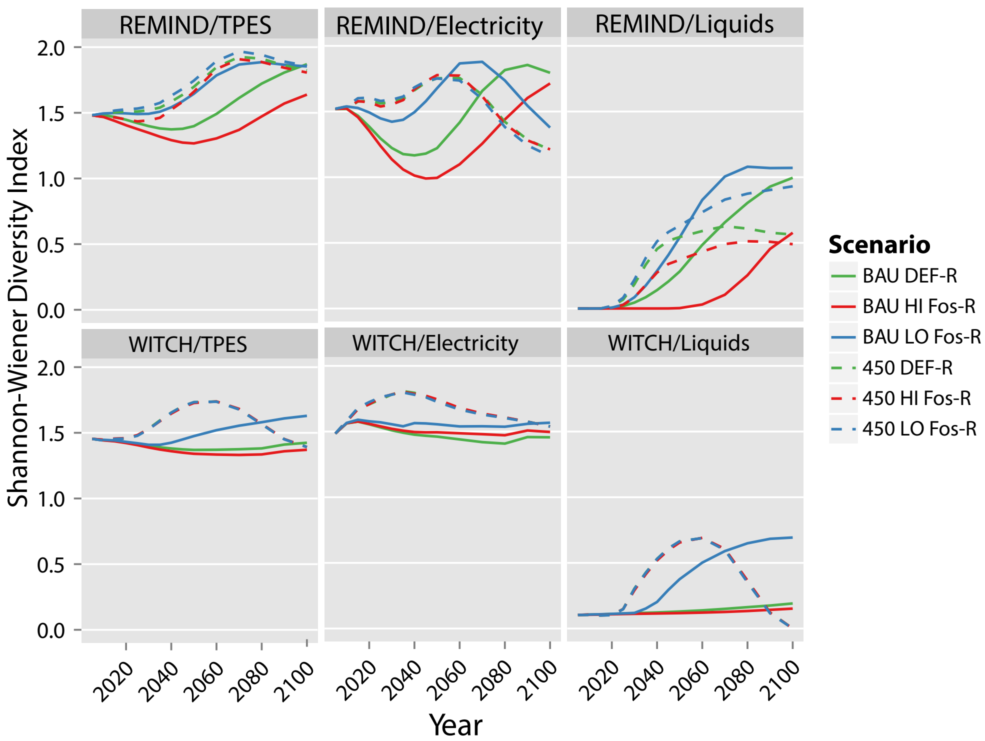



*Diversity and fossil fuel availability*

Resource availability affects the overall TPES diversity as well as the diversity of fuels used for electricity generation and liquid fuels in the Baseline-R scenarios. In the Baseline-R scenarios, low resource availability generally results in *higher* diversity. Moreover, in ReMIND high resource availability generally means lower diversity (Figure 4.25). This occurs because alternative energy options are introduced to replace scarce fossil fuels. The only exception to this general pattern is electricity in ReMIND at the end of the 21st century, which is lower in the low-availability scenario than in both medium- and high-availability scenarios because solar energy comes to dominate electricity generation much like in the climate policy scenarios.

In climate policy scenarios, alternative fuels are introduced due to low-carbon constraints rather than resource scarcity and thus fossil fuel availability does not generally affect diversity. An exception are liquids in ReMIND which are affected by fossil fuel availability even in the case of climate policies (similarly to the Baseline scenarios, they become more diverse in

**Figure 4.25:** Sensitivity of diversity to fossil fuel availability

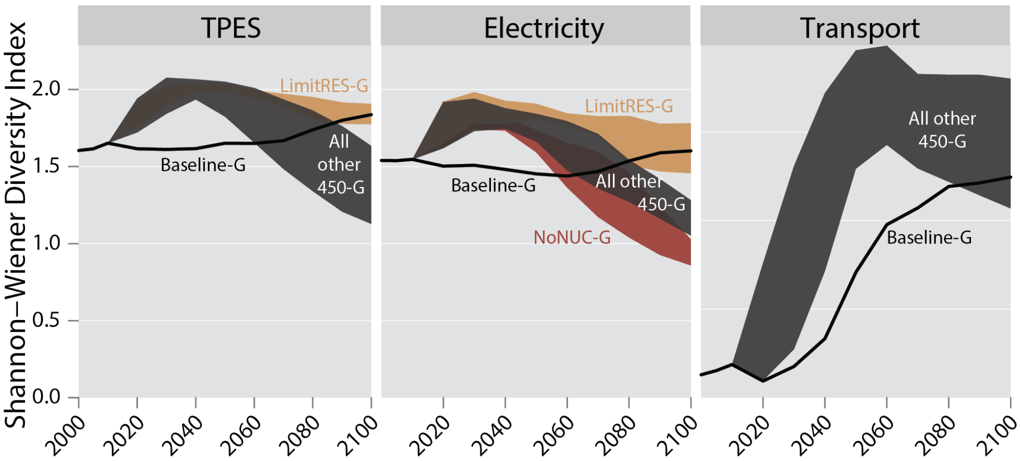



case of lower availability). As a result, by the end of the century low fossil fuel Baseline scenarios feature diversity that is generally higher than or equal to diversity under the climate policy scenarios.

*Diversity and technological choices*

Demand-side technological limitations do not affect the diversity but supply-side constraints do. These effects only appear in the second half of the century. Figure 4.26 illustrates the diversity of energy sources in the total primary energy supply (TPES), electricity generation, and the transport sector. In scenarios with limited penetration of renewables, the diversity of TPES and electricity generation is comparable to the baseline development and significantly higher than today's diversity by the end of the century. Under scenarios with unlimited renewables, however, a few renewable energy sources come to dominate the energy system by the end of the century which leads to the diversity dropping between the Baseline-G and the current level. In contrast, in scenarios with limitations on nuclear energy the

**Figure 4.26:** Sensitivity of diversity to technological constraints




diversity of electricity production declines to significantly lower levels than both the Baseline-G and the current value. The diversity of the transport sector is not impacted by these technological limitations.

## 4.3.2 Diversity of energy options in major economies

The diversity at the regional level typically follows the global patterns, however there are a few exceptions. For TPES and electricity diversity, the global rise through mid-century in diversity is more pronounced in China and to some extent in India because these energy systems start from a lower diversity level. In the Baseline-L, these energy systems continue (in the case of China) or begin (in the case of India) to be dominated by coal. Thus, under climate policies these regions experience rapid and pronounced increases in diversity. The other consistent departure from the global trends is the rise in TPES and electricity diversity under the StrPol-L scenario which closely follows the rise under the 450-L scenario because the E.U.'s Copenhagen pledges are very ambitious (more ambitious then the StrPol-L targets in the other three regions). The following section discusses in detail the regional diversity trends and where they depart from the global ones. All of the results in this section are from the LIMITS scenario exercise.

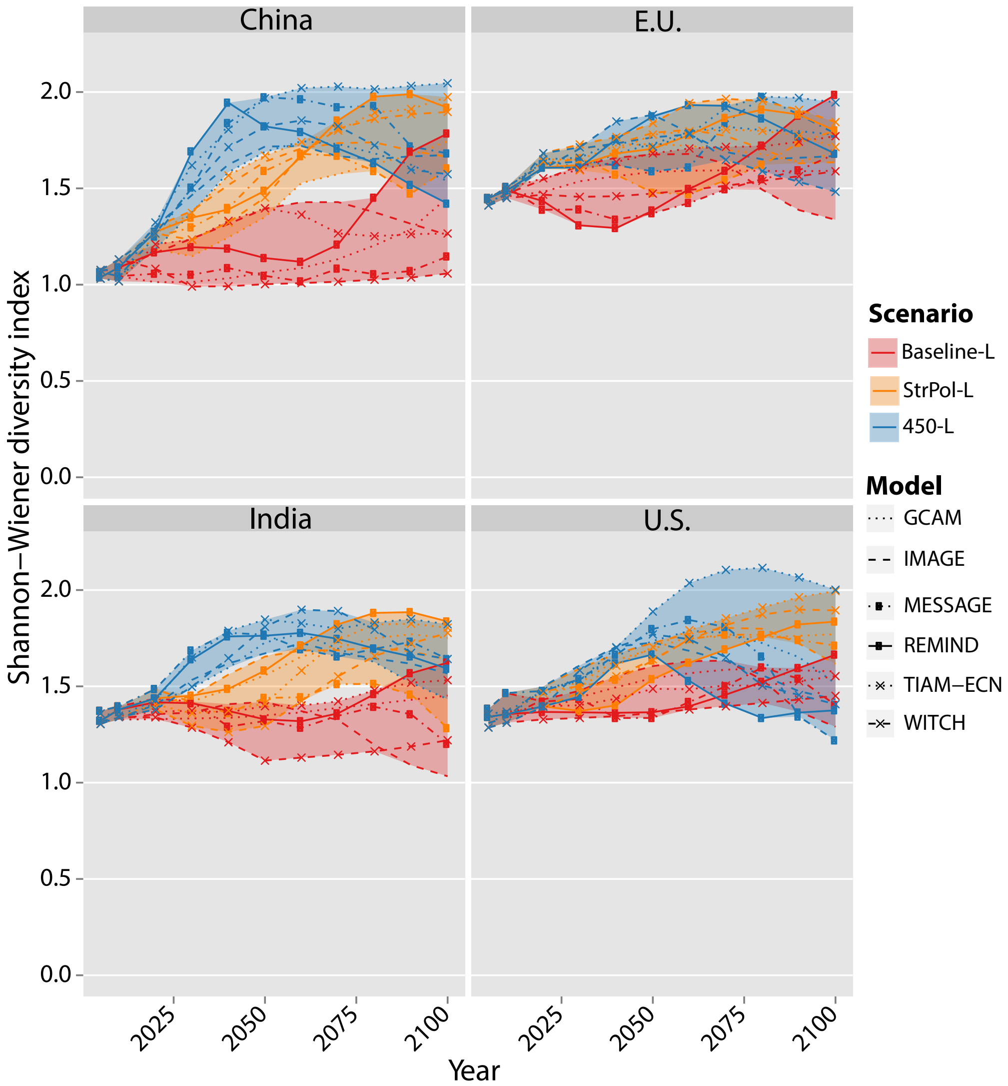
*TPES diversity*

TPES diversity rises through mid-century in all models across all regions under both StrPol-L and the 450-L scenario (Figure 4.27). The rise is most pronounced in China which starts with a relatively low-level of diversity (1.1 vs 1.3 in the U.S. and 1.4 in Europe) because coal accounts for over half of the TPES. Under the Baseline-L, China's energy system continues to be dominated by coal until 2050; however, the 450-L policy catalyzes rapid diversification of China's energy system so that it quickly catches up with that of the U.S. and E.U. The StrPol-L scenario also leads to an increase in diversity to a level higher than in the baseline but lower than in the 450-L scenario. By the end of the century, China's TPES diversity falls in the 450-L scenario slightly under the diversity of the StrPol-L scenario in most models, however, it never reaches the currently low diversity level.

Similar to China, India's TPES diversity does not rise in the Baseline-L. In fact, India's TPES diversity falls under some models as traditional biomass is phased out and replaced by coal, thus indicating that in a business as usual scenario the country would follow a traditional development path. In contrast, climate policies prevent coal from dominating the energy system. India experiences an increase in diversity under climate policies as compared to the baseline. By 2100, TPES diversity in India under the 450-L scenario falls slightly but never below 1.4.

Climate policies also result in an increase in diversity in the U.S. and the E.U., but this rise is less pronounced than in China and India because the initial diversity of the European and American energy systems is higher. In the E.U., the diversity rise through mid-century under the 450-L scenario is comparable to the rise under StrPol-L since the E.U.'s Copenhagen pledges are quite ambitious and come closer to the 450-L case. For the U.S., the StrPol-L case is between the Baseline-L and the 450-L scenario. In the latter half of the century, the E.U. experiences the same drop in TPES diversity as other regions under the 450-L scenario as China and India. In the U.S., the late century decrease in TPES diversity is more pronounced in some models with diversity falling to 1.2 in MESSAGE as about 90% of the energy system is met by solar and bioenergy combined (split about equally between the two).

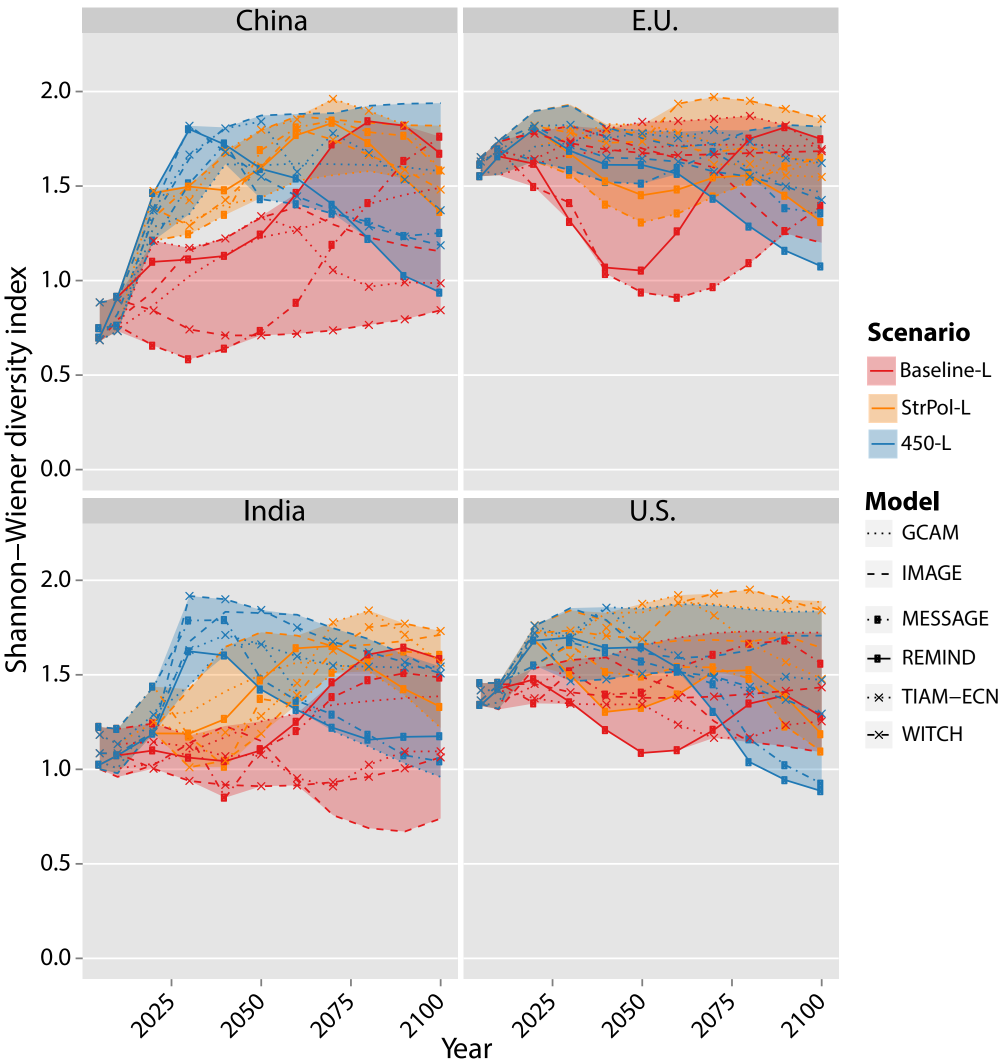
**Figure 4.27:** TPES diversity in the major economies




## *Electricity diversity*

The development in the diversity of electricity closely follows the trends in the diversity of TPES (Figure 4.28). China starts with the lowest diversity of electricity with over 75% of its generation coming from coal in 2010 (which corresponds to a diversity of <1). China's electricity diversity in the baseline stays well below current diversity levels for the E.U., India and the U.S. Under climate policies China's electricity diversity rapidly rises; this rise happens earlier under the 450-L scenario as the penetration of low-carbon sources is faster than the StrPol-L case. However in the 450-L

**Figure 4.28:** Electricity diversity in the major economies






scenario, the diversity falls by 2100 to <1 in ReMIND (from solar domination) and WITCH (from nuclear domination). India also experiences a rise in electricity diversity under climate policies, but not quite as pronounced as for China since India's current electricity generation diversity is higher than China's. In India diversity in the Baseline declines because of penetration of coal (displacing traditional biomass) under WITCH and IMAGE.

