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Jessica Jewell [1,2]*, Aleh Cherp [2], Vadim Vinichenko [2], Nico Bauer [3], Tom Kober [4], David McCollum [1], Detlef P. van Vuuren [5,6], Bob van der Zwaan [4]

Affiliation:

[1]: *International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria*

[2]: *Central European University (CEU), Central European University, Nador u. 9, 1051 Budapest, Hungary*

[3]: *Potsdam Institute for Climate Impact Research (PIK), P.O. Box 60 12 03, 14412 Potsdam, Germany*

[4]: *Energy research Centre of the Netherlands (ECN), Westerduinweg 3, 1755 LE Petten, The Netherlands*

[5]: *Utrecht University (UU), Utrecht, The Netherlands*

[6]: *PBL Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands*

* Corresponding author: jewell@iiasa.ac.at

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Abstract

This paper assesses energy security in three long-term energy scenarios (a business as usual development, a projection of Copenhagen commitments, and a 450 ppm stabilization scenario) as modeled in six integrated assessment models: GCAM, IMAGE, MESSAGE, ReMIND, TIAM-ECN and WITCH. We systematically evaluate potential long-term vulnerabilities of vital energy systems of four major economies: China, the European Union, India and the U.S., as expressed by several characteristics of energy trade, resource extraction, and diversity of energy options. Our results show that climate policies are likely to lead to significantly lower global energy trade and reduce energy imports of major economies, decrease the rate of resource depletion, and increase the diversity of energy options, particularly in the especially vulnerable transportation sector. China, India and the E.U. will derive particularly strong benefits from climate policies, whereas the U.S. may forego some opportunities to export fossil fuels in the second half of the century.

1   Introduction

Energy security is an important driver of energy policies. This means that the acceptability of low-carbon policies and international climate regimes will in part depend on their impacts on national energy security—particularly of the major emitters. Thus it is important to evaluate energy security implications of long-term climate policies.

There have been several studies addressing long-term energy security in global energy and climate scenarios. Some of these studies focus only on one energy sector (e.g. electricity in Grubb et al. (2006), oil in Rozenberg et al. (2010)) or a single region or country (e.g. the E.U. in Costantini et al. (2007) and Criqui et al. (2012), the UK in Grubb et al. (2006) and India in Shukla (2011)). Some studies only address selected energy security concerns (e.g. diversity in Grubb et al. (2006), energy resource scarcity in Turton and Barreto (2006) and Rozenberg et al. (2010), and imports in Criqui & Mima (2012). Most of these 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.

There is also a range of studies which analyze potential interactions between energy security and climate mitigation policies (Huntington & Brown, 2004; Nel & Cooper, 2009), including in terms of quantifying their co-benefits (Bollen, Hers, & van der Zwaan, 2010; McCollum, Krey, & Riahi, 2011; McCollum et al., 2013).[1] The goal of these studies dictates their excessively stylized representation of energy security (e.g. through monetization or using highly aggregated metrics) which can provide useful insights into potential synergies and tensions between climate and

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[1] These studies also quantify the climate policy co-benefits with respect to air pollution.

energy security agendas but are not sufficient to understand nuanced impacts of climate policies on the future energy security landscape.

Kruyt et al (2009) present one of the most comprehensive and transparent approaches to evaluate future energy security. They draw on a wide range of indicators to measure energy security in the E.U. and at the global level in 1970-2050 in both a baseline and climate stabilization scenario modeled in the TIMER energy system model (MNP, 2006). This study develops Kruyt et al.'s approach in several important ways. First, instead of proceeding from a set of indicators, it relies on a systematic energy security assessment framework (as proposed in (Cherp & Jewell, 2011a; 2013)) which allows us to take into account both generic and context-specific aspects of energy security. It uses only those indicators which are relevant and credibly modeled in integrated assessment models (and thus omits for example political stability). Second, it expands the scope of energy security from 'security of supply' to 'vulnerability of vital energy systems'. Third, our study expands the geographic focus of Kruyt et al from just the E.U. to include three other major economies: China, India and the U.S.. It also expands the analysis to include several scenarios from six different integrated assessment models (IAMs). This comparative approach (both between models and regions) allows us to identify uncertainties as well as potential regional winners and losers of climate policies.

The remainder of this paper is organized as follows. Section 2 explains the methodology of our study. In Section 3 we summarize the findings of the global analysis and then proceed to discuss future energy security for the four major economies under a baseline and different climate policy scenarios generated by six models that participated in the LIMITS (Low climate IMpact scenarios and the Implications of required Tight emission control Strategies) project (http://www.feem-project.net/limits/). The Discussion and Conclusions sections summarize our argument and compare it to findings of other studies.

2 Scope and Method

2.1 Major economies
This article focuses on four major economies: the E.U., the U.S., China, and India. In 2010, these economies represented 60% of the World's GDP and almost 50% of the World's CO_2 emissions (Table 1).

Table 1 GDP and Emissions of Major economies.

	GDP (2010 billion$)			CO_2 emissions (GtCO$_2$/yr)		
	2010	2030	2050	2010	2030	2050
China	4 (7%)	6-19 (9-16%)	14-37 (14-18%)	7 (20%)	10-17 (23-31%)	11-21 (21-31%)
E.U.	15 (27%)	17-25 (20-25%)	20-37 (15-19%)	4 (11%)	4-5 (8-11%)	4-6 (6-9%)
India	1 (1%)	3-6 (4-6%)	6-22 (6-12%)	1 (2%)	3-5 (7-11%)	6-10 (11-16%)
U.S.	14 (25%)	19-22 (19-26%)	25-34 (14-24%)	5 (14%)	5-7 (11-16%)	4-8 (8-14%)
Total	34 (60%)	45-72 (53-73%)	65-130 (49-73%)	17 (47%)	22-34 (49-69%)	25-45 (46-70%)
World	54 (100%)	71-115 (100%)	103-203 (100%)	35 (100%)	44-55 (100%)	54-73 (100%)

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

2.2 Energy security

We define energy security as "*low vulnerability of vital energy systems*", which is in line with mainstream definitions of energy security e.g. (Yergin, 1988) as well as the Global Energy Assessment (GEA) (Cherp et al., 2012; Riahi, Dentener, et al., 2012a). The GEA approach (conceptually explained in Cherp and Jewell (2011a,b; 2013)) has provided the methodological basis for our analysis as the most recent and the most comprehensive authoritative study of global energy security. This definition does not refer to any specific sectors or concerns and thus is flexible to be applicable to future energy systems, which may be radically transformed as a result of long-term climate mitigation policies. *Vital energy systems* are those energy systems (energy resources, technologies and uses linked together by energy flows), which are essential to support critical societal functions. Vulnerability of vital energy systems is a security concern because it may lead to a disruption of existential activities, and thus to social, political or economic instability. Incidentally, such instability may hinder the international joint effort to mitigate dangerous climate change framing another crucial aspect of the interaction between climate change and energy security. Vulnerabilities of vital energy systems are combinations of their exposure to risks and their resilience, i.e. ability to respond to disruptions. Thus, our analysis starts with (a) identifying vital energy systems and (b) assessing their vulnerabilities under long-term energy scenarios.

Our starting point for the identification of *vital energy systems* is GEA's analysis of the present-day energy security which delineates vital energy systems according to sectoral and geographic boundaries (or scales). Thus, it assesses the *global* oil, gas and coal markets and the nuclear fuel cycle as well as *national* energy systems sub-divided into energy sectors: primary energy sources, electricity and other energy carriers, and energy end-uses: transportation, industry and residential and commercial sector (Cherp et al., 2012). We adjust the GEA's sectoral scope to account for configurations of energy systems, which may emerge under long-term scenarios. Similarly to GEA, we analyze the global fossil fuel markets, but also potentially emerging global markets for synthetic fuels, bioenergy, and hydrogen. In addition to the global level, we analyze the national systems of four major economies with a focus on primary energy supply (TPES), tradable fuels, secondary energy (electricity), end-use (transport) and energy exports. Our focus on electricity as a vital energy system is justified by its increasing importance under climate stabilization scenarios and our focus on the transport sector is explained by the fact that it is presently the most vulnerable energy end-use (Cherp et al., 2012). Energy exports, or what some authors refer to as "demand security", is a vital energy system for many countries whose economies rely on the income from energy exports.

With respect to *vulnerabilities* of vital energy systems we follow the GEA's approach distinguishing between three perspectives on energy security identified and described by (Cherp & Jewell, 2011b). The rooting of these perspectives in generic 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 decisive in this century as well.

- The first perspective, *sovereignty*, views risks as hostile intentions of foreign actors. It is rooted in such historic events as energy embargoes by powerful actors. It analyses energy security in terms of the power balance, the space for maneuver and above all the degree of sovereign control over energy systems.

- The second perspective, *robustness*, views risks as disruptive natural or technical events. It is rooted in experience of electricity blackouts, infrastructure failures and resource scarcity. It analyses energy security in terms of probabilities of such disruptions reflected, inter alia in resource scarcity and demand growth. 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. Resource scarcity (even only in perception) leads to speculation, price volatility and overall uncertainty.

- The third perspective, *resilience,* views risks as largely uncertain and hence emphasizes the ability of energy systems to recover from potential disruptions of any nature. It has its roots in dealing with price volatility and other unpredictable events. In the resilience perspective, energy security is most often analyzed in terms of diversity of energy options (Stirling, 1994; 2010).

In order to systematically assess energy security under long-term energy transitions we analyze potential vulnerabilities of each of the vital energy systems from each of the three perspectives as shown in Table 2. Each cell of the matrix represents a distinct energy security concern (such as 'oil import dependence' or 'transport energy diversity').