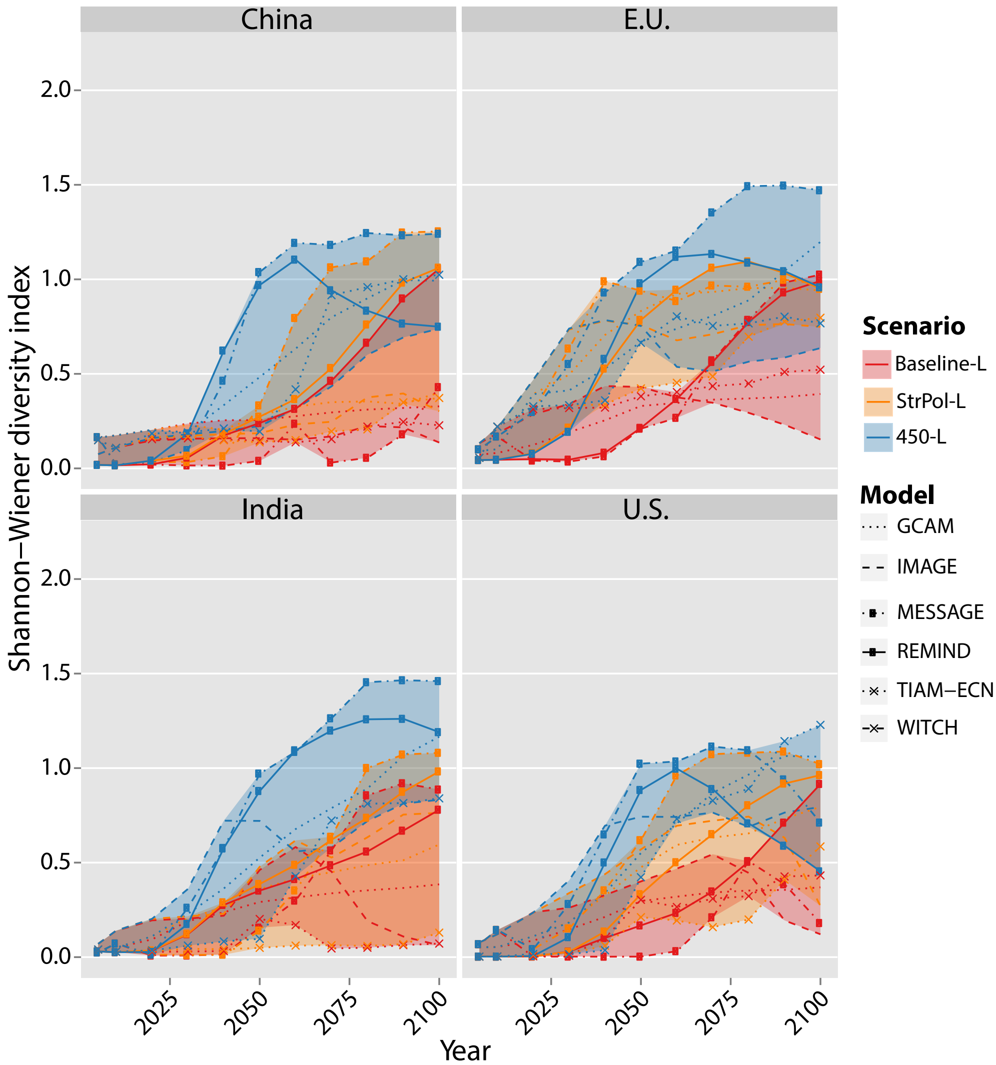
In both the E.U. and U.S., climate policies result in more modest increases in diversity of electricity generation sources since the electricity systems of these countries start out with higher diversity. StrPol-L and 450-L have a similar impact on diversity. In both regions diversity of electricity generation declines in the Baseline-L in some models: in the E.U. in ReMIND because of the domination of imported natural gas and in the U.S. because of growing gas (ReMIND) or coal (TIAM-ECN) predominance. Towards the end of the century MESSAGE and ReMIND also depict declining electricity diversity (to <1) as solar comes to dominate the U.S. electricity system.

### *Transport diversity*

For the most part, the regional transport diversity repeats the trends which I describe at the global level (Figure 4.22). This means that diversity rises much faster in the majority of models in the 450-L scenario than in the Baseline-L. The exception is TIAM-ECN where climate policies affect transport systems particularly after 2050.

Regional differences in transport diversity are visible primarily in StrPol-L scenarios. In India and China, there is virtually no effect of these policies on the transport diversity as compared to the Baseline-L because the policy targets are achieved by transforming the currently carbon intensive power generation and industrial sector rather then the transport sector. In the E.U., the transport diversity rise under the 450-L scenario is comparable to the rise under StrPol-L since the E.U.'s Copenhagen pledges are very ambitious. For the U.S., the increase is between that observed under the Baseline-L and that under the 450-L.

**Figure 4.29:** Transport diversity in the major economies



# Chapter 5

# Discussion

This dissertation asks the question: "How would climate change policies affect global energy security?" I structure the study of future energy security concerns around historically persistent themes of energy security discourses. Thus, I look at the development of energy trade patterns, resource extraction and diversity of future energy systems with and without climate policies as well as under different technological limitations, economic and resource assumptions, and policy drivers. This chapter answers the research question posed by synthesizing the main findings first at the global level and then for the six regions.

## 5.1 Overall trends in historic energy security concerns

The simple answer to the overall research question is that under climate policy scenarios historic energy security concerns are alleviated, particularly compared to business as usual development which would exacerbate them (Table 5.1). Under the Baseline scenario, oil continues to play a crucial role in the global economy throughout the middle of the 21st century. By the end of the century, the cumulative oil extraction gets uncomfortably close to today's proven oil reserves and resources. Combined with the non-substitutability of oil in transport, this would almost certainly trigger anxiety over oil scarcity potentially resulting in price volatility and international tensions. Faced with oil depletion, coal and gas overtake oil as the most heavily traded fuel in all models except TIAM-ECN and by 2100, the total energy trade would be two and a half to four times more than it is today. At the same time, the diversity of gas exporters stays at or below the diversity of today's oil exporters which would mean gas may emerge not only as a regional energy security issue as today, but also as a vulnerable *global* fuel.

In contrast to the Baseline scenarios, where energy security concerns increase over time, scenarios with climate policies—both long-term stabilization at 450 ppm $CO_2$-eq and 550pm $CO_2$-eq as well as the moderate and stringent policy case—depict a world with lower energy trade, higher diversity and virtually no concerns over fossil resource scarcity. Trade and resource use reductions are most pronounced at the end of the 21st century while diversity improvements are most pronounced at mid-century. Scenarios with long-term stabilization targets show greater improvements than the moderate and stringent policy cases and the more stringent the long-term stabilization target, the greater the improvement is. This section highlights the 450-L scenario to illustrate the improvements in energy security compared to the Baseline-L. The 450-L scenario is represented by six different models and the presented findings are robust across all these different modeling frameworks and assumptions (Table 5.1).

The 450-L scenario shows substantial improvements in energy security. TPES trade is between 20% and three times lower in this scenario by 2050 and between two and seven times lower by 2100 than in the Baseline-L as regions shift away from fossil energy to domestically-produced renewables and nuclear energy (see Figure 4.1). The shift away from fossil fuels also means that a lower share of fossil resources would be depleted. For oil—the fuel facing the greatest scarcity—between a quarter and a half of proven reserves and resources are consumed, only one-half of the share as in the Baseline-L. This would reduce concerns about scarcity and could potentially dampen oil price volatility. At the same time, by 2050, oil trade either plateaus or declines under the 450-L scenario whereas in the Baseline-L scenario it keeps growing. The gas and coal trade is also lower in the 450-L scenario. The reduced consumption of fossil resources and lower trade is consistent with other studies (Kruyt et al. 2009; Criqui and Mima 2012) and the remaining fossil resources in the ground have been interpreted as a "buffer" against energy shocks (Turton and Barreto 2006). However, some authors argue

**Table 5.1:** Global energy security in the Baseline-L and 450-L scenarios

| | | 2050 | | 2100 | |
|---|---|---|---|---|---|
| Indicator | 2010[a] | Baseline-L | 450-L | Baseline-L | 450-L |
| **Sovereignty perspective** | | | | | |
| TPES trade (EJ) | 109 | 174–390 | 85–158 | 310–487 | 35–203 |
| Oil trade (EJ) | 82 | 75–131 | 27–77 | 21–143 | 0–51 |
| Gas trade (EJ) | 14 | 33–87 | 20–49 | 59–143 | 6–63 |
| Coal trade (EJ) | 10 | 13–210 | 1–17 | 82–270 | 1–79 |
| Bio-energy trade (EJ) | - | 0–10 | 0–30 | 0–44 | 1–80 |
| TPES trade intensity | 22% | 22%–38% | 17%–27% | 29%–38% | 7%–27% |
| Oil exporter diversity (unit-less) | 1.1 | 0.6–1.4 | 0.3–1.2 | 0.7–1.7 | 0–1.3 |
| Gas exporter diversity (unit-less) | 1.0 | 0.7–1.2 | 0.2–1.2 | 0.7–1.0 | 0.2–1.2 |
| Coal exporter diversity (unit-less) | 0.6 | 1.0–1.4 | 0.6–1.4 | 0.9–1.4 | 0–1.3 |
| Bio-energy exporter diversity (unit-less) | - | 0.05–0.8 | 0.02–1.4 | 0.6–1.4 | 0–1.2 |
| **Robustness perspective** | | | | | |
| Cumulative oil extraction (ZJ) | 6.6 | 8–11 | 6–8 | 16–25 | 8–15 |
| Oil extraction as a proportion of R&R[b] | - | 22%–32% | 18%–23% | 47%–106% | 23%–61% |
| Cumulative gas extraction (ZJ) | 3.2 | 6–9 | 4–7 | 16–27 | 7–15 |
| Gas extraction as a proportion of R&R | - | 3%–5% | 2%–3% | 8%–37% | 3%–21% |
| Cumulative coal extraction (ZJ) | 6.7 | 8–10 | 3–6 | 26–35 | 3–12 |
| Coal extraction as a proportion of R&R | - | 2% | 1% | 6%–11% | 1%–4% |
| **Resilience perspective** | | | | | |
| TPES diversity (unit-less) | 1.5 | 1.4–1.6 | 1.8–1.9 | 1.3–1.9 | 1.4–1.9 |
| Electricity diversity (unit-less) | 1.6 | 1.3–1.7 | 1.7–1.9 | 1.3–1.8 | 1.0–1.9 |
| Transport diversity (unit-less)[c] | 0.1 | 0.1–0.4 | 0.4–1.0 | 0.2–0.9 | 0.7–1.4 |
| Energy intensity (MJ/$2005) | 7.6 | 4–5 | 2–5 | 1–3 | 0.9–2 |

Notes: The oil trade ranges include all five models (IMAGE, MESSAGE, ReMIND, TIAM-ECN, and WITCH). The trade ranges for TPES, natural gas, coal and bioenergy exclude WITCH since WITCH only tracks oil trade. MESSAGE only models biofuel trade while the other three model bioenergy trade at the primary level.

[a] For sovereignty and resilience indicators, 2010 values are calculated as the mean between the models. For the robustness indicators this refers to cumulative extraction through 2010 and is compiled from Rogner et al. 2012 and British Petroleum 2012.

[b] R&R refers to proven resources and reserves from Rogner et al. 2012. This refers to the proportion of R&R resource consumption in the scenarios between 2010 and 2100.

[c] Diversity of sources used in transportation between ″fossils″, ″bioenergy″, ″other renewable sources″ and ″nuclear energy″.

that the cost of non-exploited resources under climate scenarios is higher than the cost of adapting to a warmer climate (Nel and Cooper 2009).

While fossil trade would eventually decrease under climate scenarios, global energy security may get worse before it gets better. This is not because fossil trade is replaced with "new" fuels but because when fossil fuels are phased out their extraction is increasingly concentrated in a few regions with cheaper (conventional) resources. In regions with unconventional or at least more expensive fossil resources, investments are directed away from developing such deposits towards renewable energy sources, nuclear energy and energy efficiency. Additionally, for the most part climate policies do not notably affect energy interregional trade in the near term (to 2030). This is because while climate policies foster the growth of non-traded energy sources (renewables, nuclear energy,[50] some forms of biomass) they also limit the use of domestic coal, so in the short term there is only a small impact on the import dependence between the Baseline-L and 450-L scenarios.

One "new" fuel, bioenergy, emerges as a big player under the 450 scenarios. Bioenergy trade under two of the models (IMAGE and ReMIND) almost reaches today's oil trade volumes by the end of the century. The models, however, do not agree as to what the bioenergy trade landscape would look like, which forms of bioenergy would be traded or which regions would be the major suppliers. In fact the two models where bioenergy trade does play a significant role show virtually opposite results in terms of who would be the main sellers and who the main buyers.