These concerns can be reflected in *indicators* of energy security, which deserve a special brief discussion because much of the recent energy security literature has been focused on proposing hundreds of such indicators, sometimes aggregated in sophisticated indices (for a review of this literature see Kruyt et al. (2009), Jewell (2013) or Cherp and Jewell (2011a). The indicators used in this study have been proposed by Jewell et al. (2012) and are largely similar to those used in previous studies (e.g. Kruyt et al. (2009), Turton and Barretto (2006), and Grubb et al. (2006)). A distinct feature of our analysis is that we systematically apply these indicators to explore each of the perspectives on vulnerabilities of vital energy systems at the global level and in each of the major economies under several scenarios as represented by different models. Not all indicators could be meaningfully evaluated for every model, particularly because trade was not systematically modeled for all fuels and carriers (see Table 3 and related discussion). The energy security concerns and related indicators are summarized in Table 2 and the detailed indicator formulas are provided in the Appendix (see Supplementary materials).

Table 2 Energy security concerns explored in this study

Vital energy systems	Sovereignty	Robustness	Resilience
Total Primary energy supply (TPES)			Diversity of primary energy sources at the global and regional level
Tradable fossils: oil and oil products gas, coal	Global trade Regional import dependence Regional exports	Resource extraction as share of resources and reserves	
Other tradable energy: biofuels, hydrogen			
Electricity			Diversity of primary energy sources in electricity
Transport			Diversity of primary energy sources in transport

2.3 Scenarios

Our analysis is structured to look at three different types of climate policies using the scenarios developed in the LIMITS project. The scenarios, which are referred to throughout the paper are described here; a more detailed description can be found in Kriegler et al. (n.d.), in this issue.

- The first scenario has no climate policies where the present trends of energy systems evolution continue for the rest of the 21st century. It is referred to as the 'Baseline scenario' (**Baseline**).

- The second scenario projects the most ambitious interpretation of Copenhagen emission reduction pledges over the 21st century. It is referred to as the 'StrPol scenario' (**StrPol**). This scenario is similar to the IEA's "New Policy Scenario".

- The last scenario is identical to the stringent policy scenario until 2020, but introduces a global carbon tax to reach a 450 ppm CO_2-eq greenhouse gas concentration in 2100. It is referred to as the '450 scenario' (**450**).[2]

The StrPol and the 450 scenarios are jointly referred to as the 'climate policy scenarios'. It should be noted, however, that they lead to very different climate results. While the latter most likely leads to an increase of global mean temperature of less than 2°C, the former is more likely to reach a temperature increase of around 3°C by the end of the century.

In this scenario exercise models vary in their GDP and population baselines, energy demand and supply sectors, GHG emissions sources and techno-economic assumptions. In 2050, Gross World Product varies between U.S.$_{2005}$ 124 trillion and 186 trillion and world population ranges between 8.9 and 9.3 billion (for more discussion and details see Table 1 and the supplementary material in Kriegler et al., (2013, this issue) as well as the discussion of regional trends in energy consumption in van Sluisveld et al (2013, this issue)). The key assumptions, however, are the same within a given model between different scenarios. Consequently, in this article the bulk of our conclusions come from comparing different scenarios within the same model to determine how climate policies impact global energy security and the energy security of four major economies. Using this multi-model approach allows us to identify the conclusions which are robust under a range of modeling frameworks and assumptions.

2.4 Models

This paper includes results from 6 models: GCAM (Calvin, n.d.), IMAGE (MNP, 2006; van Vuuren, 2007), MESSAGE (Riahi, Grubler, & Nakicenovic, 2007), ReMIND (Leimbach, Bauer, Baumstark, & Edenhofer, 2009; Luderer, Leimbach, Bauer, & Kriegler, 2011), TIAM-ECN (Keppo & van der Zwaan, 2011; van der Zwaan, Keppo, & Johnson, n.d.), and WITCH (Bosetti, De Cian, Sgobbi, & Tavoni, 2009; Bosetti, Galeotti, & Lanza, 2006). We only analyze trade for the five models listed in Table 3.

Table 3 Trade in fuels and energy carriers reported by different models

	Primary energy sources					Secondary energy carriers				
	Crude oil	Natural gas	Coal	Uranium	Bio-mass	Oil products	Electricity	Bio-fuels	Hydrogen	Syn-fuels
MESSAGE	X	X	X			X	X	X	X	X
IMAGE	X	X	X	X	X			X	X	
TIAM-ECN	X	X	X		X	X	X	X		
ReMIND	X	X	X	X	X					
WITCH	X	X	X							

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[2] This is the StrPol-450 scenario in the LIMITS project.

3 Results

3.1 Global context

3.1.1 Global trade

Fgure 1 displays global energy trade differentiated by fuel and carrier for 2010, 2050, and 2100. It shows that the trade in the Baseline scenario is projected to significantly grow as compared to the 2010 level. All models show that climate policies decrease the total energy trade as well as the trade in each fossil fuel. In IMAGE, MESSAGE and TIAM-ECN oil remains the most important traded fuel through 2050. By 2100, however, most models project coal as the dominantly traded fuel in the Baseline scenario. Coal trade is especially high in ReMIND and WITCH in 2050 and in ReMIND, MESSAGE and IMAGE in 2100 due to these models assumptions of regional endowments of coal and the demand dynamics. With the 450 scenario, 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 due to a higher penetration of coal-based CCS.

For oil (including oil products), there is a small decrease in trade in all models by 2050 between the Baseline and 450 scenario and a larger decrease by 2100. 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. The exception is TIAM-ECN where the transport sector only starts to transform after 2050 when hydrogen comes in to replace oil (discussed in Section 3.1.3).

The decrease in natural gas trade under the 450 scenario is lower than in case of the other fossil fuels. Most models show a decrease in natural gas trade under climate policies, however in MESSAGE, it rises with the "Reforming economies" region (which is mostly 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 (IMAGE and ReMIND) and hydrogen (MESSAGE). These increases do not offset the overall decline in energy trade as a result of climate policies. The rise in bioenergy trade is particularly pronounced in IMAGE and ReMIND due to flexible bioenergy markets and weak constraints on biomass production.

Figure 1. Global energy trade in five models and three scenarios in 2050 and 2100
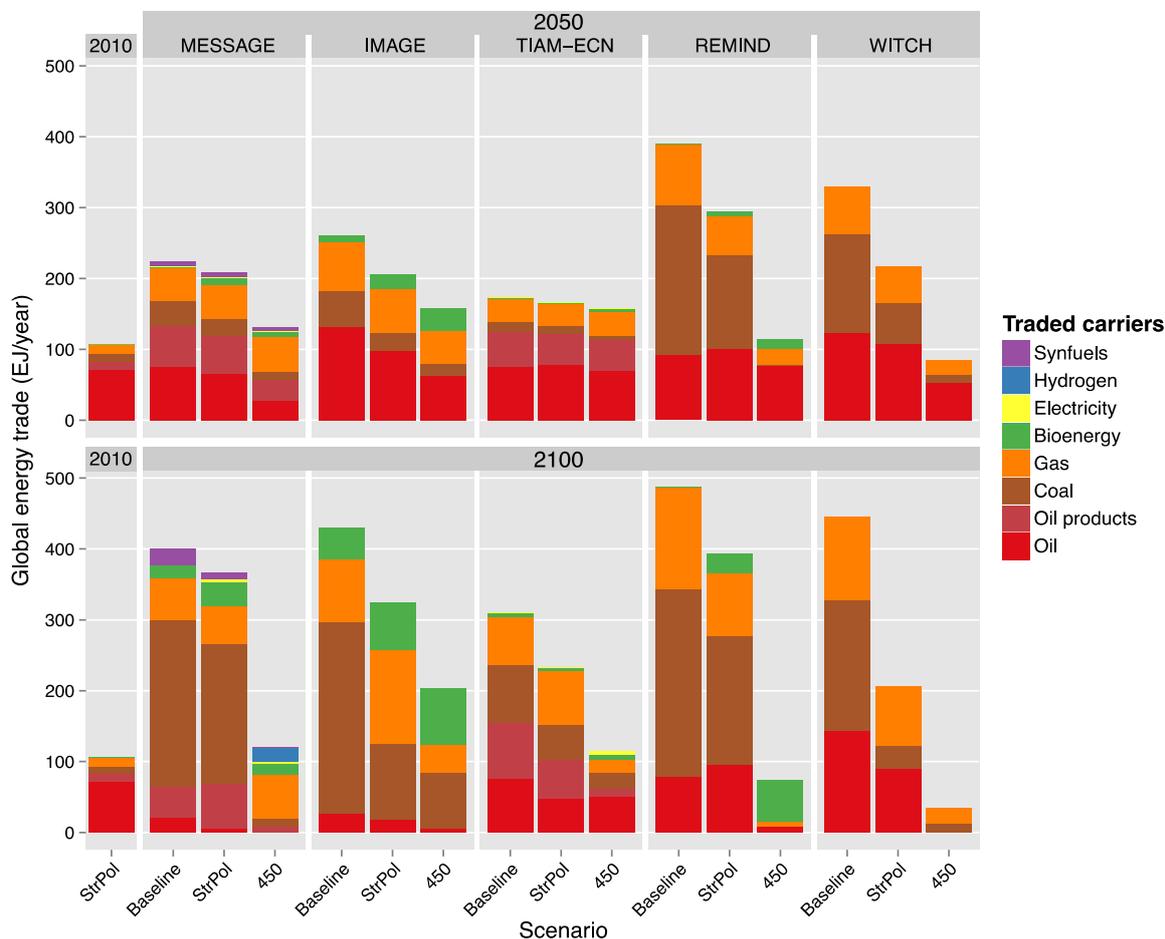
Note: Global trade for the year 2010 is taken from MESSAGE since this model trades the most fuels and carriers which are relevant to current data.