Perhaps the largest energy security benefit from climate policies is that they would almost certainly result in energy systems with dramatically increased resilience. The 450-L scenario leads to consistently lower energy intensity which translates into lower exposure to price shocks and volatility. The diversity gains of the 450-L scenario, particularly for TPES and electricity, are most pronounced by mid-century when the fossil and low-carbon systems coexist which is consistent with earlier studies of electricity diversity under low-carbon scenarios (Grubb, Butler, and Twomey 2006). The increase in electricity diversity peaks mid-century (Figure 4.21, Figure 4.23,

50. While "nuclear energy" is not traded, uranium resources and the enriched fuel are. The geographic concentration of the nuclear industry (both enriched fuel and nuclear power plant construction) is more of an energy security issue than uranium than uranium trade (Cherp et al. 2012).

Figure 4.24, Figure 4.25, Figure 4.26, Figure 4.28). In some models, over the long-term, solar comes to dominate the electricity system and the electricity diversity drops—both below the Baseline and the current level. In contrast, the diversity of the transportation system rises rapidly by mid-century in almost all models (Figure 4.22, Figure 4.26, Figure 4.29)[51] and continues to rise throughout the century. This is probably the most remarkable benefit as the low diversity of today's energy options for transport is at the core of today's energy security concerns.

## 5.2 Climate policies as a hedge against uncertainty

Climate policies are also a hedge against uncertainty of fossil resource availability and GDP growth. Changes in the fossil fuel availability and GDP growth rates invariably lead to large changes in energy trade under the Baseline-R scenarios but almost no change in the 450-R scenarios. Changing the resource availability assumptions increases the annual energy trade by up to 150 EJ for oil and coal and up to 200 EJ for gas (Figure 4.3). That means that under a scenario with high fossil availability (or low oil availability when trade is measured with respect to coal and gas) trade would be as much as three times higher as under a low availability scenario in any given year! Differences begin to emerge by 2020 for oil and gas and by 2040 for coal.

In contrast, under the 450-R scenarios, annual oil and coal trade volumes are virtually unaffected by fossil availability throughout the 21st century. Gas trade under the 450-R scenario only varies by some 60 EJ, or three times less than the effect in the Baseline-R between the low fossil case (which leads to relatively higher trade because the low fossil availability assumption disproportionately reduces resource assumptions in certain regions) and the high fossil case at mid-century. Towards the end of the century trade volumes converge in the 450-R scenarios.

GDP growth rates have a smaller effect in the Baseline, but they still impact the trade volumes. A higher growth rate (2.9% versus 1.9%) leads to higher energy demand, more resource extraction and higher trade. Coal trade

51. TIAM-ECN depicts the transport diversity gain in transport from hydrogen penetration which only happens in the latter half of the century.

varies by as much as 50 EJ between the high- and slow- growth cases and oil and gas by some 40 EJ (about 30% of the overall trade for each fuel). The 450-R scenarios feature almost no difference in fossil fuel trade under different GDP growth assumptions.

In sum, in a world without climate policies, fossil fuel availability concerns would be accompanied by higher energy trade in an energy security one-two punch. Furthermore, GDP growth rates would impact trade volumes which may lead to greater instability in energy exporting and importing regions as fossil fuel demand rises and falls with business cycles. In contrast, the phase out of fossil fuels in a 450-world would buffer the instability and uncertainty coming from variable fuel demand and fossil resource availability. This finding is new, but is consistent with earlier work which has found that climate policies offer a protection against oil price hikes (Maisonnave et al. 2012; Rozenberg et al. 2010).

## 5.3 Qualifications regarding global energy security

For the most part, as discussed in the previous two sections, climate scenarios alleviate historic energy security concerns which would intensify under business as usual development. At the same time, there are certain qualifications which emerge from the analysis:

- sensitivity of diversity results to fossil fuel scarcity in the Baseline-R scenarios;
- trade-offs between different risks linked to different technological choices in 450-G scenarios; and
- increasing divergence between regions under climate policy scenarios.

None of these qualifications negate the overall conclusion of this thesis that climate scenarios improve energy security but they are important to bear in mind in terms of preparing for strategic uncertainties.



### 5.3.1 Increased diversity in low resource availability baseline

The first sensitivity relates to how lower resource availability may trigger higher diversity of energy options in a business as usual, fossil-dominated world. Lower resource availability leads to higher diversity because alternative sources are introduced to replace scarce fossil fuels. As a result, by the end of the century low fossil fuel Baseline-R scenarios feature diversity of electricity and TPES (in ReMIND and WITCH) and liquids (in WITCH) that is higher than or equal to diversity under the climate policy scenarios. Thus, ironically, facing scarcity issues may drive the business-as-usual energy system towards more resilience. In such a world, long-term energy security may be higher but it may pass through periods where energy security gets worse before it gets better.

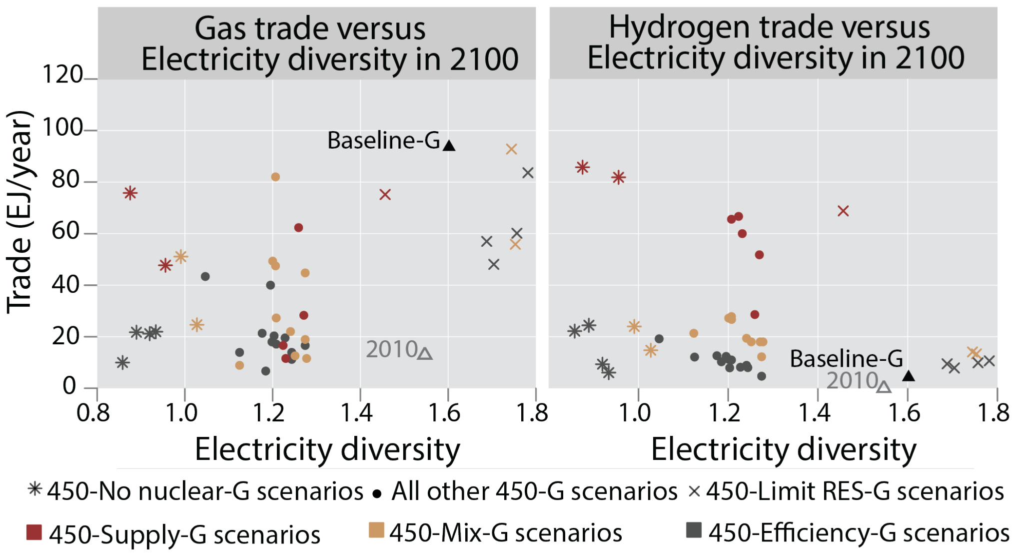
### 5.3.2 Technological choices and energy security trade-offs under decarbonization

Under climate scenarios, there is a trade-off between energy trade and diversity of energy options used for electricity. Over the long-term, under certain assumptions, policy-makers may need to choose between the risks associated on the one hand: high energy trade in and high concentration of production of gas and hydrogen; and on the other hand low diversity of electricity generation options. These potential long-term energy security concerns are triggered by different combinations of supply and demand choices (Figure 5.1):

- Higher gas and/or hydrogen trade is observed in **limited renewables** or **no-nuclear** GEA Supply scenarios;
- Lower diversity of electricity and TPES production is observed in scenarios with **unlimited renewables**, particularly combined with advanced transport and limitations on nuclear energy.

Thus limitations on renewables lead to higher energy trade, particularly in Supply and Mix scenarios whereas unlimited renewables are associated with lower diversity of energy options. Figure 5.1 shows that only a limited number of scenarios are located in "dangerous" corners where either trade is too high or diversity is too low. The relatively secure scenarios are Efficiency scenarios with limitations on renewables: in these scenarios both high diversity and low energy trade can be reached simultaneously. In other words pursuing the most energy efficient pathways may spare policy-makers from facing these difficult energy security trade-offs.

**Figure 5.1:** Technological trade-offs under 450-G scenarios



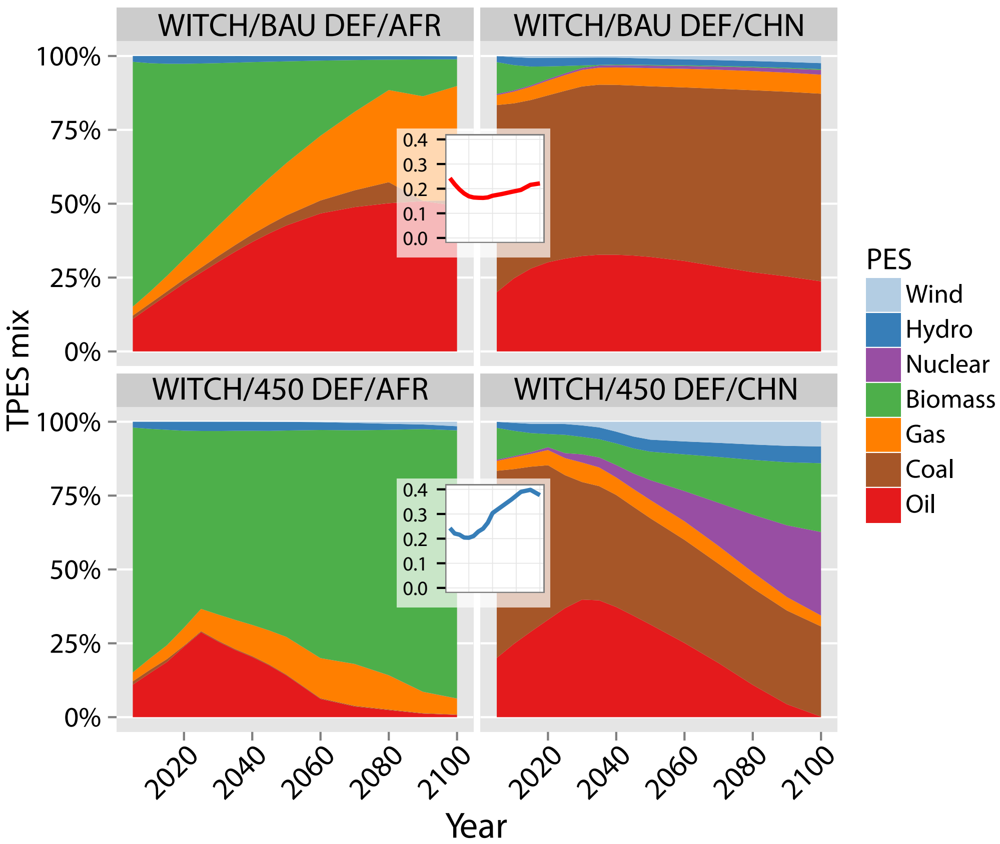

The lower right corner represents the most secure situations with low trade and high diversity, whereas the upper left corner shows a danger zone with high trade and low diversity.

### 5.3.3 Increasing regional divergence under climate policies

A profound trade-off is between increased regional-convergence in a business as usual development and regional divergence of energy systems under climate policies. Until now, I have talked of decreasing energy trade as universally beneficial to energy security and in one sense it is. Historical energy security concerns have been associated with energy imports: cut energy trade and regional imports fall. However, cut energy trade and another thing falls as well: connection between countries. Thus the business as usual world may be described as “We’re all in this together” while the climate stabilization leads to “Going it alone”. There is a theory, originally proposed by Kant and more recently elaborated by Weede (1996), that trade interdependence prevents war was. Increased regional divergence does not necessarily mean an increase in war but it may lead to a decrease in energy cooperation.

The regional diversity (and the diversity of underlying energy mixes) increases in climate stabilization scenarios whereas in business as usual development they either stay the same or even converge. This can be illustrated most clearly by looking at the energy system mixes of different regions.

**Figure 5.2:** Energy mix in China and Africa and (inset) the standard deviation of energy diversity in all the world regions under the Baseline-R and 450-R scenarios




Notes: The graphs show the share of different sources in energy supply in China and Africa modeled in WITCH under the Baseline-R (upper chart) and the 450-R (lower chart) scenarios. The diversity of TPES in China significantly increases under the 450-R scenario, because in the Baseline-R it is largely dominated by coal. The diversity of TPES in Africa decreases under the 450-R scenario as the energy system becomes dominated by biomass. The insets show the standard deviation of regional energy diversity for all world regions. This deviation increases under the 450-R scenario indicating that the difference between regional energy systems increases under climate policies.

Take for example, the energy mix in Africa (AFR) versus China (CHN) in a Baseline-R versus the 450-R scenario (Figure 5.2). In the Baseline-R scenario, the energy mix of these two different regions becomes more similar.

However, in the 450 scenario, the two regions do not converge at all: the difference between their energy systems increases. This trend is seen across all regions in the RoSE scenario exercise (Figure 5.2 inset). Some regions (e.g. Middle East, Europe, FSU and North America in WITCH) follow the global trends, whereas in some (Latin America and Africa in ReMIND and WITCH) the diversity under climate policies is consistently lower than under the Baseline and in some regions it is consistently higher (Europe in ReMIND, India in WITCH, China in both ReMIND and WITCH)).

This phenomenon can be explained by the fact that in the Baseline-R scenario the energy mix is dominated by tradable fossil fuels and thus tends to be similar across different regions which are all part of the global energy market. Under climate policies, fossil fuels are phased out, there is less global energy trade and each region gravitates to its own unique energy mix based on its resource endowments as well as pathways of economic and demographic development. This "Go it alone" path would endanger the very political balancing that in the past has led to solidarity and cooperation between countries facing similar energy security issues. For example, the creation of the IEA could have never been possible without the importance of oil security to all OECD countries. Thus, while climate policies do lead to a reduction of historic energy security concerns, they may lead to a divergence between countries and reduce the incentives for international cooperation in ensuring energy security.

## 5.4 Regional energy security under climate policies

### 5.4.1 Major economies

At the level of major economies, the global trends described in the previous section would mean generally smaller energy imports and higher diversity of energy options. Some of the fossil fuel exports possible under certain modeling assumptions in the Baseline scenario would be foregone in the climate policy scenarios. At the same time, there may be a possibility for bioenergy exports (although on a smaller scale). In addition to these cross-cutting trends, climate policies has energy security implications specific to the major economies covered in this thesis. The following four sections summarize the main findings in relation to each major economy.

### *China*

China is a rapidly growing economy rich in coal and poor in oil and gas resources. Under the Baseline-L scenario, it would experience increasing reliance on domestic coal. At the same time it would practically wipe out its modest reserves of oil and gas and would become fully import dependent on these fuels (Table 5.2). There is some divergence between models as to how China's overall import dependency would develop. In IMAGE, ReMIND and WITCH it rises from 11% to some 60% by 2050. However, TIAM-ECN, which has less flexible trade, depicts import dependence between 10% and 20% throughout the century. On the other end of the spectrum is MESSAGE which depicts China as a major coal exporter throughout the century under the Baseline exporting in total some 1700 EJ (Figure 5.3). While the volume is large, the value of these exports amounts to only ∼6 billion dollars over the 21st century which is only about 0.2% of the country's GDP.