3.1.2   Resource extraction

Table 4 shows the global cumulative extraction of fossil fuels in the 21st century compared to the reserves and resource (R&R) as estimated in the Global Energy Assessment (Rogner et al., 2012). The R&R estimates in the Global Energy Assessment are compiled from the main organizations which publish such data (British Petroleum, the Canadian Association of Petroleum Producers, the International Energy Agency, the German Federal Institute for Geosciences and Natural Resources (BGR), and the U.S. Geological Survey (USGS), the World Energy Council) as well as key academic papers on the topic. Thus the range of R&R in Table 4Table 4 and Table 6 represents the range of estimates in the literature. It is important to note though that the R&R estimates do not include "additional occurrences" which are either not economic and/or undiscovered (see Figure 7 in Rogner, 1997).[3] However, most

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[3] The R&R estimates also exclude gas hydrates and are conservative in their estimate of unconventional oil.

models *do* include such additional occurrences, which explains why, in several cases in Table 6, the "proportion of depletion" exceed 100%.

Table 11 in the Supplementary material synthesizes the references and main assumptions for all the models discussed in this paper.

As shown in Table 4, climate policies result in a notable decrease in the oil, coal and gas extraction volumes in all models. The exception is TIAM-ECN where gas extraction in StrPol is the highest followed by the 450 scenario and then by the Baseline. In TIAM-ECN's StrPol scenario coal is substituted by natural gas leading to an increase of the gas extraction. However, the emissions of natural gas technologies (even with CCS) are too high to support the 450 scenario in this model and therefore the cumulative gas extraction is relatively lower as compared to the StrPol scenario.

Table 4 Oil gas and coal extraction in the three scenarios

	Extraction 2010–2100 ZJ *(proportion of depletion)*				*Reserves + Resources (R&R) ZJ*
	Baseline	StrPol		StrPol-450	
Oil	16 – 25 *(47% - 106%)*	14 – 20 *(41% - 82%)*		8 – 13 *(23% - 61%)*	*24 – 34*
Gas	16 – 27 *(8% - 38%)*	15 – 21 *(7% - 29%)*	8 – 17 *(4% - 24%)*	*72 – 205*
Coal	26 – 35 *(6% - 11%)*	11 – 23 *(2% - 7%)*	3 – 12 *(1% - 4%)*	*308 – 456*

Notes: Figures in parentheses 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). Models have their own resource availability and cost curves which are synthesized in

Table 11 in the Supplementary material.

From an energy security perspective, the implication of these different extraction volumes are most obvious for oil. In the Baseline scenario, between 50% and 100% of available resources are extracted, which would inevitably result in anxiety over scarcity. In the 450 scenario, only between 23% and 61% of oil resources are extracted which would arguably lead to less concerns.

3.1.3 Global diversity

Figure 2shows the global diversity of primary energy sources in the first half of the century. The diversity of TPES in the Baseline scenario through 2050 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 to between 1.7 and 1.9 by 2050 in the case of the 450 scenario or 1.6-1.7 in the case of StrPol. This occurs because low-carbon technologies are rapidly introduced in energy systems and start balancing out the dominant fossil fuel ones. This pattern is even more pronounced in the diversity of electricity systems.

Figure 2 also 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, oil trade is likely to decline and the diversity of transport energy sources rises but models differ in their depiction of when and how this will happen and in how different the diversity is between the Baseline and the climate policy scenarios. No models show a significant difference in transportation diversity between the Baseline and climate policies by 2020. Starting in 2030, the transportation diversity in the Baseline and climate policy scenarios diverges in MESSAGE and IMAGE but in GCAM, ReMIND and TIAM-ECN the diversity of energy options in transport rise at a similar rate in this period.

In MESSAGE and IMAGE, the Baseline scenario is characterized by a continued dominance of oil through mid-century (over 90% of transportation demand from oil through 2050). In contrast, the 450 scenario in these two models shows a diversification away from oil to biofuels in IMAGE and biofuels and electricity in MESSAGE. The penetration of both electricity and biofuels into the transport sector in MESSAGE means that the diversity of the sector rises by to over 1.5 by 2050 versus remaining under 1.5 throughout mid century in the Baseline. In IMAGE, biofuel penetration leads to a diversity of 1.0 by 2050 versus 0.6 in the Baseline.

The other three models, GCAM, ReMIND and TIAM-ECN, display similar diversity trajectories in both the Baseline and climate policy scenarios. The rise in transport diversity in the Baseline is driven by an increase in liquefied coal in ReMIND, an increase in liquefied coal and biofuels in TIAM-ECN, and liquefied coal, biofuels, and electricity in GCAM. ReMIND and TIAM-ECN show a big difference in energy sources used in transportation in the 450 scenario: for ReMIND the sector experiences increasing penetration of biofuels and electricity; for TIAM-ECN, the transportation sector shows increasing penetration of and eventual domination by hydrogen, however most of this happens only in the second-half of the century (this pattern is described in (van der Zwaan et al., n.d.). In contrast, GCAM depicts more similar transportation sectors in the Baseline and climate policy scenarios by 2050; the Baseline transportation sector has relatively less biofuels and electricity and more liquefied coal but these differences are far less pronounced than in the other four models.

In sum, two of the five models (IMAGE and MESSAGE) depict diversity gains in the transportation sector by 2050 resulting from climate policies. The other three models (GCAM, ReMIND and TIAM-ECN) depict almost no difference between the diversity trajectory under the Baseline and those under climate policies. This is despite the fact that, the energy mix in the transportation sector in two of these three models (ReMIND and TIAM-ECN) is drastically different between the Baseline and climate policy scenarios in 2050.

Figure 2 Global diversity of primary energy sources in 2010-2050
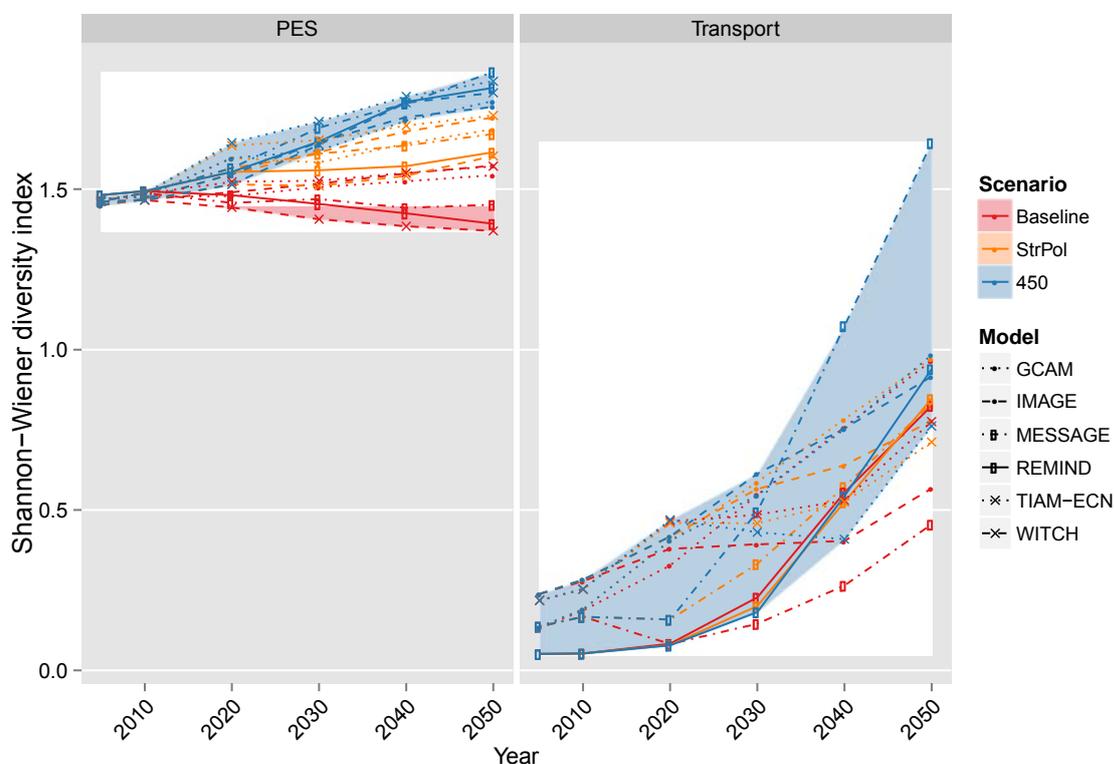
Notes: Diversity is calculated using Shannon Wiener diversity index (Shannon & Weaver, 1963). As described in the Supplementary material, the diversity represents diversity between the following sources: coal, oil, gas, bioenergy, nuclear energy, hydropower, wind, solar, and geothermal. The transport diversity excludes WITCH.

In the second half of the century, the range between the diversity for models rises. It is also more difficult to make sense of diversity indices calculated for the very distant future. Imagine the Hapsburg Empire a century ago, before World War I. What technological categories would we consider distinct for transport? Horses, bicycles, and trains? Maybe in 100 years there will be five different types of solar power, sufficiently distinct to become different categories for the purpose of diversity analysis. Nevertheless, there are a few trends which should be noted since the end of the century is really when the low-carbon transition would come to fruition. In mid-century, aspects of the old and the new system co-exist so in many cases the diversity dips slightly in the latter half of the century. In electricity, ReMIND shows the biggest dip as the electricity system comes to be dominated by solar electricity (both photovoltaic and concentrated solar power).

3.2 Energy imports and exports in 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[4], some

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[4] 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 (Cherp et al.,

forms of biomass) they at the same time limit the use of domestic coal, so in the short term there is only a small difference in import dependence between the Baseline and climate policy scenarios. The one exception is the rapid development of coal trade in ReMIND in the Baseline.

Over the long-term, however, climate policies have a significant impact on net import dependence in the major economies. The results for China, the E.U., and the U.S., are somewhat different between models, due to the sensitivity of trade patterns to regional assumptions such as resource cost curves and emphasizes the significant uncertainties of future energy trade patterns.

3.2.1   China

China had been up a net exporter of energy until the 21st century, a net oil exporter until 1993 and a net coal exporter until 2009 (British Petroleum, 2012; World Bank, 2012). But most models depict China as a net *importer* of coal and all other tradable fuels throughout the 21st century in all scenarios (Figure 3). A notable exception is the Baseline and the StrPol scenarios in MESSAGE where China exports between 1,500-1,700 EJ of coal over the twenty-first century (worth four to five trillion dollars or about 0.2% of the country's GDP over that time). These coal exports are driven by China's cheap coal along with the high demand and limited domestic supply in India.

In IMAGE, ReMIND and WITCH China's cumulative energy imports are significantly lower (by 2500-8800 EJ or by 40-80%) in the 450 scenario than in the Baseline. These import reductions occur primarily in the 2nd half of the century. In ReMIND and WITCH, this decline is primarily due to a drop in coal imports; for IMAGE, the drop is distributed between all three fossil fuels. These findings are in line with the composition of global energy trade in each of these models. This reduction of cumulative imports translates into lower import dependence of up to 11% in IMAGE, 38% in WITCH and 61% in ReMIND. In contrast to these three models, in TIAM-ECN China's cumulative imports are approximately the same in all three scenarios.

In MESSAGE, under the 450 scenario China foregoes the opportunity to export coal: its coal exports drop to some 400 EJ over the entire century and China becomes a net energy importer. In ReMIND in the 450 scenario, China exports almost 700 EJ of bioenergy because of a decrease in population (after peaking) and the large availability of cropland. Interestingly, in the same scenario in IMAGE the country *imports* about two-thirds that amount due to the model's stricter constraints on the production of bioenergy. Thus whether China imports or exports bioenergy is dependent on population and cropland assumptions.

In summary, three out of the five models project significant reduction of China's import dependence as a result of climate policies. One model predicts a reduction in Chinese exports of coal as a result of climate policies. 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 correspondingly no impact of climate policies on China's energy trade.

2012) since nuclear power plant refueling typically provides fuel for two to three years (Nelson & Sprecher, 2008) and can even be stockpiled for up to ten years (IAEA, 2007).

Figure 3 Cumulative energy imports to (positive) and exports from (negative) China to 2050 and 2100
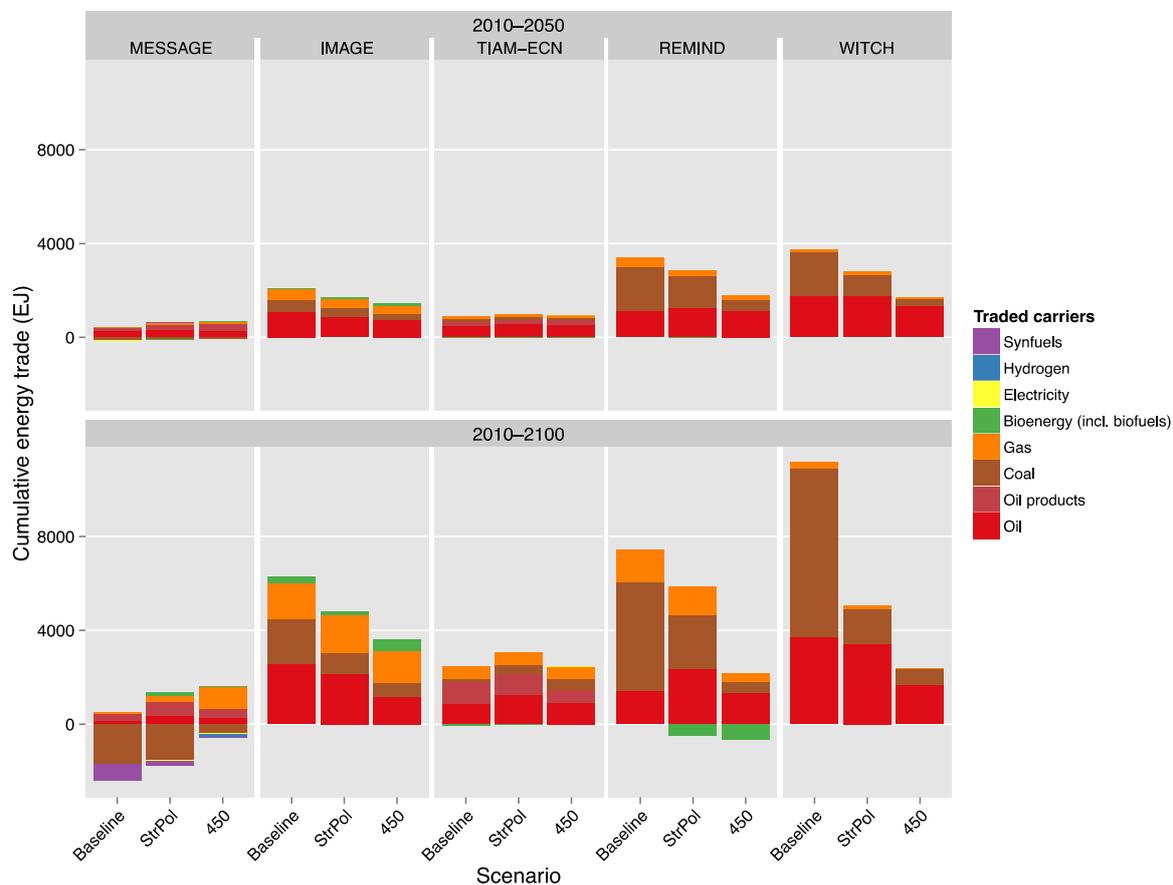

3.2.2 India

Among the major economies, India has the least fossil energy resources. 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 scenario (Figure 4).

In the Baseline scenario India imports between 4,500 and 9,800 EJ (or between 40% – 70% of its TPES). Its imports more than halve in the 450 scenario to between 1,400 and 4,500 EJ (or 20% – 50% of TPES) due to a shift away from imported fossil fuels to domestic renewables and higher energy efficiency. In IMAGE, climate policies have a smaller impact on energy imports in India because while fossil imports halve in the 450 scenario, bioenergy imports triple to over 1,300 EJ. 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 assumes both peaking population and high agricultural yields, depicts the country as a modest net-exporter of bioenergy (~300 EJ in the second half of the 21st century).

*Figure 4 Cumulative energy imports to India to 2050 and 2100*
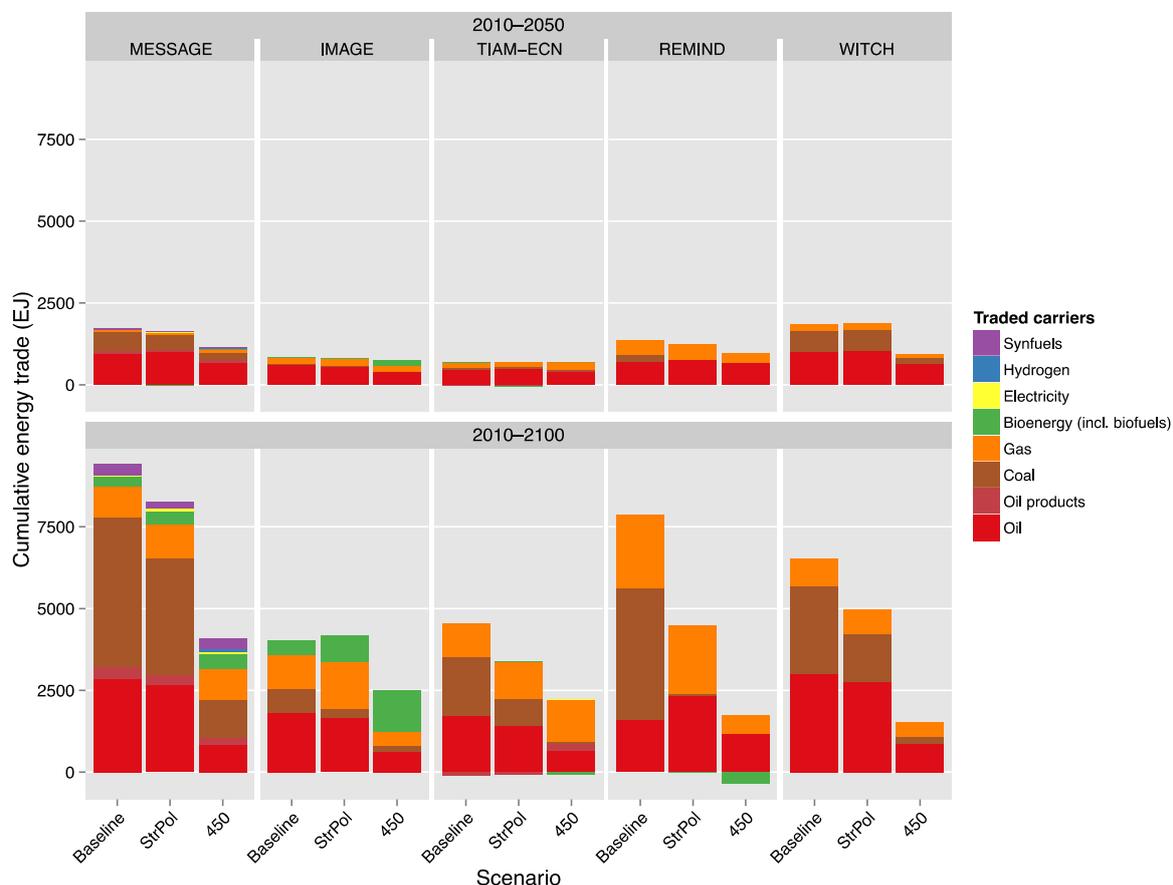
3.2.3 E.U.