China's energy system has very low resilience today with one of the lowest electricity diversity levels (for a large country) and highest energy intensity levels in the world. With a high level of energy used for every dollar of GDP produced, the country is extremely vulnerable to energy shocks (from either price or physical availability). Over 75% of China's electricity comes from coal giving the country a diversity index of 0.8 compared to 1.7 and 1.4 for the E.U. and U.S. respectively. Under the Baseline-L, energy intensity would be cut by between a third and a half but electricity generation options would continue to stay below the diversity of developed economies through 2050. The diversity of transportation would follow the global trend meaning it would stay low through 2050 in the Baseline-L.

Under the 450-L scenario, China would be able to preserve a buffer of oil and gas reserves and also import less of these fossil fuels. However, China would forego the opportunity to export large amounts of coal and synthetic fuels in the 2nd half of the century. It is possible that these lost revenues could be in part substituted by the possibility to export bioenergy: in ReMIND, which depicts a peak and subsequent decrease in population and a large availability of cropland, the country exports some 500–600 EJ of bioenergy over the century (Figure 5.3). However, in IMAGE with more restrictive bioenergy limits, the country imports approximately the same amount of bioenergy. The 450-L scenario leads to much higher resilience

**Table 5.2:** China's energy security in the Baseline-L and 450-L scenarios

| Indicator | 2010[a] | 2050 Baseline-L | 2050 450-L | 2100 Baseline-L | 2100 450-L |
|---|---|---|---|---|---|
| **Sovereignty perspective** | | | | | |
| TPES net-imports (EJ/yr) | 20 | 1–145 | 12–57 | -88–147 | -17–30 |
| Oil net-imports (EJ/yr)[b] | 12 | 8–47 | 2–23 | -8–34 | 0–4 |
| Gas net-imports (EJ/yr) | 1 | 2–31 | 1–19 | 0–14 | -2–24 |
| Coal net-imports (EJ/yr) | 5 | -8–95 | -3–10 | -52–111 | 0–13 |
| Bio-energy net-imports (EJ/yr)[c] | 0 | 0–3 | 0–5 | -3–6 | -20–5 |
| Net import dependence | 11% | 0%–60% | 11%–47% | -40%–48% | -15%–19% |
| **Robustness perspective** | | | | | |
| Proportion of oil R&R extracted[d] | - | 17%–170% | 16%–86% | 22%–560% | 21%–160% |
| Proportion of gas R&R extracted[d] | - | 6%–14% | 6%–16% | 17%–50% | 11%–55% |
| Proportion of coal R&R extracted[d] | - | 2%–3% | 1%–2% | 4%–10% | 1%–2% |
| **Resilience perspective** | | | | | |
| TPES diversity (unit-less) | 1.1 | 1.0–1.4 | 1.7–2.0 | 1.1–1.8 | 1.4–2.0 |
| Electricity diversity (unit-less) | 0.8 | 0.7–1.3 | 1.4–1.9 | 0.8–1.8 | 0.9–1.9 |
| Transport diversity (unit-less)[e] | 0.1 | 0.04–0.3 | 0.2–1.0 | 0.1–1.1 | 0.7–1.3 |
| Energy intensity (MJ/$2005) | 12 | 4–6 | 2–5 | 1–4 | 0.7–3 |

Notes: Energy trade ranges include five models (IMAGE, MESSAGE, ReMIND, TIAM-ECN, and WITCH). Diversity, intensity and resource extraction ranges include GCAM in addition to the other five.

[a] For import dependence data, 2010 values are calculated from IEA data. Energy intensity for 2010 is from US EIA Energy Information Administration 2013. For diversity, these values are the mean between the models. For the robustness indicators this refers to cumulative extraction through 2010 from Rogner et al. 2012 and British Petroleum 2012.

[b] For models which include crude oil and oil products this represents the sum of the two.

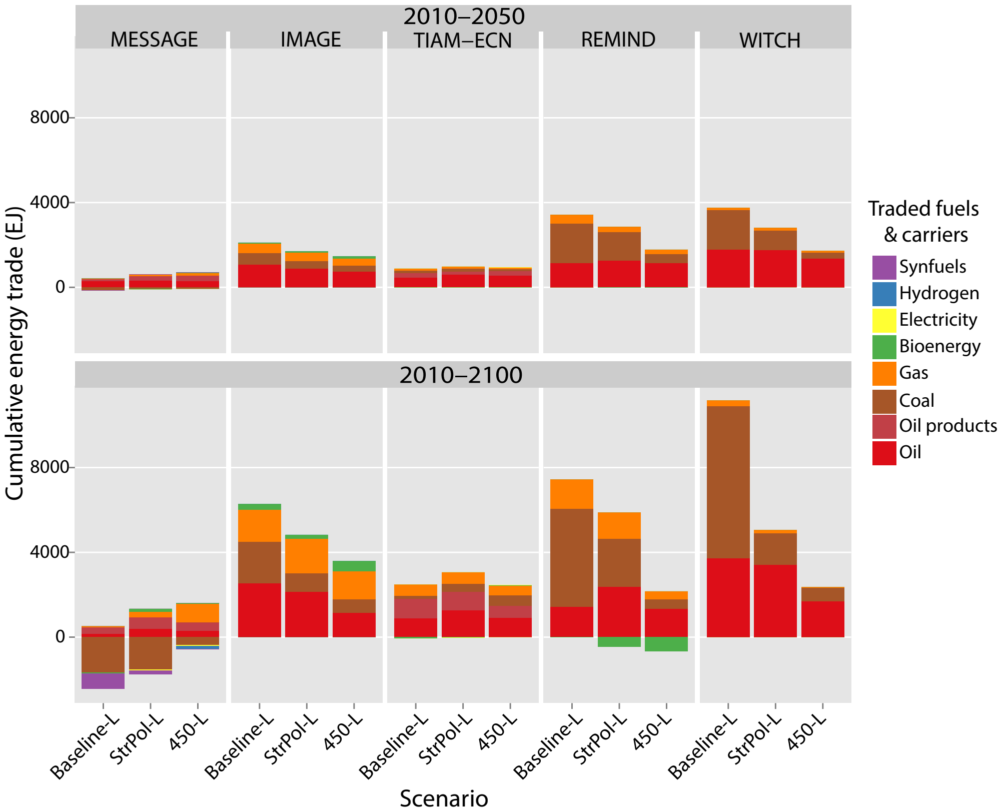
[c] For models which include primary biomass and secondary biofuel trade, this value represents the sum of the two.

[d] R&R refers to proven resources and reserves from Rogner et al. 2012. This refers to the proportion of R&R resource consumption in the scenarios between 2010 and 2100.

[e] Diversity of sources used in transportation between "fossils", "bioenergy", "other renewable sources" and "nuclear energy".

levels by 2050 than under the Baseline-L. Energy intensity is between 50% and 20% lower in 2050 than under the Baseline-L scenario. The country's energy system would also become significantly more diverse, catching up with the diversity levels of the E.U. and the U.S. between 2030 and 2050 which would be particularly beneficial in the electricity and transport sectors (Figure 4.28). China's energy security gains under the StrPol-L are

**Figure 5.3:** Cumulative energy imports to (positive) and exports from (negative) China




much less pronounced. Energy imports and resource depletion would be comparable to the Baseline-L and the energy intensity and diversity gains are in between the 450-L and Basline-L.

In sum, today China is a country with low import dependence, high domestic coal resources but low oil and gas resources, very high energy intensity and very low electricity diversity. Under the Baseline-L the country would most likely see growing import dependence and continued low diversity of energy options. Nevertheless, it would benefit from a dramatic drop in energy intensity and possibly some export revenues from coal. Under the 450-L scenario, the country would experience a rapid growth in diversity and an even more dramatic drop in energy intensity. At the same time, the country would forgo the opportunity to export its vast coal resources. The StrPol-L scenario depicts some energy security gains compared to the Baseline-L but they are much less pronounced than the 450-L scenario.

### *India*

India is similar to China in many respects, but it has even less domestic fossil resources and higher import dependence today (Table 5.3). India has tremendous demand pressure from its rapidly growing economy and large population without access to modern forms of energy.

**Table 5.3:** India's energy security in the Baseline-L and 450-L scenarios

| | | 2050 | | 2100 | |
|---|---|---|---|---|---|
| **Indicator** | **2010[a]** | **Baseline-L** | **450-L** | **Baseline-L** | **450-L** |
| **Sovereignty perspective** | | | | | |
| TPES net-imports (EJ/yr) | 8 | 23–86 | 22–42 | 70–233 | -3–66 |
| Oil net-imports (EJ/yr)[b] | 5 | 16–47 | 11–20 | 10–24 | 0–5 |
| Gas net-imports (EJ/yr) | 0.5 | 5–23 | 4–11 | 16–33 | 2–31 |
| Coal net-imports (EJ/yr) | 1 | 0–34 | 0–8 | 28–168 | -4–10 |
| Bio-energy net-imports (EJ/yr)[c] | 0 | 0–3 | -1–5 | 0–15 | -7–32 |
| Net import dependence | 26% | 25%–80% | 30%–50% | 33%–81% | -4%–41% |
| **Robustness perspective** | | | | | |
| Proportion of oil R&R extracted[d] | - | 57%–430% | 55%–390% | 66%–2300% | 62%–800% |
| Proportion of gas R&R extracted[d] | - | 2%–6% | 1%–5% | 3%–18% | 2%–13% |
| Proportion of coal R&R extracted[d] | - | 6%–23% | 4%–12% | 17%–94% | 6%–30% |
| **Resilience perspective** | | | | | |
| TPES diversity (unit-less) | 1.4 | 1.1–1.4 | 1.7–1.8 | 1.0–1.6 | 1.4–1.8 |
| Electricity diversity (unit-less) | 1.1 | 0.9–1.2 | 1.4–1.8 | 0.7–1.6 | 1.0–1.5 |
| Transport diversity (unit-less)[e] | 0.1 | 0.2–0.5 | 0.1–1.0 | 0.1–0.9 | 0.8–1.5 |
| Energy intensity (MJ/$2005) | 6 | 5–7 | 2–6 | 2–3 | 1–2 |

Energy trade ranges include five models (IMAGE, MESSAGE, ReMIND, TIAM-ECN, and WITCH). Diversity, intensity and resource extraction ranges include GCAM in addition to the other five.

[a] For import dependence data, 2010 values are calculated from IEA data. Energy intensity for 2010 is from US EIA Energy Information Administration 2013. For diversity, these values are the mean between the models. For the robustness indicators this refers to cumulative extraction through 2010 from Rogner et al. 2012 and British Petroleum 2012.

[b] For models which include crude oil and oil products this represents the sum of the two.

[c] For models which include primary biomass and secondary biofuel trade, this value represents the sum of the two.

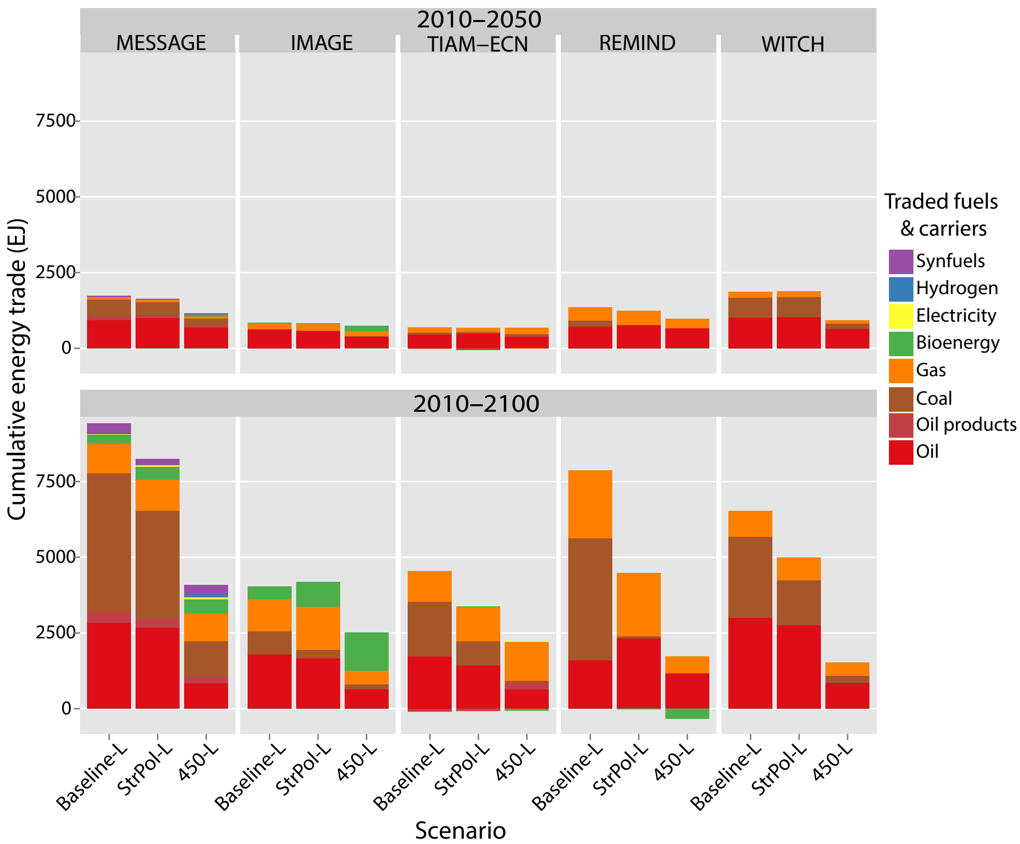
[d] R&R refers to proven resources and reserves from Rogner et al. 2012. This refers to the proportion of R&R resource consumption in the scenarios between 2010 and 2100.

[e] Diversity of sources used in transportation between "fossils", "bioenergy", "other renewable sources" and "nuclear energy".

In the Baseline-L, the country would face growing import volumes (between three and nine times higher than today) and could face higher net-import dependence. At the same time, the whole TPES and the electricity system would either maintain the same diversity level they have today or drop if traditional biomass currently used in the country were replaced by coal, which happens in IMAGE and WITCH. The energy intensity would stay roughly the same.

In the 450-L scenario, India's import dependence would be reduced and the diversity of energy options would be higher. Since the country has such high energy demand pressures combined with very low domestic resources, the import dependence rises even in the 450-L scenario; however, this rise is between three and five times higher versus up to nine times in the Basline-L. There is one additional factor which prevents India from experiencing the same dramatic drop in energy imports which the other major economies experience under the 450-L: bioenergy imports. The bioenergy story in In-

**Figure 5.4:** Cumulative energy imports to (positive) and exports from (negative) India



dia, however, conflicts between models (Figure 5.4). In IMAGE the country imports about 1300 EJ of bioenergy, mostly in the latter half of the century. However, ReMIND, which has fewer restrictions on bioenergy production depicts India as a net-exporter of bioenergy.

The diversity increase for India under the 450-L scenario is not quite as dramatic as for China, but India's diversity today is not as low as China's. Nevertheless, India would have TPES and electricity diversity comparable to the the E.U. level by 2040. The StrPol-L scenario would have little impact on India's import dependence, scarcity issues, or diversity because India's Copenhagen commitments are very modest.

*Europe*

The European Union is a developed economy poor in fossil resources with high import dependence but high resilience from a high degree of interconnections, relatively low energy intensity, and a high diversity of energy options in electricity and TPES (Table 5.4). Under the Baseline-L, energy imports and import dependence either rise slightly or fall through mid-century as the EU either maintains an energy system similar to today's or modestly grows its domestic energy sources (primarily nuclear, some coal and renewables). Towards the end of the century, the region's energy imports and import dependence drops. In WITCH and IMAGE, eastern Europe even becomes a modest coal exporter as coal resources elsewhere become depleted (in IMAGE) or as high coal demand in the Baseline-L makes the region's coal competitive on the global market (in WITCH). The diversity of electricity production stays the same or slightly rises in four of the six models through mid-century; however, in MESSAGE and ReMIND, electricity generation comes to be dominated by imported natural gas. TPES diversity in all models stays relatively high throughout the century.

Under the 450-L scenario, the region's energy imports fall, particularly in the latter half of the century. At the same time, the TPES and electricity diversity stays high throughout the century (except in ReMIND where the electricity sector becomes dominated by solar energy). The transport diversity follows the global trend and rises under the 450-L. The E.U. stands out from the other major economies in that the diversity rise in all three sectors (TPES, electricity and transport) under the StrPol-L scenario is

**Table 5.4:** The E.U.'s energy security in the Baseline-L and 450-L scenarios

| | | 2050 | | 2100 | |
|---|---|---|---|---|---|
| Indicator | 2010[a] | Baseline-L | 450-L | Baseline-L | 450-L |
| **Sovereignty perspective** | | | | | |
| TPES net-imports (EJ/yr) | 40 | 18–59 | 10–40 | -8–41 | -10–9 |
| Oil net-imports (EJ/yr)[b] | 22 | 17–36 | 3–14 | 0–16 | 0–6 |
| Gas net-imports (EJ/yr) | 12 | 12–34 | 4–33 | 4–21 | 0–3 |
| Coal net-imports (EJ/yr) | 3 | -14–8 | 0–2 | -28–10 | -16–1 |
| Bio-energy net-imports (EJ/yr)[c] | 0 | -1–2 | 0–6 | -3–5 | -11–5 |
| Net import dependence | 62% | 24%–66% | 24%–55% | -11%–49% | -18%–13% |
| **Robustness perspective** | | | | | |
| Proportion of oil R&R extracted[d] | - | 12%–48% | 11%–34% | 15%–340% | 13%–140% |
| Proportion of gas R&R extracted[d] | - | 12%–33% | 13%–31% | 34%–78% | 21%–64% |
| Proportion of coal R&R extracted[d] | - | 1%–6% | 1%–3% | 3%–20% | 1%–6% |
| **Resilience perspective** | | | | | |
| TPES diversity (unit-less) | 1.5 | 1.4–1.7 | 1.6–1.9 | 1.3–2.0 | 1.5–1.9 |
| Electricity diversity (unit-less) | 1.7 | 0.9–1.8 | 1.5–1.8 | 1.2–1.7 | 1.1–1.8 |
| Transport diversity (unit-less)[e] | 0.1 | 0.2–0.4 | 0.7–1.1 | 0.2–1.0 | 0.6–1.5 |
| Energy intensity (MJ/$2005) | 6 | 2–4 | 1–3 | 0.9–2 | 0.6–1 |

Energy trade ranges include five models (IMAGE, MESSAGE, ReMIND, TIAM-ECN, and WITCH). Diversity, intensity and resource extraction ranges include GCAM in addition to the other five.

[a] For import dependence data, 2010 values are calculated from IEA data and refer to the import dependence of EU27. Energy intensity for 2010 is from US EIA Energy Information Administration 2013. For diversity, these values are the mean between the models. For the robustness indicators this refers to cumulative extraction through 2010 from Rogner et al. 2012 and British Petroleum 2012.

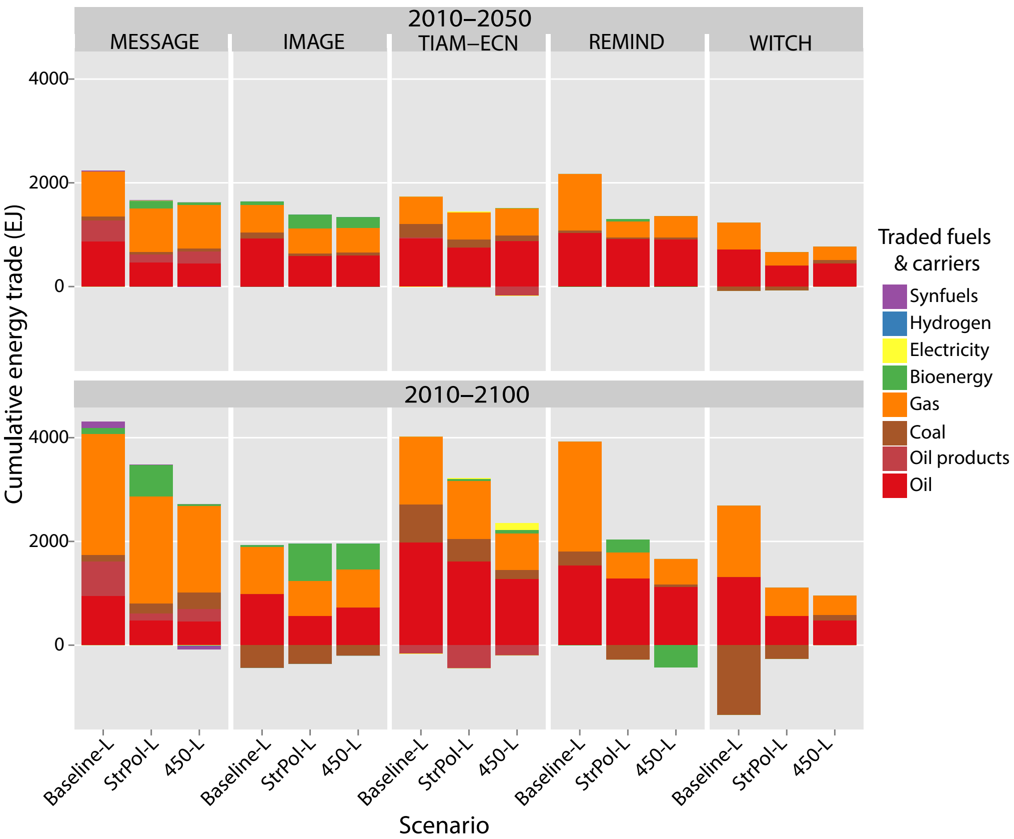
[b] For models which include crude oil and oil products this represents the sum of the two.

[c] For models which include primary biomass and secondary biofuel trade, this value represents the sum of the two.

[d] R&R refers to proven resources and reserves from Rogner et al. 2012. This refers to the proportion of R&R resource consumption in the scenarios between 2010 and 2100.

[e] Diversity of sources used in transportation between "fossils", "bioenergy", "other renewable sources" and "nuclear energy".

**Figure 5.5:** Cumulative energy imports to (positive) and exports from (negative) the E.U.




comparable to the diversity rise in the 450-L scenario since the region's Copenhagen pledges are very ambitious. Similar to India and China, the E.U.'s bioenergy trade varies between models. In ReMIND, which assumes peaking population, high yields and good transport infrastructure, the region exports about 400 EJ of bioenergy over the second half of the century; in contrast, IMAGE and MESSAGE depict the region *importing* that same amount of bioenergy (Figure 5.5).

### *The United States*

Like Europe, the U.S. is a developed economy with a well-developed diversity of energy options; also like Europe it is a net importer and has been since the 1940s over which time it has imported about a fifth of its TPES (World Bank 2012). However, while the U.S. has been a net importer for the last six decades, with the development of drilling technologies for

**Table 5.5:** Self-sufficiency and net energy exports in the U.S. in StrPol-L[b]

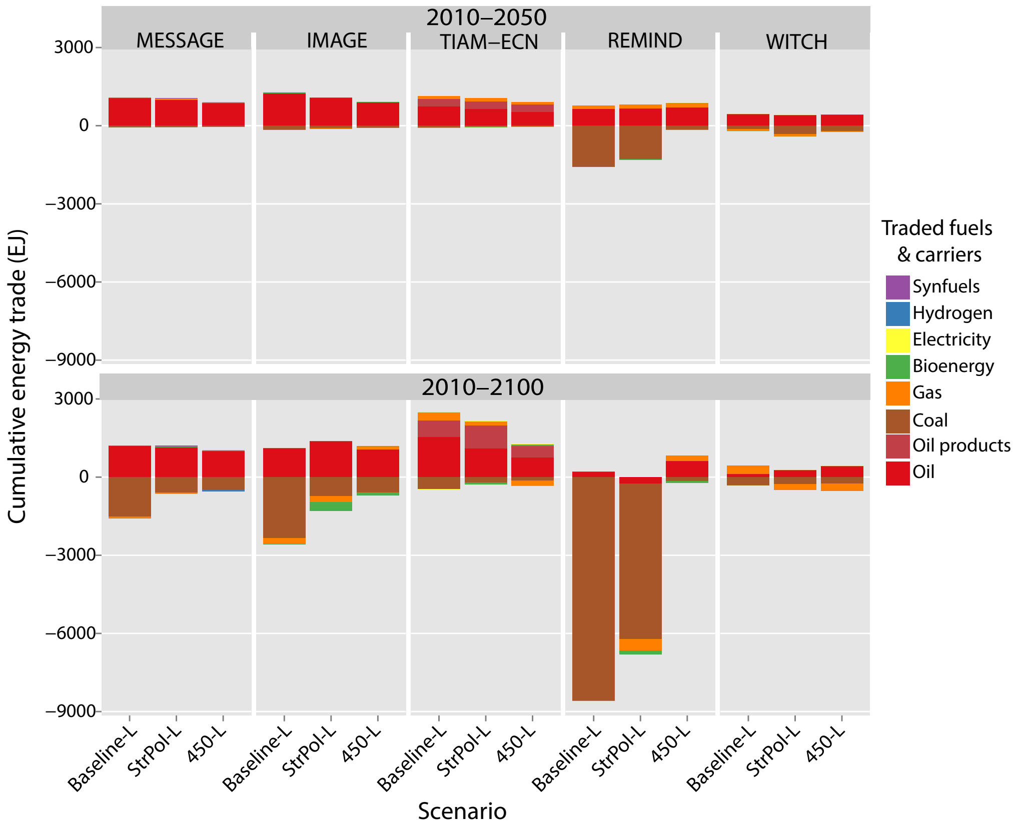
| Model | Year | Milestone | Cumulative net exports in 21st cent. |
|---|---|---|---|
| WITCH | 2025 | Self-sufficient | coal (270 EJ) gas (220 EJ) |
| ReMIND | 2030 | Major energy exporter | coal (6,000 EJ) gas (450 EJ) oil (260 EJ) |
| MESSAGE[c] | 2060 | Self-sufficient | coal (580 EJ) gas (30 EJ) |
| IMAGE | 2070 | Self-sufficient | coal (720 EJ) gas (210 EJ) |
| TIAM-ECN | 2100 | Net importer for most of 21st cent. | coal (210 EJ) |
| *IEA WEO[d]* | *2035* | *Self-sufficient* | *coal, gas, and bioenergy* |

Notes:
[a] "Self-sufficiency" is defined as when a country imports less than 5% of its TPES
[b] The StrPol-L scenario is used because it is most similar to the IEA's *New Policy Scenario*.
[c] In MESSAGE, these results to a region which includes the US and Canada.
[d] Reference for these data: IEA (2012d, 75).

unconventional oil and gas and its large fossil resource endowments, it is poised to become energy self-sufficient in the next two decades and could even become a major coal exporter (Table 5.5). In both the Baseline-L and StrPol-L scenarios, the U.S. still imports large volumes of oil in the first half of the century, but in the second half it exports coal, natural gas and even oil in three models (Figure 4.18). These large exports are driven by a growing global market which would require extraction of unconventional resources. This result is consistent with recent findings from the IEA (IEA 2012d, 75–76) and British Petroleum (British Petroleum 2013, 4) that the U.S. will become self-sufficient by 2030 (IEA) or 2035 (BP). However, it is important to note that the models in this thesis do not have as low prices of unconventional resources as is currently in the market-place or, as is included in the IEA and BP scenarios.

Under the 450-L scenario, the U.S. would forgo its coal exports (Figure 5.6). This could significantly impact any climate negotiations or agreements because while it is possible that a small subset of large countries could come to an effective climate agreement without OPEC countries (today's major energy exporters), mitigating climate without the buy-in of the U.S. would be almost impossible given that the country is the second-largest emitter. The U.S. does see modest bioenergy exports under the 450-L scenario but these are not even on the same order of magnitude as its potential coal exports. Since the U.S. does not face significant scarcity issues under the

**Figure 5.6:** Cumulative energy imports to (positive) and exports from (negative) the U.S.




Baseline-L, the reduction in extraction under the 450-L scenario is a cost rather than a blessing.[52]

As a developed economy, the U.S. today has a relatively high diversity of energy options, both in its TPES and in electricity generation (Table 5.6). Under the Baseline-L, the diversity of electricity generation stays roughly the same or rises slightly as renewables penetrate the energy system as a whole and the electricity system in particular; however, electricity diversity drops in ReMIND as the country's generation comes to be dominated by coal. Under the 450-L scenario, electricity generation rises through mid century before falling towards the end of the century in some models where the system becomes dominated by solar energy. The diversity of transport in the U.S. follows the global trend: in the Baseline-L it stays low through

52. In fact some authors have even argued (on the global level) that the cost of forgoing fossil resources under a climate policy is higher than the cost of mitigating climate change (Nel and Cooper 2009).