In 2010 the E.U. imported about 50% of its TPES (World Bank, 2012). Most models show continuous import dependency over the 21st century in the Baseline scenario Figure 5. In MESSAGE, ReMIND and TIAM-ECN, the E.U. imports between 4,000 and 4,600 EJ in the Baseline (or about 48–55% of its TPES). In contrast, IMAGE and WITCH depict the region as a net exporter of coal in the second half of the century (ranging between some 400 EJ in IMAGE to 1,300 EJ in WITCH). This makes the E.U.'s net-imports less than half of the level of the other three models (between 1,500 and 1,700 EJ or about 20% of the region's TPES). These exports of lower-quality and more expensive coal are triggered in IMAGE by the depletion of cheaper coal reserves worldwide and in WITCH by high Chinese demand for coal.

In the three models with high import dependence (MESSAGE, REMIND and TIAM-ECN) the 450 scenario decreases net imports over the 21st century in these four models by between 20% and 52% (to between 23% and 41% of the region's TPES). In WITCH and IMAGE, similar to other models, climate policies lead to a modest decrease in net energy imports in the E.U. in the first half of the century. However, since in the second half of the century under the Baseline these two models depict the E.U. as a modest coal exporter, combined with the efficiency gains of the 450

scenario, the scenario actually leads to a slight increase in import dependence in comparison to the Baseline. Similarly to India and China, in the 450 scenario in ReMIND under climate policies the E.U. exports ca 400 EJ of bioenergy (due to peaking population, high yields and good transport infrastructure) whereas in IMAGE the E.U. *imports* about 500 EJ of bioenergy. Interestingly the E.U. actually imports bioenergy in ReMIND and MESSAGE under the StrPol scenario due to the region's high demand for biofuels under the ambitious Copenhagen targets.

Figure 5 Cumulative imports to the E.U. to 2050 and to 2100
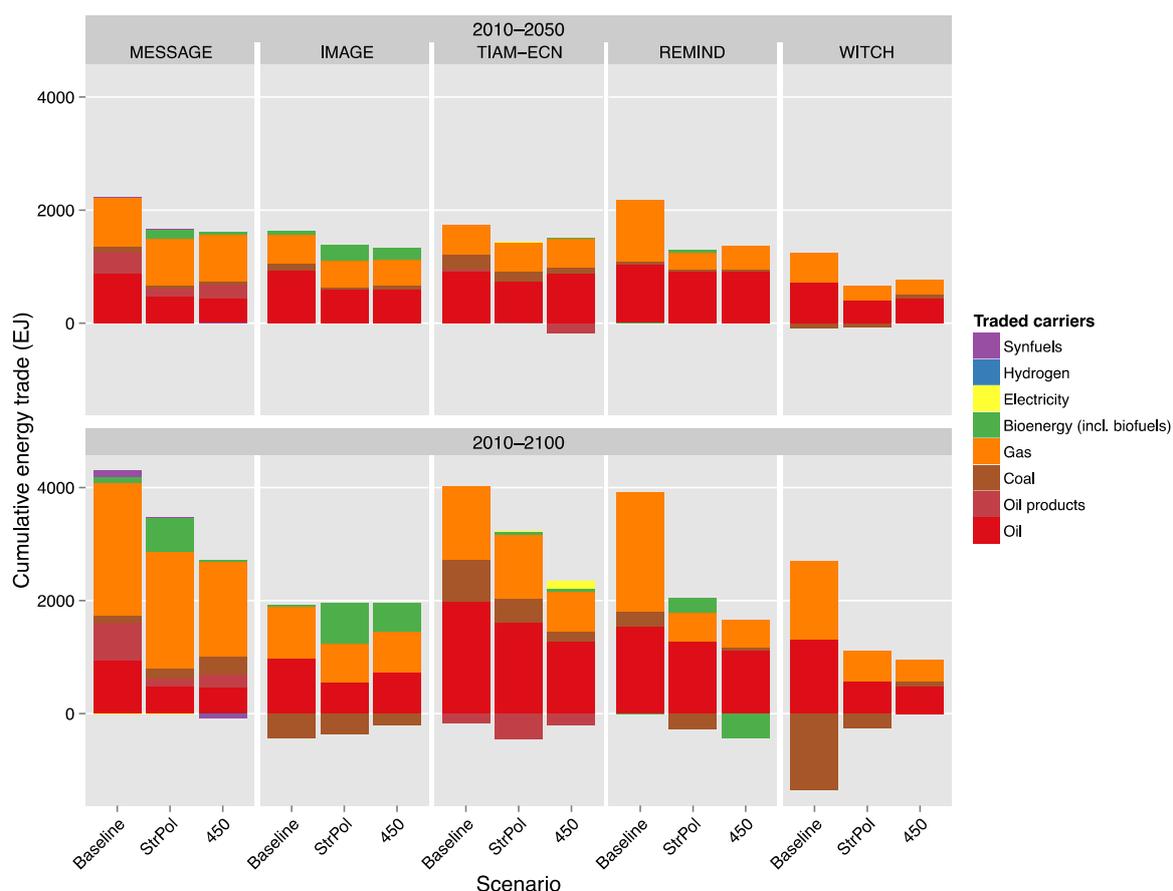
3.2.4   U.S.

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). However, with the development of drilling technologies for unconventional oil and gas the U.S. could become nearly energy self-sufficient by 2035 and even a net exporter of gas (International Energy Agency, 2012a). In all models except TIAM-ECN, the U.S. eventually becomes a net energy exporter in all scenarios, however, the timing of this development varies between models (Table 5). This is in line with the IEA findings from the New Policies Scenario, which is closest to our StrPol scenario.

Table 5 The U.S. becomes self-sufficient[a] by mid-century in most models in StrPol

| Model	Year	Milestone	Cumulative exports
WITCH	2025	Self-sufficient	coal (270 EJ) gas (220 EJ)
ReMIND	2030	Becomes a major net-energy exporter	coal (5,900 EJ) gas (450 EJ) oil (260 EJ)
MESSAGE[b]	2060	Self-sufficient	coal (580 EJ) gas (30 EJ)
IMAGE	2070	Self-sufficient	coal (720 EJ) gas (210 EJ) bioenergy (300 EJ)
TIAM-ECN	2100	Net energy importer for most of the 21st century	coal (210 EJ)
IEA WEO[c]	*2035*	*Self-sufficient*	*coal, gas, and bioenergy*

Note: [a]"Self-sufficiency" is defined as when a country imports less than 5% of its TPES. [b]In MESSAGE these results relate to a region which includes the U.S. and Canada. [c]Reference for these data: (International Energy Agency, 2012a).

Climate policies do not change this pattern but generally reduce the amount of energy exports in the later part of the century Figure 6

The effect of climate policies is the strongest in ReMIND which models the largest amounts of exports for the U.S. (8,600 EJ of coal in the Baseline) which drops by 30% in StrPol and virtually disappears in the 450 scenario. In IMAGE, the export volumes (2,300 EJ in the Baseline) are lower but the drop in coal exports is 70% and 75% respectively in StrPol and the 450 scenarios. In TIAM-ECN, the U.S. only becomes self-sufficient at the very end of the 21st century because its oil imports throughout the 21st century are larger than its coal exports. TIAM-ECN models more stable long-term production of low-cost oil in the Middle East which provides a source for these U.S. oil imports. This is in contrast to other models which indicate a rapid peak and decline of conventional oil production. In sum, the U.S. would lose the most among the major economies in terms of forgone resource revenues.[5]

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[5] For a discussion of the export revenues of the Middle East and Russia (the two largest energy exporters today), see Tavoni et al. (2013, in this issue).

Figure 6 Cumulative energy imports to (positive) and exports from (negative) the U.S. to 2050 and to 2100
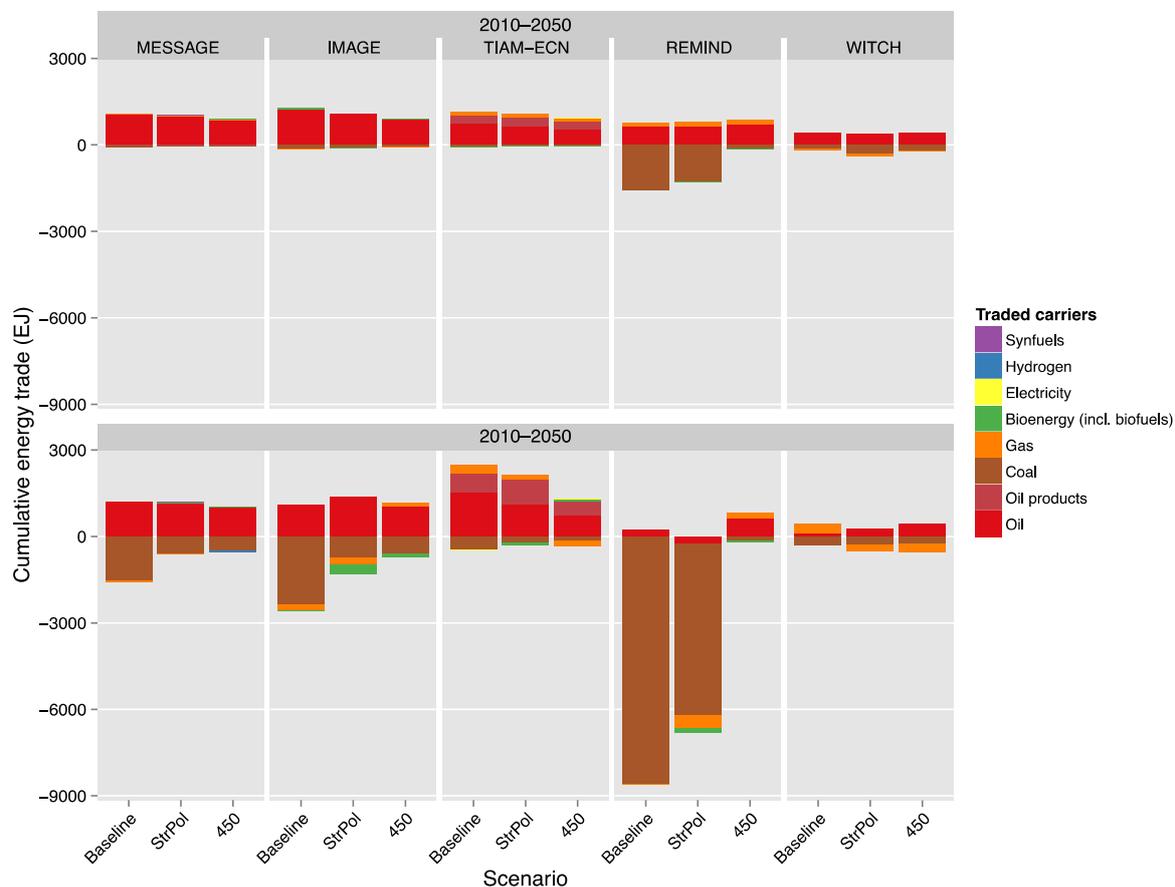
3.3 Resource extraction in major economies

Domestic resource scarcity is an energy security concern. As discussed in Section 2.2, domestic scarcity, even only in perception, leads to increased price volatility overall uncertainty in the energy sector. The following section discuss the domestic scarcity issues that each of the major economies face. Cumulative extraction volumes for coal, gas and oil for the four major economies are shown in Table 6 with the estimates of reserves and resources synthesized from the literature by Rogner et al. (2012).

Table 6 Cumulative fossil fuel extraction in the major economies

		Extraction (2010–2100) EJ *(Proportion of depletion)*						*Reserves and Resources (R&R) E^J*
		Baseline		StrPol		450		
China	Oil	130 – 2,200	*(20% - 560%)*	130 – 1,000	*(22% - 260%)*	120 – 620	*(21% - 160%)*	*390 – 580*
	Gas	560 – 1,500	*(17% - 50%)*	730 – 1,300	*(22% - 45%)*	350 – 1,700	*(11% - 55%)*	*3,000 – 3,300*
	Coal	4,900 – 13,400	*(4% - 10%)*	3,200 – 8,200	*(2% - 6%)*	1,200 – 2,900	*(1% - 2%)*	*129,000*
India	Oil	40 – 1,200	*(67%- 2300%)*	40 – 1,100	*(66% - 2200%)*	40 – 400	*(62% - 805%)*	*50 – 60*
	Gas	140 –800	*(8% - 47%)*	110 – 750	*(6% - 44%)*	90 – 590	*(5% - 35%)*	*1,700*
	Coal	1,000 – 5,800	*(17% - 94%)*	640 – 2,600	*(10% - 43%)*	380 – 1,800	*(6% - 30%)*	*6,200*
E.U	Oil	140 – 1,200	*(15% - 340%)*	160 – 820	*(17% - 240%)*	120- 570	*(13% - 140%)*	*340 – 915*
	Gas	600 – 1,400	*(34% - 78%)*	600 – 1,400	*(33% - 76%)*	380 – 1,200	*(21% - 64%)*	*4,400 – 4,600*
	Coal	500 – 3,400	*(3% - 20%)*	150 – 1,700	*(1% - 10%)*	90 – 1,100	*(1% - 6%)*	*16,605*
U.S.	Oil	610 – 3,400	*(3% - 65%)*	600 – 3,000	*(3% - 57%)*	150 – 1,300	*(1% - 25%)*	*5,200 – 19,000*
	Gas	1,100 – 3,500	*(8% -25%)*	1,500 – 3,100	*(10% - 22%)*	880 – 2100	*(6% - 15%)*	*14,300 – 14,500*
	Coal	2,600 – 10,000	*(1%-5%)*	1,300 – 7,100	*(1%-4%)*	480 – 2,400	*(1%)*	*190,000*

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. Models have their own resource availability and cost curves whose references are summarized in Table 11.

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3.3.1   China

The upper estimates for oil resource extraction (by MESSAGE and WITCH) indicates the extracted volumes close to or over 2,000 EJ (or five times the estimated R&R) in the Baseline scenario which declines to some 900 EJ (still over two times the estimated R&R) in the StrPol scenario and up to 550 EJ in the 450 scenario (up to one and a half times the lowest estimate of R&R). Three other models project more modest depletion levels ranging from just over 300 EJ (Baseline in IMAGE) to just under 100 EJ (450 scenario in TIAM-ECN) which are well within the R&R estimates and decline less drastically in response to climate policies. Finally, GCAM falls between these two groups with some 1,000 EJ of extraction of oil in the Baseline and StrPol which drops to about 600 EJ in the 450 scenario. Irrespective of the differences between models, these results indicate that there is a significant danger of China severely depleting its known oil resources thus eliminating a buffer against potential disruption of imports under the Baseline scenario. This danger is significantly lower in the case of climate policies (particularly the 450 scenario).

For gas, the results are more consistent between four out of the six models. In IMAGE, MESSAGE, ReMIND, and WITCH, gas extraction is between 1100 and 1500 EJ and slightly drops to between 870 and 1300 EJ in StrPol (staying within the 30%–50% of the estimated R&R) and 350 EJ–760 EJ in the 450 scenario. Similar to oil, GCAM sees cumulative gas extraction between these two endpoints and sees almost no drop between the Basleine and StrPol scenario. In contrast, in TIAM-ECN China's gas extraction is lower in the Baseline but higher in the 450

scenario. This is because in TIAM-ECN China's energy sector is heavily dependent on coal in the Baseline, leaving only a minor role for natural gas. Since natural gas substitutes coal under climate policies its extraction increases in the second half of the century.

With respect to coal, climate policies result in the large reduction of extraction volumes (by about four times in all the models), which in all scenarios stay well below 10% of its estimated vast coal reserves. In MESSAGE a large part of the coal extracted in the Baseline scenario is used for exports as we describe in Section 3.2.1.

3.3.2 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 growing demand. Due to its very low oil R&R, the country faces oil scarcity in all scenarios. In five of the six models, the country exploits between 40 and 90 EJ in the Baseline and StrPol scenarios (or between two-thirds and twice its estimated R&R). The 450 scenario has almost no impact on oil extraction. GCAM shows a much higher (1,200 EJ) oil extraction in the Baseline, which drops three times in the 450 scenario.

Climate policies also have little impact on cumulative extraction of natural gas in India. In the Baseline, all models except GCAM project that India extracts between 140 EJ and 470 EJ (or 8% to 28% 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, ReMIND and WITCH 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 (see Section 0). GCAM shows a significantly higher gas extraction in the Baseline: 800 EJ or almost half of the country's estimated R&R. This extraction drops to 750 EJ under StrPol and 112 EJ under the 450 scenario.

India extracts between 1,000 and 2,500 EJ of coal (or 16%–40% of its R&R) in the Baseline in all models except IMAGE in which it extracts and 5,800 EJ (or 94%). The StrPol scenario has virtually no effect on coal extraction in MESSAGE, ReMIND, and TIAM-ECN, but in the other three models (GCAM, IMAGE and WITCH) coal extraction approximately halves. In the 450 scenario, coal extraction further drops by between 37% and 84% compared to the Baseline. Thus under the Baseline scenario, the country faces coal scarcity in some models. Climate policies cause India to avoid these limits.

3.3.3 E.U.

Like 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 (see also Section 3.1.2). Nevertheless, climate policies lead to lower volumes extraction (a drop from a maximum of 1200 to 570 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 policy scenarios (but as a result the region's import dependence on gas is slightly lower).

For coal, the models depict two different realities. Half of the models (MESSAGE, ReMIND, and TIAM-ECN) depict E.U. coal extraction as <1300 EJ in the Baseline scenario. GCAM, IMAGE and WITCH depicts E.U. coal extraction as 2500–3400 EJ in the Baseline. In IMAGE and WITCH, the region becomes a net exporter of coal in the latter half of the century as discussed in Section 3.1.2. Climate policies lead to a ten-to two-fold decrease in coal extraction.

3.3.4 U.S.

Among the major economies, the U.S. has the largest fossil fuel resources and therefore it faces fewer scarcity issues. 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 through the exploitation of oil shale (see

Table 11 for an explanation of how unconventional resources are dealt with in different models). In general, climate policies lead to a drop in oil extraction by at least 50% (but do not impact oil imports). In TIAM-ECN, oil extraction in the Baseline is 610 EJ (3% of estimated R&R), which is relatively lower than the other models due to higher transport efficiency improvements and low-prices for Middle Eastern oil over the long term as discussed in Section 0; as a result, oil extraction does not change significantly under climate policies.

For gas, the U.S. extracts between 2,300 and 3,500 EJ (16% to 25% of its estimated R&R) 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 scenario leads to a small drop in gas extraction by as much as 33%. Under the 450 scenario, the U.S. extracts less gas. In TIAM-ECN, like other regions, gas extraction increases in the StrPol and the 450 scenarios since the Baseline this is coal-intensive and climate policies lead to gas displacing coal.