**Table 5.6:** The U.S.' energy security in the Baseline-L and 450-L scenarios

| | | 2050 | | 2100 | |
|---|---|---|---|---|---|
| Indicator | 2010[a] | Baseline-L | 450-L | Baseline-L | 450-L |
| **Sovereignty perspective** | | | | | |
| TPES net-imports (EJ/yr) | 22 | -111–26 | -3–16 | -120–13 | -36–2 |
| Oil net-imports (EJ/yr)[b] | 21 | -10–26 | 0–10 | -26–24 | 0–10 |
| Gas net-imports (EJ/yr) | 3 | -5–6 | -4–3 | -11–10 | -5–0 |
| Coal net-imports (EJ/yr) | 0 | -109–6 | 0–72 | -107–-14 | -26–0 |
| Bio-energy net-imports (EJ/yr)[c] | 0 | 0–1 | 0–1 | 0–2 | -6–1 |
| Net import dependence | 26% | -100%–27% | -5%–19% | -140%–11% | -53%–2% |
| **Robustness perspective** | | | | | |
| Proportion of oil R&R extracted[d] | - | 1%–6% | 1%–5% | 3%–65% | 1%–25% |
| Proportion of gas R&R extracted[d] | - | 4%–8% | 5%–6% | 8%–25% | 6%–15% |
| Proportion of coal R&R extracted[d] | - | 0%–1% | 0%–1% | 1%–5% | 0–1% |
| **Resilience perspective** | | | | | |
| TPES diversity (unit-less) | 1.4 | 1.3–1.6 | 1.7–1.9 | 1.3–1.7 | 1.2–2.0 |
| Electricity diversity (unit-less) | 1.4 | 1.1–1.7 | 1.5–1.9 | 1.1–1.7 | 0.9–1.8 |
| Transport diversity (unit-less)[e] | 0.1 | 0.003–0.4 | 0.4–1.0 | 0.1–0.9 | 0.5–1.2 |
| Energy intensity (MJ/$2005) | 8 | 2–4 | 2–3 | 1–3 | 0.7–1 |

Notes: Energy trade ranges include five models (IMAGE, MESSAGE, ReMIND, TIAM-ECN, and WITCH). Diversity, intensity and resource extraction ranges include GCAM in addition to the other five.

[a] For import dependence data, 2010 values are calculated from IEA data. Energy intensity for 2010 is from US EIA Energy Information Administration 2013. For diversity, these values are the mean between the models. For the robustness indicators this refers to cumulative extraction through 2010 from Rogner et al. 2012 and British Petroleum 2012.

[b] For models which include crude oil and oil products this represents the sum of the two.

[c] For models which include primary biomass and secondary biofuel trade, this value represents the sum of the two.

[d] R&R refers to proven resources and reserves from Rogner et al. 2012. This refers to the proportion of R&R resource consumption in the scenarios between 2010 and 2100.

[e] Diversity of sources used in transportation between "fossils", "bioenergy", "other renewable sources" and "nuclear energy".

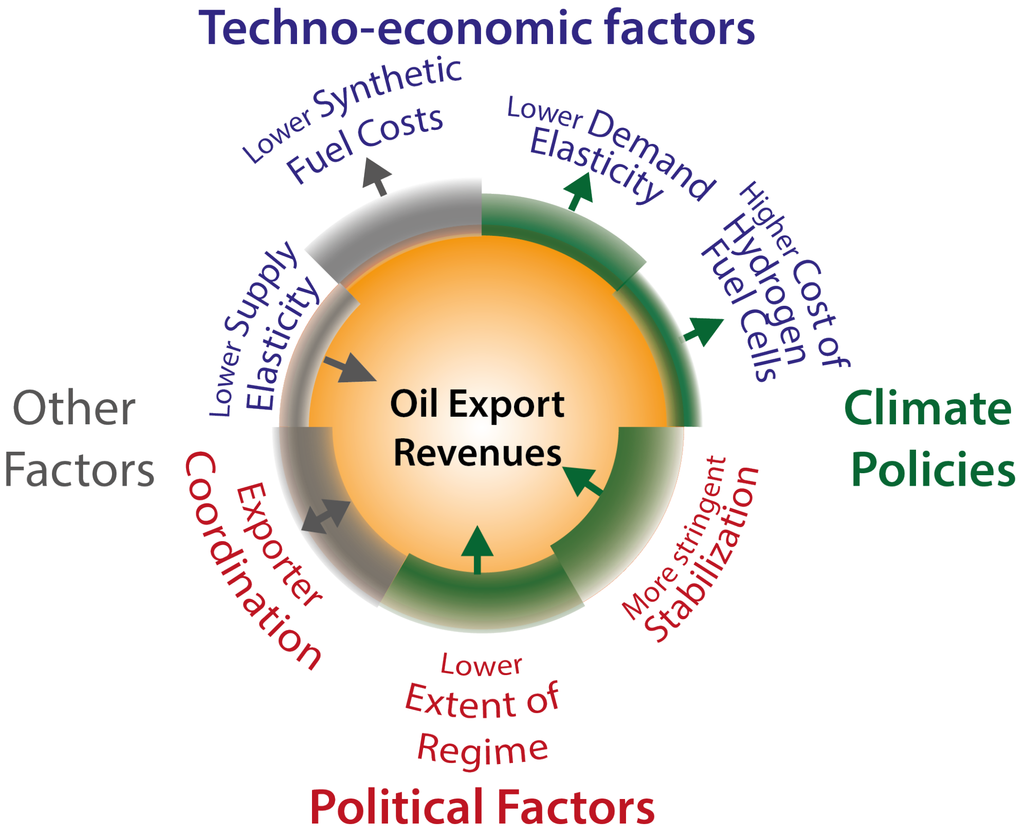
mid-century whereas in the 450-L scenario it rises. The country has relatively high energy intensity for a developed economy. Its energy intensity drops under all scenarios. StrPol-L depicts a future halfway between the Baseline-L and 450-L in terms of diversity.

In sum, the U.S. is the major economy which could significantly lose under a global stabilization target. While the U.S. today imports about a quarter of its TPES, without any climate policies it would become self-sufficient as early as 2025 and at least by the end of the century. At the same time, without a global carbon target, it would export large volumes of coal. This potential loss may trigger and sustain opposition from the U.S. to an ambitious global climate deal. The country's diversity of energy options is fairly high and, under most models, the diversity stays high through mid-century while the energy intensity falls, thus making the country even less vulnerable. Nevertheless, under certain assumptions in the Baseline-L, the diversity of electricity generation drops and the transport diversity stays low throughout the century. Thus, the 450-L scenario would ensure high diversity of electricity production (at least through mid-century) and the rise in transport energy diversity, which is crucial to the country's economy particularly given its car culture.

### 5.4.2 Energy exporters

Energy exporters are generally poised to lose under climate policies. However, as the multi-model comparison and the synthesis of existing literature shows, there is a great deal of uncertainty about if and by how much energy export revenues would change for major exporters. There are two questions related to energy export revenues under climate scenarios: would energy export revenues decline and if so how could resource-rich countries be compensated. I relied on the existing literature on oil-producing countries to explore the first question and a scenario from the LIMITS multi-model comparison to answer the second. While oil-producing countries have argued that their oil export revenues would decline under climate policies, quantitative modeling studies indicate that such revenues may increase or decrease depending on the modeling assumptions and various uncertainties. As shown in Figure 5.7, the overall estimates range from a 35% of decline in oil export revenues under climate policies to some 20% increase compared to a business as usual scenario. Since the existing studies proceed from different assumptions, address various time horizons and use various modeling approaches their findings are not directly comparable: however, the literature offers several interesting insights in relation to the main uncertainties which energy exporters face.

**Figure 5.7:** Uncertainties of OPEC revenue under climate regimes




The orange circle depicts cumulative MENA oil export revenues projected under business-as-usual scenarios. The labels in the outer circle correspond to the main techo-economic (at the top) and political (at the bottom) factors reported in the literature as potentially affecting these revenues under climate policy scenarios. The factors more directly related to climate policies are placed on the right and those more independent of climate policies are on the left. The colored areas along the edge of the circle symbolize the estimated scale of effects of all these factors and the arrows show the direction associated with the uncertainty in those factors. For example, higher costs of hydrogen and fuel cell technologies lead to higher oil export revenues. Oil demand elasticity is influenced by the costs of electric vehicle technologies, energy efficiency in transport, attractiveness of alternative mobility arrangements and other factors which are not quantitatively modeled in existing studies. The impact of export coordination may be different for countries that participate in such coordination and those that stay out.

There are both techno-economic and political factors (some of which are related to climate policies and some which are not) which would impact oil export revenue. Two of the techno-economic factors directly relate to the cost of substitutes for conventional oil: higher hydrogen and fuel cell costs would result in higher oil export revenues whereas lower costs of fossil fuel alternatives (taxed under global climate regimes) would, somewhat paradoxically, lead to higher MENA conventional oil export revenues. The third techno-economic uncertainty includes a variety of additional factors which influence oil demand elasticity (such as attractiveness of alternative forms of mobility, biofuels, etc.). Lower demand elasticity would once again result in higher oil export revenues. The fourth and final techno-economic factor relates to supply rather than demand for oil. Lower supply elasticity has been shown to lower projected oil export revenues.

Two of the political factors relate to the nature of the climate regime. A more stringent stabilization target would eventually lower oil export revenues. A lower geographical extent of climate policies (for example, if resource exporting countries do not participate in a climate deal) would also result in lower oil export revenues than under a global carbon tax regime covering oil importers and exporters simultaneously. Finally, a political factor which is independent of climate policies is the degree to which OPEC acts as a cartel. Increasing exporter coordination (i.e. greater cartelization) may increase or decrease oil export revenues for OPEC depending on the oil price and the behavior of non-cartel countries. Finally, energy exporters could be compensated through the carbon market within a specific climate regime. In an "equal effort" burden sharing regime, while all models compensate the two main resource exporters, models differ in the magnitude of compensation: some depict compensation which is greater than lost export revenues while others "under-compensate" these regions.



## 5.5 Differences between models

Different models depict certain variations to the common themes of energy security in long-term scenarios. Some of these variations concern the global level while others are relevant to specific major economies (Table 5.7). With respect to trade, models vary in the flexibility of trade. TIAM-ECN has relatively inflexible trade with coal trade growing only to some ∼10 EJ by

**Table 5.7:** Differences between the models with respect to energy security

| Dimension | Model | Differentiating feature |
|---|---|---|
| Coal trade in the Baseline scenario | ReMIND | Large global coal market supplied by the U.S. and consumed by China. |
| | MESSAGE | Significant global coal market supplied by the U.S. and China |
| | TIAM-ECN | Small global coal market |
| Bioenergy trade under climate policies | ReMIND | Notable global trade in bioenergy. China, the E.U. and India are exporters. |
| | IMAGE | Largest global trade in bioenergy. China, the E.U. and India import bioenergy. |
| Transport energy diversity | MESSAGE & ReMIND | Rapid rise in transport diversity under climate policies due to penetration of electricity and biofuels. |
| | IMAGE | Rise of transport energy diversity in the baseline due to penetration of biofuels. Transport dominated by hydrogen by the end of the century. |
| | TIAM-ECN | Transport is dominated by hydrogen after 2050. Before 2050, no change takes place in the transport sector. |

2050 and ~80 EJ by 2100. At the other end of the spectrum is ReMIND which indicates the coal market growing to ~120 EJ/year in 2050 in the Baseline-L growing to some ~240 EJ/year by 2100 primarily supplied by the U.S. and largely consumed by China.

The general storyline of ReMIND is one of co-operation and free international trade and the model does not impose restrictions on trade or import dependence. Under this free international trade, it makes sense for China to import cheaper coal from the U.S., due to its own high coal transportation costs. This is in line findings from Lin and Liu (2010) of possibly large coal imports to China. Another model, MESSAGE, depicts a smaller coal market (~30EJ in 2050 and 210 EJ by 2100) supplied concurrently by the U.S. and China. Such developments would represent unfamiliar patterns of global energy interdependence. This massive coal trade disappears under the climate policy scenarios in all models. This means that the global energy trade is not only considerably smaller under climate policies but also less dependent on resource availability assumptions, which is of course good news for energy security, for which uncertainty is a liability.

Another difference between models concerns the production and trade of bioenergy. Both IMAGE and ReMIND are different from other models indicating notable global bioenergy trade (which is still relatively small compared to both the current and future trade in fossil fuels). IMAGE imposes stricter requirements on where bioenergy can be produced and thus indicates a larger global trade in bioenergy. In IMAGE, India, China and the E.U. import bioenergy. In ReMIND, these regions export smaller volumes of bioenergy due to assumptions of peaking populations and higher agricultural yields.

The final notable difference between models from an energy security perspective concerns the diversity of energy sources used in the transport sector. In ReMIND and MESSAGE, climate policies result in very rapid rise in transport energy diversity because they trigger penetration of both electricity based on renewable energy sources and biofuels as transport energy sources. TIAM-ECN, on the other hand has rather conservative assumptions on available biomass from sustainable resources and therefore models almost no changes in the transport sector before 2050. However, TIAM-ECN indicates strong deployment of hydrogen in transport starting in 2050. In fact, in IMAGE, TIAM-ECN, and some GEA-Supply scenarios in MESSAGE, transportation becomes dominated by hydrogen by the end of century; thus while the diversity of primary energy sources would likely still be higher than the current transport diversity (since hydrogen can be produced using different energy sources), the sector would be dominated by a single energy carrier. Finally, in IMAGE the transport energy diversity rises even in the absence of climate policies because of biofuel penetration in the transport sector.

# Chapter 6

# Summary and Conclusion

Adding to knowledge is like working at the bottom of a narrow, deep, dark coal pit…with a toothpick. The Literature Review documents the paths I traveled to reach the bottom of this mine while in the Methodology chapter I describe how I found, prepared, and used the toothpick once I got there. In the Results and Discussion chapters I present what I found in my digging and what it means. This chapter takes the reader from the bottom of the mine back up to the surface. I summarize the intellectual history of energy security and climate change as policy problems and how this explains a divide between the two. Subsequently, I describe my contribution to bridging this divide and provide a synthesis of my findings. I conclude with a description of the novelty of my research and a future research agenda which emerges from this work.

## 6.1 Revisiting the research problem

Ensuring energy security and mitigating climate change are arguably the two most important energy policy priorities. Yet in many ways these twin challenges are incompatible:

*Ensuring energy security ...*

- is a key *national* energy issue;
- is an *immediate and urgent* concern of today's energy policies;
- is a politically-constructed *fuzzy concept* difficult to define and measure;
- calls for *stability* of energy systems;
- historically began as a policy problem and later became an area of scholarly inquiry.