In all models except GCAM and ReMIND, the U.S. extracts between 2,400 and 4,800 EJ of coal in the Baseline (<3% of the estimated R&R). This drops up to 6 fold under climate policies which also leads to a drop in coal exports (Section 0). In ReMIND, U.S. coal extraction drops from 10,000 EJ in the Baseline to less than 1,000 EJ in the 450 scenario. GCAM depicts the U.S. as extracting some 7,600 EJ of coal over the century which drops to some 2,400 EJ in the 450 scenario.

## 3.4 Diversity of energy options in major economies

3.4.1 Diversity of total primary energy supply (TPES)

TPES diversity rises under all models across all regions under both the StrPol and 450 scenarios (Figure 7). The rise is most pronounced in China which starts with a relatively low-level of diversity (1.1 versus 1.3 in the U.S. and 1.4 in Europe) since in China coal accounts for over half of the TPES. Under the Baseline, China's energy system continues to be dominated by coal until 2050; however, the 450 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 scenario also leads to an increase in diversity to the level higher than in the Baseline but lower than in the 450 scenario.

Similar to China, India's TPES diversity does not rise in the Baseline. In fact, India's TPES diversity falls under some models as bioenergy is phased out and replaced by coal. In contrast, climate policies prevent coal from ever dominating the energy system and trigger an increase in diversity of energy options in India compared to the Baseline.

Climate policies also result in increasing 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 energy systems is higher. In the E.U., the diversity rise under the 450 scenario is comparable to the rise under StrPol since the E.U.'s Copenhagen pledges are very ambitious and would result in notable changes in energy systems. For the U.S., the StrPol case is between the Baseline and the 450 scenarios.

Figure 7 TPES diversity in major economies
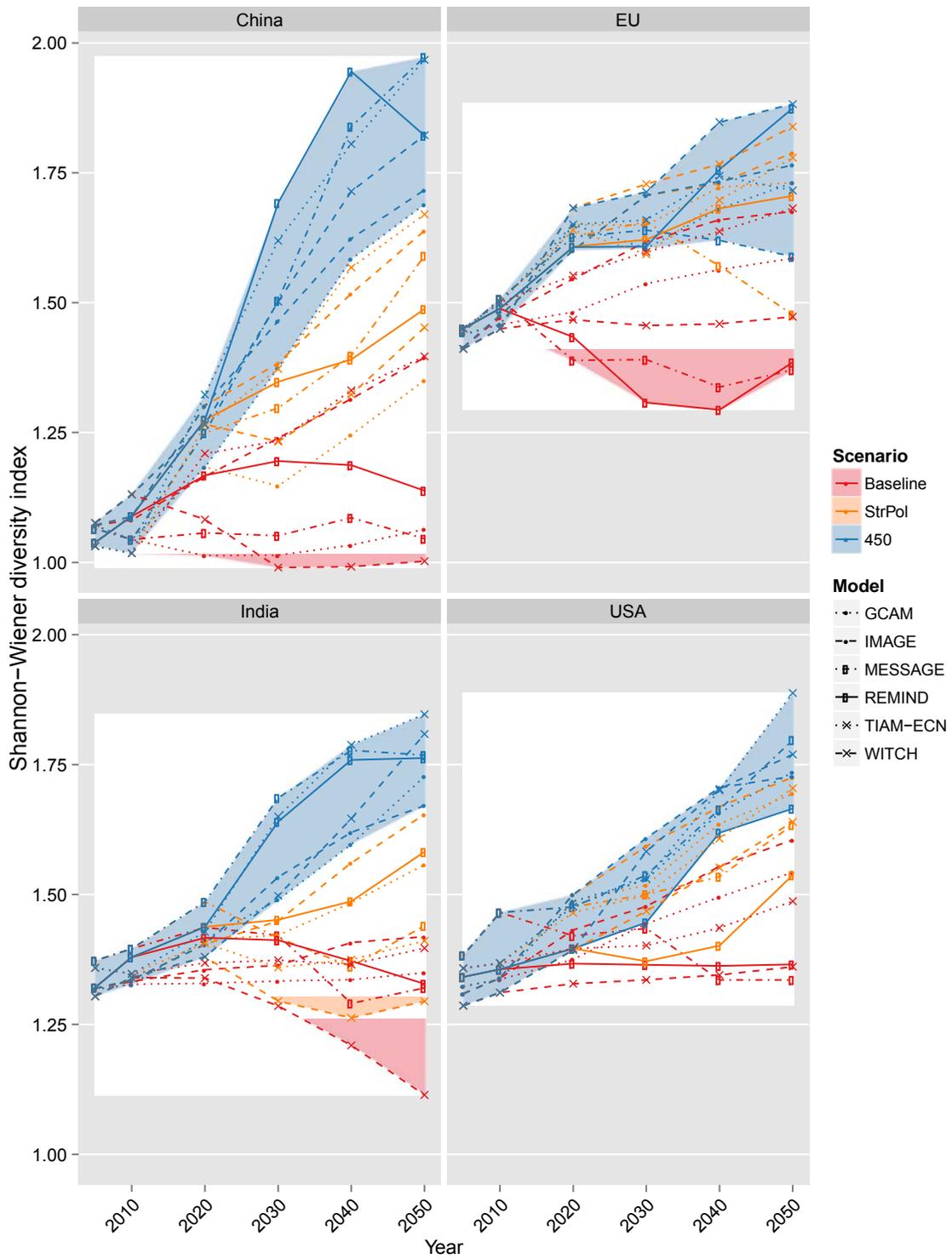
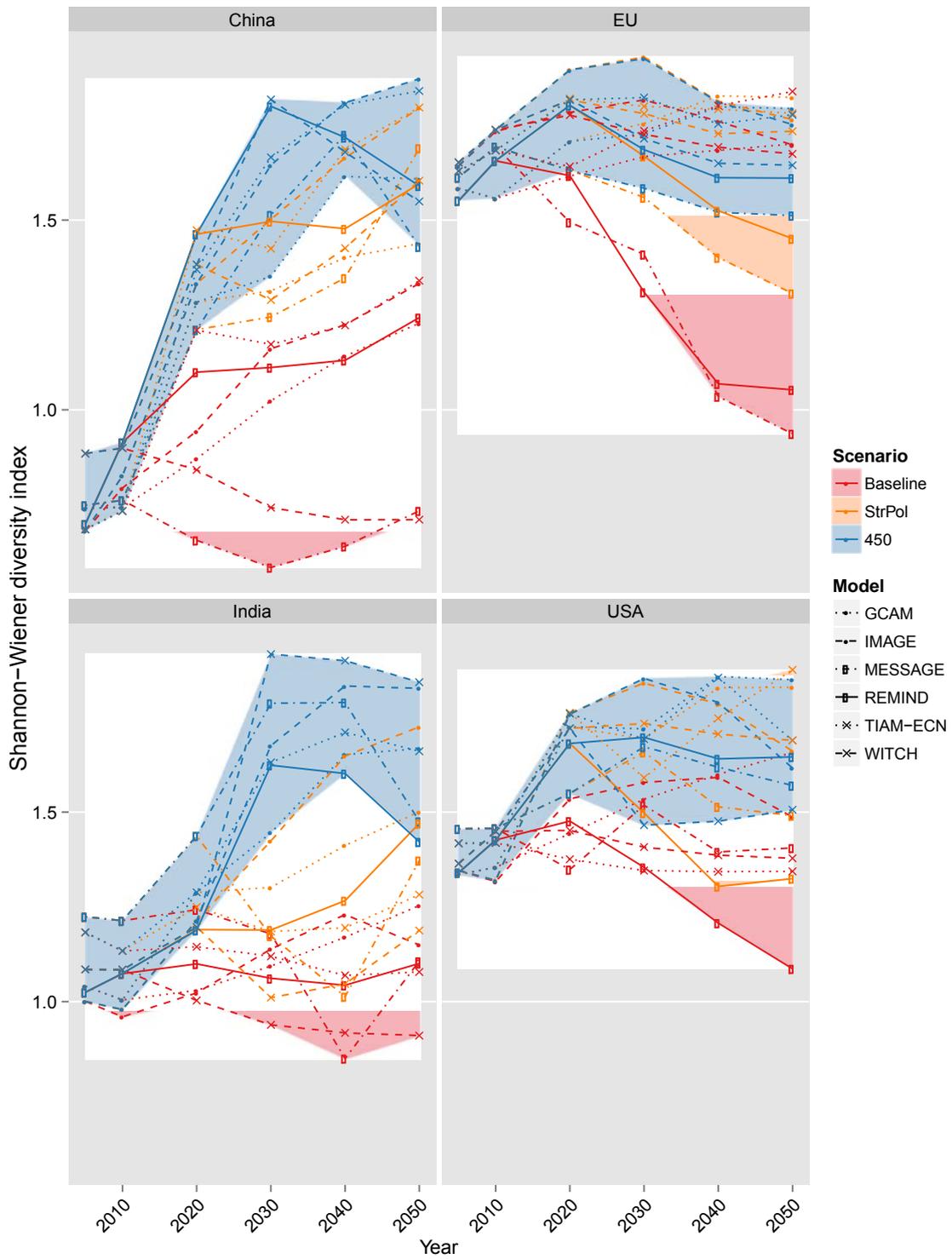### 3.4.2   Diversity of energy sources used for electricity generation

The development in the diversity of electricity closely follows the trends of TPES diversity described in the previous subsection (Figure 8). China starts with the lowest diversity of electricity with over 75% of its electricity generation coming from coal in 2010 (which corresponds to a diversity index of <1). China's electricity diversity in the Baseline stays well below current diversity levels for the E.U., India and U.S. Under climate policies China's electricity diversity rapidly rises; this rise is slightly more pronounced in the 450 scenario as the penetration of low-carbon sources is sustained throughout the century as opposed to plateauing in 2020 the StrPol case.