*Mitigating climate change ...*

- is a key *global* issue;
- is a *long-term* concern potentially extending for decades or centuries;
- is based on a set of scientifically *well-defined* concepts and is relatively straightforward to measure;
- requires massive *change* of energy systems;
- historically began as a scientific curiosity and only recently entered the policy arena.

The gap between energy security and climate mitigation is a specific case of a larger problem: how do global climate goals connect to national capacities and motivations? Though the benefits of decarbonizing energy systems are *global*, most of the action will need to be driven by national policies. Thus, understanding the interaction between the global climate change agenda and national interests will be key to deploying effective climate mitigation strategies. This thesis is one contribution to that broader research agenda. My aim is to contribute to a more rigorous and systematic understanding of the interaction between climate change and energy security through evaluating the energy security implications of decarbonization scenarios under various policy, technological and economic assumptions.

## 6.2 Innovations in conceptualizing and assessing energy security

Faced with the question of evaluating energy security under decarbonization scenarios I encountered three challenges. Firstly, energy systems must be concretely depicted so they can be connected to climate-neutral futures. There is a genre of literature which connects energy security and climate change through energy utopias where all problems are either resolved, or are nightmares where the race to the last drop of oil exacerbates environmental destruction (Lovins and Lovins 1982; Klare 2008). While this literature is inspirational and powerful in its own right, it remains disconnected from climate change research which over the past twenty years has made great strides in connecting the scientific knowledge of the greenhouse effect to the realities of energy systems. To make use of these recent advances in knowledge, I used data from six Integrated Assessment Models through three different scenario exercises at the cutting edge of energy system transformation research.

Then, the question becomes, what to measure in these long-term energy scenarios? This brings us to the second big challenge in this project: the scholarly disagreements about the meaning and boundaries of energy security. Part of the disagreements arise from its contextual nature and that it means different things to different actors (Cherp and Jewell 2011a; Chester 2009). But another part of the disagreement is the increasing complexity of energy systems and their vulnerabilities. Amidst this growing complexity many energy security scholars exhibit a penchant for uncritically expanding the boundaries of energy security, dividing it into a growing number of "dimensions" and coming up with tens or hundreds of indicators which can measure these dimensions (Sovacool and Mukherjee 2011; Vivoda 2010; von Hippel et al. 2011). While this has sparked a healthy debate on the epistemological boundaries of energy security, it is of little use to the task of evaluating future energy security because it has failed so far to produce policy relevant and intellectually robust boundaries of energy security.

Against this backdrop of conflicting definitions and dimensions, one approach would be to avoid all controversial aspects of energy security and only focus on evaluating aspects where there is consensus. For example, no one disputes that oil import dependence is a problem in many countries or that electricity reliability is central to energy security. Thus, one could simply project current energy security concerns such as E.U. oil and gas import dependence (Costantini et al. 2007) or electricity security (Grubb, Butler, and Twomey 2006) into the future. The problem with this approach is that consensus would lead us to only focus on concerns which exist in the current configuration of energy systems. This results in the third challenge of evaluating energy security under de-carbonization scenarios: if energy systems undergo radical transformations (for example, if oil is no longer the dominant fuel in the transport sector), present energy security concerns may subside and new ones may emerge.

Thus, to evaluate future energy security my advisor and I developed an energy security assessment framework which is generic enough to be relevant under radical energy system transformations while at the same time specific enough to reflect current vulnerabilities of energy systems and concerns of policy-makers. This framework is based on the idea of *vital energy systems* whose failure may disrupt the functioning and stability of society. This idea was influenced by the argument that even security of supply is a result of the security of the whole supply chain (Le Coq and Paltseva 2009) and more general energy security is a result of security of the whole energy system (Scheepers et al. 2007; Hughes 2012). An energy *system* emerges when elements within the system are more connected to each other than elements outside of it. These systems can be drawn in many configurations such as oil imports to the European Union or China's electricity system. In my evaluation of future energy security, I draw the boundaries of these systems in two ways: geographically at the global and regional level and sectorally between sources, carriers, and end-uses of energy.

Once the system boundaries are drawn, the next step is to identify which vulnerabilities to evaluate. When I developed the *Model of short-term energy security (MOSES)* at the IEA, I worked with national policy-makers to evaluate the short-term energy security of their respective countries (Jewell 2011b; IEA 2011c). In this context, it worked well to use the distinction between external versus internal and risks versus resilience capacities since it separates vulnerabilities into factors which are completely out of a policy-makers' control (external risks) from those which they have the most influence over (internal resilience). In order to achieve the aim of my thesis this approach needed to be more generic to move from assessing only physical short-term disruptions to vulnerabilities (both shocks and stresses) and of a physical and economic nature; from the focus on the 28 IEA member countries to the focus on large global regions; and from the present to the future configurations of energy systems.

To formulate a framework for analyzing future energy system vulnerabilities, my advisor and I did a historical analysis of how energy security emerged and evolved as a policy problem and the related academic concept. We identified three persistent themes and discourses in energy security each rooted in actual policy problems and specific disciplinary outlooks on the nature of energy systems' vulnerabilities (Cherp and Jewell 2011b). Between the turn of the last century when Churchill switched the British navy from coal to oil, through the Arab oil crisis, energy security meant securing *foreign oil* through geopolitical arrangements and international arrangements. This **sovereignty** perspective is deeply rooted in international relations and protecting against the oil (and more recently gas) "weapon".

The second period emerged in the 1970s when, coinciding with the Arab oil embargo, the *Limits to Growth* began to ring the bell on impending oil scarcity. Around the same time, there was a warning that not only does the world face resource scarcity but electricity, natural gas, oil and nuclear power systems were "Disasters Waiting To Happen" (Lovins and Lovins 1982, 87–174). And thus emerged the second perspective on energy security: **robustness**. Rooted in engineering and natural sciences this perspective focuses on calculable risks related to resource scarcity and critical infrastructure.

In the 1980s and 1990s, along with the deregulation of energy markets, there was a growing recognition that energy systems will inevitably encounter disruptions: the key is to build markets and measures which ensure resilience (Yergin 1988, 112). Inspired by *Small is Beautiful* (Schumacher 1973) and the ideas of *Resilience and Stability of Ecosystems* (Holling 1973), the **resilience** perspective was influenced by concepts from ecology (Lovins and Lovins 1982, 195). It was further developed by Stirling's work on ignorance and uncertainty in energy system planning (Stirling 1994, 1998). This came on the tails of electricity deregulation in the U.K., which broke up the coal miner unions that for several decades had been the biggest threat to the country's energy security. Thus this perspective is inherently linked to economics (and market ideology) as well as to complex systems studies.

Thus at the core of my assessment framework is the concept of vital energy systems and their vulnerabilities which I view from the angle of three 'timeless' perspectives on energy security: sovereignty, robustness, and resilience. The framework itself includes several sequential stages, where vital energy systems and their vulnerabilities are systematically identified, appropriate indicators for these vulnerabilities are selected, measured and interpreted to answer the questions posed by the assessment (Cherp and Jewell 2013). This approach, which in its earlier form was tested in two chapters of the

*Global Energy Assessment* where I was a lead author, is different from the current approaches to measuring energy security in that (a) it focuses on explicitly defined vital energy systems rather than on 'energy' as a whole (or on ad hoc entities such as oil supply); (b) it explores generic vulnerabilities categorized into the 'three perspectives'; and (c) instead of starting the assessment with a set of indicators it involves a set of reflective stages where indicators are carefully selected and interpreted to represent key vulnerabilities of vital energy systems.

At the stage of interpreting the data I carefully considered the idea to use aggregate or compound indices produced through mathematical manipulations with several indicators. Eventually I decided that for the purpose of my study such aggregation is not necessary, but our energy security assessment framework envisions situations where aggregation may be helpful and lays out principles for doing it in a sound and rigorous way. I believe that this novel way of conceptualizing energy security and the framework to measure it will serve scholarly and policy communities who seek to analyze energy security in different contexts.

In this thesis, I use this framework and draw from the growing literature on energy security indicators to identify measures for vulnerabilities which may either intensify or emerge under a low-carbon energy system. All in all, I used over 30 indicators of energy security in this study. I tapped into three ongoing energy scenario projects and worked with six different modeling teams on a total of some 70 scenarios. To my knowledge no one has done such a detailed analysis of energy security in decarbonization scenarios. However, working with this amount of data was only part of my research contribution.



## 6.3 How would climate change policies affect global energy security?

Overall, energy security vastly improves under climate policies, particularly compared to a business as usual development (Table 5.1). Under the Baseline-L scenario trade in oil, gas and coal grow through the mid-century reaching as much as five times current trade volumes by the end of the century. At the same time, the world would use almost all proven oil reserves which would likely lead to increased anxiety over oil scarcity and to price volatility. This would negatively affect the majority of the world population especially the over 3 billion people who live in 83 countries which currently import over 75% of their oil (Cherp et al. 2012). The transportation sector would likely continue to be tied to oil which would continue to expose countries oil shocks. China and India would likely face growing energy imports and electricity systems dominated by imported coal and far less diverse than that of developed economies. At the same time, the U.S. would likely reemerge as a major energy exporter taking advantage of its large reserves of coal, gas and possibly unconventional oil.

Under the 450 scenarios, as countries turn to domestic renewable resources, global trade in fossil fuels would plateau and the diversity of energy systems would increase. These changes in trade would only impact import dependence after 2030 because, while climate policies foster the growth of non-traded energy sources (renewables, nuclear energy, some forms of biomass), they also limit the use of domestic coal. Trade in oil is phased out in most models and as a result, the world only extracts up to 50% of the proven reserves and resources. While trade in other fossil fuels would stay far below the Baseline levels, trade in gas, coal and bioenergy may grow to be comparable to today's oil trade (though within a much larger global energy system). The models, however, differ considerably on both which fuel reaches these high trade volumes and the geographic pattern of trade. For example, MESSAGE depicts high trade in gas with high concentration of exports while IMAGE depicts high trade in both coal and bioenergy with lower concentration of exports. Thus, though there is an agreement that there would be less energy trade under climate stabilization than under the Baseline, there is a high degree of uncertainty over what would be the most intensely-traded fuels in a 450-World and which regions would be the main sellers and which the main buyers.[53]This uncertainty is particularly pronounced in the case of bioenergy which reaches some 80 EJ in IMAGE and 60 EJ in ReMIND by the end of the 21st century. Moreover, the main importing regions under one model are the very regions which export bioenergy under the other.

53. Models also diverge on these factors in the Baseline but there is more consistency then under the 450 scenario.

Concurrent with the falling energy trade would be a rising diversity of energy systems, particularly over the short-term. The TPES diversity rises through mid-century across all models before slightly falling under certain assumptions which lead to solar energy assuming greater importance. Electricity diversity exhibits similar, but more pronounced dynamics to the TPES diversity. One of the most notable improvements in energy security is the rise in the diversity of the transportation sector which today is over 90% dependent on oil. This rise in transportation diversity happens in all models except TIAM-ECN by 2050 and continues throughout the century. In TIAM-ECN and IMAGE the transport sector is dominated by hydrogen by the end of the century. However, hydrogen can be produced from several different energy sources and thus does not represent as significant of a vulnerability as today's oil products, all tied to the same primary energy source.

### 6.3.1 …under different climate policies

I have found that the stringency of climate stabilization is directly proportional to their effects on reducing energy trade and enhancing the diversity of energy systems. In case of more stringent and earlier stabilization targets trade declines and diversity increases faster. This also leads to an eventual fall in diversity observed when renewable energy sources start to dominate energy systems. National climate targets without global stabilization lead to an increase in diversity of energy systems but the decrease in trade and resource extraction is significantly less.

### 6.3.2 …under different fossil resource availability and GDP assumptions

Climate policies are a hedge against uncertainties related to both fossil fuel availability and GDP growth rates. Fossil fuel availability has little effect on energy trade or diversity under climate policies, however under the Baseline it has a large impact. In the Baseline scenario, increasing the availability of fossil resources can increase the trade of fossil fuels by between 150EJ (for oil and coal) and 200 EJ (for gas). This would as much as triple the trade volumes of each fuel. In contrast, under the climate stabilization scenarios, fossil availability assumptions have little impact on oil and coal trade. Fossil availability does, however affect gas trade in the 450-World. Lowering the availability of fossil resources would lead to an *increase* in gas trade since the assumptions disproportionately lower the resource base for energy importers. I also observed that lower fossil availability *increases the diversity* of energy systems in the Baseline scenarios. A business as usual world, facing low resource availability would force energy systems to diversify which could lead to higher resilience. In this future, long-term energy security may increase, but short-term energy security would be compromised with concerns about scarcity and associated price volatility. Climate policies would avoid this trajectory since byshifting the energy system away from fossil resources without facing any scarcity issues.

GDP growth rate assumptions also have a much larger impact on energy trade in the Baseline than under climate policies. Increasing the GDP growth rate from some 2% to 3% increases the energy trade by about 30% or about 40 EJ for each fuel in the Baseline and has virtually no effect on trade under climate policies (since the extra growth in this case is fueled by increased energy efficiency and non-tradable renewable energy). In summary, energy security under climate policy scenarios is not only higher than in the business as usual scenarios, but it also does not depend as much on uncertain assumptions about fossil fuel resources and GDP growth.

### 6.3.3 …under different technological assumptions

Technological choices do have an impact on energy security in future energy systems. All else being equal, investing in energy efficiency consistently decreases energy trade and as a result regional import dependence. Since increasing energy efficiency also typically decreases energy intensity, and therefore an economy's exposure to price shocks, energy efficiency investments provide a security double dividend. The other demand-side investment which consistently decreases energy trade is the electrification of the transport system. It is however surprising that electrification of transport has virtually no effect on diversity of energy sources used in transport. This is due to the fact that even in the conventional (i.e. non-electrified) transportation scenarios, the transportation sector "diversifies" away from oil to synthetic fuels based on gas and coal with CCS and biofuels.

Supply-side constraints affect energy trade and the diversity of energy options. Limiting renewable energy sources, nuclear energy, and bioenergy, particularly when combined with a conventional (non-electrified) transportation system and/or low energy efficiency improvements all increase energy trade in de-carbonization scenarios. In two cases, energy trade in a single fuel exceeds the present volume of oil trade: for gas this occurs in some scenarios with limits on RES; and for hydrogen this occurs in low efficiency scenarios without nuclear energy. The high gas trade is particularly notable because it also features very low diversity of energy exporters of natural gas. The only obvious option to avoid this increase in gas trade is to remove the limitations on the use of RES; however, this has the downside of eventually reducing diversity of electricity generation. This is especially pronounced in scenarios with no nuclear power. Thus, for energy security, phasing out nuclear power delivers a one-two punch: it may ultimately lead to very low diversity in electricity production and higher energy trade of fossil fuels and hydrogen. All these pitfalls are avoided in scenarios with high gains in energy efficiency where both trade can be kept at lower levels and the diversity can be kept at higher levels.

### 6.3.4 …in major economies

The shifting global energy landscape under climate policies leads to improved energy security for the major economies but to differing degrees. India is the largest winner under the 450-L scenario. Under the Baseline scenario India's energy security gets progressively worse throughout the century with growing imports, high depletion of fossil reserves and a decrease in electricity diversity as coal comes to dominate the sector. In contrast, the 450-L scenario leads to much lower import dependence (cumulative imports drop by between 40% and four times) and a radical increase in electricity diversity over the next three decades. The European Union is also a big winner under climate policies, but the dividends are are not as high since its energy security situation and prospects are not as dire to begin with. The E.U.'s situation is also unique in that it experiences almost as much energy security benefits under the StrPol-L scenario (which does not achieve global climate goals) as under the climate stabilization scenario since its ambitious Copenhagen pledges are *very* ambitious.

In China and the United States, energy security would likely improve in some ways but these two countries may also suffer losses under the climate stabilization scenario. In China, under most models, import dependence drops significantly between the Baseline-L and the 450-L scenario, however, one of the models (MESSAGE) depicts massive energy exports which the country would forgo in a 450-World. China's electricity diversity today is far below other regions in this study with over 75% of its generation originating from coal in 2010.[54] Under the climate stabilization scenario, China's electricity diversity rapidly catches up to the levels in the industrialized economies of the E.U. and the U.S. by 2030–2040. In the StrPol-L scenario this effect is achieved around 2050.

Under the Baseline-L scenario, the U.S. becomes self-sufficient in energy by between 2030 and 2070. At the same time it may face declining diversity of electricity production (though its current electricity diversity is not particularly low). But the big story with the U.S. is that in ReMIND under the 450-L scenario, it misses out on as much as 8,500 EJ of coal exports which would occur under the Baseline-L. However, while the volume is large it would would only account for at most 2.7% of the country's GDP.[55] Nevertheless, while most energy security indicators would improve under the 450-L scenario, under certain conditions there may be tension between climate mitigation and energy export revenues in China and the U.S.

### 6.3.5 …for energy exporters

The fate of major oil and gas exporters under a stabilization scenario is far from certain. On the one hand, oil and gas exports from the Middle East and Russia may decrease due to depressed global demand as energy systems move away from fossil fuels. On the other hand, under climate constraints, it is possible that energy export revenue would *increase* as more expensive unconventional resources in other regions would not be developed. The most important techno-economic determinants would be the elasticity of supply and demand, the latter influenced by the price of alternative fuels (namely



54. This results in a diversity of 0.7 compared to 1.0 in India, 1.4 in the U.S. and 1.6 in the E.U.
55. Norway's fuel exports accounted for about 20% of GDP in 2010 and Saudi Arabia's for some 50% (World Bank 2012).

hydrogen and synthetic fuels).[56] The most important political uncertainties would be the degree of coordination (cartel behavior) between exporters as well as the stringency and extent of the climate regime. Energy exporters have little influence over the techno-economic uncertainties, which are the main factors which could lead to an increase in export revenues under a climate regime, but they do have influence over their own coordination as well as over the extent and stringency of the climate regime.

## 6.4 Novelty in findings

Prior to this thesis, there was a handful of studies on energy security in low-carbon energy futures (Table 2.1). The overall findings of these studies were that climate policies generally lower energy trade, lower resource use and increase diversity of energy options. Indeed, this general conclusion can be arrived at through relatively simple common-sense reasoning: climate policies increase domestic renewable sources and decrease reliance on fossil fuels which lowers energy trade and resource use as well as increases the diversity of energy options. So what is new and different in this thesis?

First of all, I examine this common-sense conclusion to see if it holds. While at present only fossil fuels are globally-traded, low-carbon energy systems trade may include bioenergy, hydrogen and possibly other new fuels and carriers. My analysis shows that even with these potential new trade flows, global energy trade is still lower than in a baseline scenario and may even be lower than at present. To the best of my knowledge, this the first comprehensive study of new energy trade.

Secondly, the business as usual development itself is far from obvious. It could be that without any climate policies, energy security naturally improves as a result of technological developments and resource depletion. My thesis shows otherwise. Under all baseline assumptions that I looked at, energy trade and net import dependence in most major economies continues to rise through the century. Even in the face of low oil availability, energy trade rises because gas and coal trade offset the drop in oil trade. Furthermore under the business-as-usual development, electricity diversity

56. None of the studies tested the effect biofuels would have on oil demand. This could be an interesting area of future research.

may actually drop in certain economies such as in the U.S. and India with increasing use of coal.

The U.S. becomes self-sufficient in all models by the end of the century in the business as usual scenarios. While the short-term (through 2035) part of this trend is consistent with recently-published studies (IEA 2012d; British Petroleum 2013), the long-term aspect is new. I find that under the baseline, the U.S. could become a major exporter of coal; this development is absent under climate stabilization. The risk of forgoing significant energy export revenues could significantly affect the U.S. position in climate negotiations.

Concerning the gains for energy security as a result of climate change policies, the common-sense argument is nicely represented in the trade-off graph in Figure 2.1 which shows that policies with positive climate characteristics almost universally lead to improved energy security. My analysis of the long-term interaction between energy security and climate change based on the 450 scenarios gives a more nuanced representation of this trade-off space. For example, while climate policies would indeed result in lower energy imports in most major economies, these benefits would not be apparent until 2050. This is because while climate policies *do* increase the penetration of renewable energy sources, they also *limit* domestic coal use. Thus, in the short-term the decrease in imports as a result of climate policies is often a wash. Secondly, while the 450 scenarios generally lead to lower oil trade, as oil is phased out, its geographic concentration increases meaning that again, the trade benefits of climate policies may not be felt till later in the century and may even exacerbate vulnerabilities in the short-term. The lower energy trade leads to a logical but surprising result: divergence between regional energy systems which could significantly impact the global energy security balance as discussed in subsection 5.3.3.

The trade-off space (Figure 2.1) characterizes energy security as trade. In my thesis, I also deal with diversity of energy options, intensity and resource scarcity. This allows me to look at new types of long-term trade-offs between different types of energy security concerns. The 450 scenarios lead to an increase in diversity in the short-term but a decline by the end of the century. While I discuss the limitation of this finding in the Methodology chapter, it may mean that climate policies over the long-term may be hindered by a decrease in energy security energy options, at least if no radically new technologies are found. Some supply technology constraints may exacerbate this trend especially in the long-term. Phasing out nuclear energy reduces diversity and at the same time leads to higher energy trade. Limiting renewable energy sources can prevent the fall in diversity but it comes at a cost: higher energy trade. Thus in my thesis I identify a new type of energy security trade-off: lower energy trade versus higher energy diversity based on technological choices. This means that in the long-term, policy-makers may need to decide between higher import dependency and lower diversity of energy options. This choice may not be so stark if either nuclear energy is retained in the energy mix or very aggressive energy intensity improvements are pursued (Figure 5.1).

These findings also contrast with the literature which depicts energy security and climate change as either a utopian dream with small, decentralized and environmentally-benign energy systems or a nightmare, with resource wars, environmental destruction and economic calamity from energy systems (section 2.3). What my thesis shows is that low-carbon systems are by no means necessarily small, distributed and secure. Some actually have energy trade which is higher and more concentrated than in today's world. On the other hand, the business-as-usual development does indeed go in the direction of a nightmare, with global energy trade skyrocketing and the diversity of energy options of some regions and sectors remaining dangerously low or even dropping. Although the scarcity of fossil fuels is not in sight, the pattern of their extraction and trade may become very different from the one today, altering the global energy geography. With the U.S. poised to become a major energy exporter and uncertainty over China's energy balance, it is possible that the resource nationalism which dominated the global energy landscape during the first half of the 20th century could be reignited. Moreover, U.S. energy self-sufficiency combined with China's and India's dash for fossil resources may dramatically alter the presence of these major geopolitical players in such fossil-rich regions as Russia, Central Asia, the Middle East and parts of Africa. My research shows that climate policies would prevent such rapid shifts in geopolitical power balances.

## 6.5 Future work

My research is one specific contribution to developing a broad understanding of how *global* climate policies connect to *national* interests and capacities. In this thesis I have focused on one of the most important national interests: energy security. There are several avenues of future research: some related to the energy security line of inquiry, some to the broader view of national interests and some to the broader connection between climate futures and national capacities.

In terms of energy security, the relative importance of different energy technologies for different regions (and thus countries) could be investigated. In this thesis I identify how different technological constraints impact global energy security but I do not look at what that means at the regional level (except for discussing how future technological developments might impact oil and gas export revenues).

On a broader level, the research presented in this thesis might also serve as a good starting point for national energy security evaluations of climate policies or for extending the comparative analysis presented here to more countries. National energy security assessments often present a global analysis and storyline in which to frame the findings related to a specific country (see for example Australian Government Department of Resources Energy and Tourism (2011) or Wicks (2009)). Since this thesis provides a description of the context of global energy security under climate policies as well as a few national case studies, it could be useful in framing and interpreting nationally-constrained results.

Another line of inquiry related to the interaction between energy security and climate change would be to model scenarios in which regions pursue energy security policies and targets and see what this does both to the cost and feasibility of achieving climate targets. There are a handful of studies which model highly stylized energy security policies either in the form of import taxes (Huntington and Brown 2004), domestic reserve conservation (Turton and Barreto 2006) or the economic cost related to oil and gas imports (Bollen, Hers, and van der Zwaan 2010). However, no studies model more realistic national energy security policies. While it wouldn't be possible to model empirically observed national policies from every single country, it would be feasible to model stylized energy security policies of, for example the major economies.

A second line of modeling research would be to test feasibility of reaching climate targets if the U.S. does not forego its potential revenues from exporting fossil fuels. Climate stabilization targets would reduce the U.S.' oil imports but it would also eliminate the possibility of large fossil exports which could only partially be compensated by bioenergy exports. This has significant implications for the political viability of climate stabilization targets. In early climate negotiations, the major oil exporters were disruptive and demanded to be paid for any lost oil export revenue. While in principle the world could mitigate climate change without OPEC on-board, doing so without the U.S., one of the top emitters would be near impossible. Thus the geo-political resource implications for the U.S. could seriously impede progress on a climate deal. In addition, it may be promising for future studies of energy security to learn from the tradition of evaluating critical infrastructure vulnerability and emergency preparedenes exercises. This can be done with modeling exercises such as has been done with electricity (Lilliestam and Ellenbeck 2010; Frontier Economics 2011) or with stakeholders such as is already practiced by policy makers in relation to oil supply shocks (IEA 2012c). Although designed to deal with present energy systems, such approaches can probably be applied to modeled systems of the future.

Finally, there is a need to analyze how global climate futures connect to interests and capacities of individual countries to follow energy transition pathways. National motivations and capacities will likely constrain what global energy futures are feasible. For example, only a handful of the more than 50 countries which are planning to build nuclear power plants has the capacity to do so (Jewell 2011a). Incorporating these national realities into global futures will be key for gaining support and momentum for a global energy transformation. Integrating nationally-relevant perspectives on energy security with the global climate scenarios done in this thesis is a step in the direction of this more ambitious research agenda.

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# Appendix: Regional mapping

Dividing the world into regions is not always consistent across the models. In multi-modeling scenarios exercises conventions on regional definitions are usually followed. These conventions were followed in all trade calculations. For the major economies analysis, more specific mappings were provided from most models.

In the *Global Energy Assessment* I worked with 11 regions analyzed in MESSAGE model:

**Sub-Saharan Africa:** Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe

**Centrally planned Asia and China:** Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam

**Central and Eastern Europe:** Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, The former Yugoslav Rep. of Macedonia, Latvia, Lithuania, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia

**Former Soviet Union:** Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan (the Baltic republics are in the Central and Eastern Europe region)

**Latin America and the Caribbean:** Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela)

**Middle East and North Africa:** Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen

**North America:** Canada, Guam, Puerto Rico, United States of America, Virgin Islands Pacific OECD: Australia, Japan, New Zealand

**Other Pacific Asia:** American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa

**South Asia:** Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka

**Western Europe:** Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom

In *LIMITS* project I worked with the following definition of 10 regions harmonized across several models:

**NORTH_AM:** Canada and the United States of America

**EUROPE:** 27 E.U. member countries and Norway, Switzerland, Iceland, Turkey

**PAC_OECD:** Australia, New Zealand, Japan, Republic of Korea, Fiji, French Polynesia, Guam, Japan, New Caledonia, New Zealand, Samoa, Solomon Islands, Vanuatu

**REF_ECON:** Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Serbia, Tajikistan, TFYR Macedonia, Turkmenistan, Ukraine, Uzbekistan

**CHINA+:** China (PR), China Hong Kong SAR, China Macau SAR, Republic of China (Taiwan),

**INDIA+:** Bangladesh, India and Pakistan

**REST_ASIA:** Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Democratic People's Republic of Korea, East Timor, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Singapore, Sri Lanka, Thailand, Viet Nam

**AFRICA:** Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lebanon, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Zambia, Zimbabwe

**MIDDLE_EAST:** Algeria, Bahrain, Egypt, Morocco, Iran, Iraq, Israel, Jordan, Kuwait, Libyan Arab Jamahiriya, Morocco, Oman, Quatar, Tunisia, Syrian Arab Republic, United Arab Emirates, Yemen

**LATIN_AM:** Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela

**REST_WORLD:** the remaining countries

In *ROSE* I analyzed the following 9 regions were used and harmonized across several models:

**OAS:** East and South Asia: Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Democratic People's Republic of Korea, East Timor, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Singapore, Sri Lanka, Thailand, Viet Nam

**IND:** India

**EUR:** European Union + Central and Eastern Europe

**CHN:** China

**LAM:** Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela

**MEA:** Algeria, Bahrain, Egypt, Morocco, Iran, Iraq, Israel, Jordan, Kuwait, Libyan Arab Jamahiriya, Morocco, Oman, Quatar, Tunisia, Syrian Arab Republic, United Arab Emirates, Yemen

**FSU:** Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan

**ROW:** South Korea, South Africa and Australia

**USA:** United States of America

**JPN:** Canada, Japan and New Zealand

**AFR:** Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lebanon, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa,

Sudan, Swaziland, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Zambia, Zimbabwe