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 both the U.S. and the E.U., climate policies result in more modest increases in diversity of electricity generation sources under StrPol, which has a similar effect to the 450-policies. In both regions, diversity of electricity generation declines in the Baseline in some models: in the E.U. in ReMIND because of the domination of imported natural gas and in India in WITCH because of penetration of imported coal (displacing the traditional biomass).

All regions experience a peak in diversity under the 450 scenario in some models even by mid-century and virtually all model/region combinations exhibit a peak in electricity diversity by the end of the 21st century. This peak occurs when the old, fossil-intensive system, and the new, low-carbon system, co-exist. Under the 450 scenario, as the electricity system "squeezes out" the remaining carbon intensive generation sources, the electricity diversity inevitably declines. This pattern is most pronounced in ReMIND which has distinctly optimistic cost developments for solar electricity and as a result depicts solar energy coming to dominate electricity systems. It is also evident in the in GCAM in the E.U. and U.S. with a growth of electricity from biomass.[6]

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[6] The pattern of "peaking" electricity diversity under climate policies is discussed in more detail in Jewell et al.(Jewell, Cherp, & Riahi, n.d.) and Cherp et al. (Cherp et al., n.d.).

Figure 8 Diversity of energy sources used for generation of electricity in major economies

3.4.3   Diversity of energy sources used in transport

For the most part, the regional transport diversity repeats the trends at the global level (section 3.1.3). This means that in four of the six models, trasnport diversity rises at the same rate in the Baseline and climate policy scenario but in IMAGE and MESSAGE, transport diversity rises faster in the 450 and StrPol scenarios than in the Baseline (Figure 9). The main regional exception to this pattern is in the E.U. where there is a clear difference in the trend of transport diversity in the StrPol and 450 scenarios compared to the Baseline.

Figure 9 Diversity of energy sources used in transport in major economies until 2050
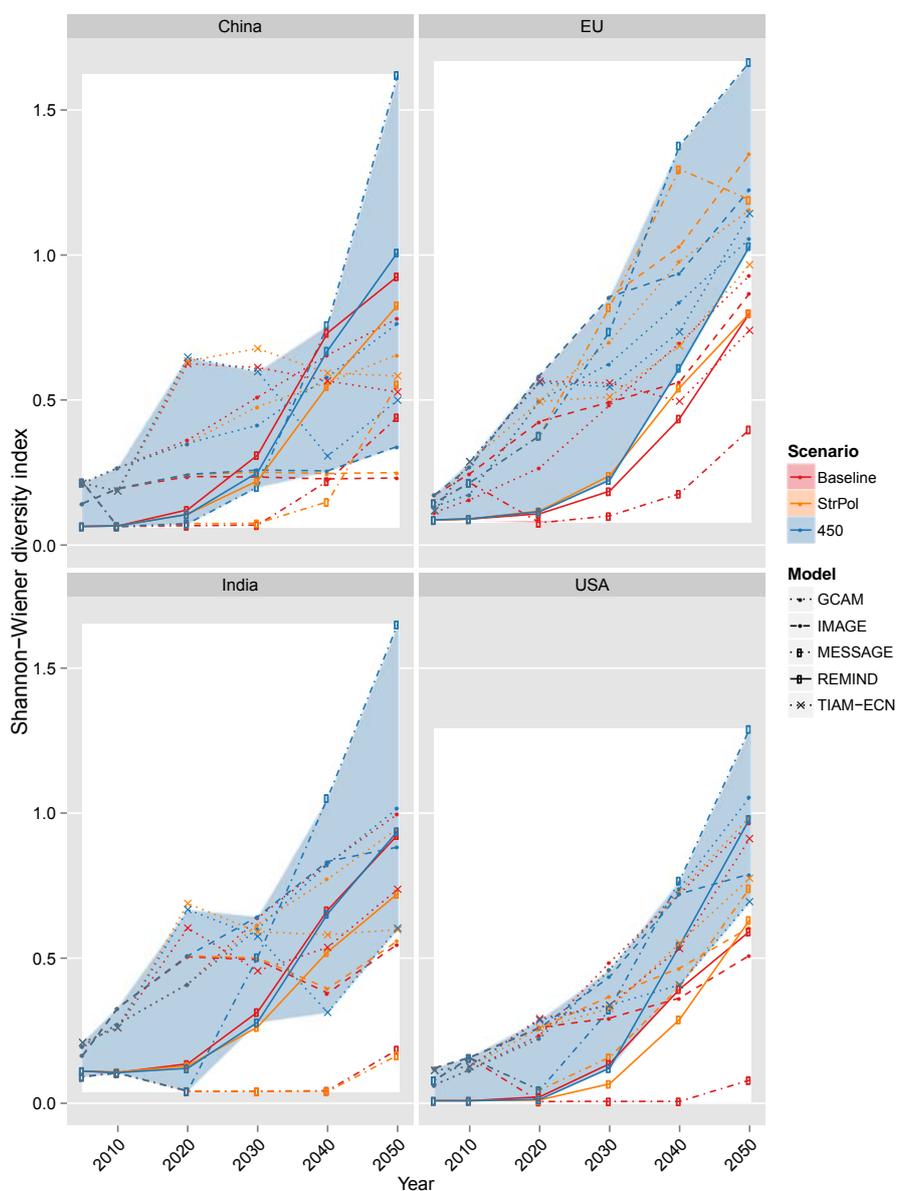
4 Discussion

Our analysis shows that in the Baseline scenario the present energy security concerns will become more acute and new ones may emerge during the 21st century (Table 7). In energy systems dominated by non-renewable fossil fuels, many regions will not have sufficient domestic resources to support their economies and thus the global energy trade will increase. In addition to the increasing oil trade, there may be even larger global markets for coal and natural gas.

To supply the growing global demand, oil will have to be extracted in volumes exceeding the currently estimated reserves, which will almost definitely trigger anxiety over oil scarcity potentially resulting in price volatility and international tensions. This will be aggravated by the fact that the transport sector will continue to rely primarily on oil products, only gradually and slowly switching to other energy carriers such as synthetic fuels produced from gas and coal, biofuels and electricity.

Table 7 Most significant global energy security concerns and developments in long-term scenarios

Concern	Baseline	Climate policies
Large and vulnerable global energy trade	Global trade grows dramatically, not only in oil but also in other fossil fuels and related carriers	Much lower global energy trade compared to the Baseline with levels comparable to today's energy trade (in a much larger energy system)
Scarcity of fossil fuels	Projected extraction exceeds the currently estimated reserves and resources in several models for oil	Projected extraction is within the estimated reserves and resources. 'Safety buffers' of non-renewables are left in the ground
Excessive reliance of the transport sector on oil and its products	In most models the diversity of energy options in transport sector stays at the same level or rises	Energy sources other than oil are rapidly introduced in transport in two models; in the other three models the diversity follows the Baseline development

In all major economies, these global trends will have important consequences. First, they would generally need to import increasing volumes of fossil fuels. Second, under certain modeling assumptions some of them may have an opportunity to *export* some fossil fuels (mainly coal) to the expanding global market. Third, most of them would significantly deplete their domestic resources of oil and gas.

Under climate policy scenarios, most of these undesirable trends would be reversed. In particular, the global energy trade will be much lower (in both absolute and relative terms) because of the lower energy use and the increasing shares of non-tradable low carbon energy sources, such as wind and solar energy. This result is consistent with other studies of energy security under low-carbon transitions (Criqui & Mima, 2012; Leimbach, Bauer, Baumstark, Luken, & Edenhofer, 2010; Riahi, Dententener, et al., 2012b).

Oil trade would experience the most significant decline, although mostly in the 2nd half of the century. At the same time, a much smaller share of oil reserves and resources will need to be extracted, thus leaving a "buffer" against uncertainties and reducing potential anxieties and tensions over the remaining oil resources. This finding is consistent with Turton & Barreto (2006). Oil will become even less of an energy security concern because other fuels

and technologies will penetrate the transport sector in most models already in the 1st half of the century reducing the vulnerability of this vital energy system to oil supply disruptions. No other fuel as insecure as oil at present is likely to emerge in future low-carbon energy systems.

At the level of major economies, these global trends would mean generally smaller energy imports and larger diversity of energy options (Table 8). Some of the fossil fuel exports possible under certain modeling assumptions in the Baseline scenario will 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 worldwide trends, climate policies will have some energy security implications specific to individual major economies covered in this study. China, which is a rapidly growing economy rich in coal and poor in oil and gas resources, would experience increasing reliance on domestic coal and possibly even export large amounts of coal in the Baseline scenario. At the same time it will practically wipe out its modest reserves of oil and gas and would become fully import dependent on these products. The diversity of its energy options will be very low not only in transport but also in the electricity sector dominated by coal.

Under the climate policy scenario, China will be able to preserve a buffer of oil and gas reserves and also import less of these fossil fuels. Its energy system and particularly electricity generation will become significantly more diverse, catching up with the diversity of energy options in the E.U. and the U.S. Under some modeling assumptions China will forego the opportunity to export large amounts of coal and synthetic fuels in the 2nd half of the 21st century, but it may be partially substituted by the possibility to export bioenergy under other modeling assumptions.

India is similar to China in many respects, but it has even less domestic fossil resources. In the Baseline it will become an extremely import-dependent economy with declining diversity of its energy options which will be increasingly dominated by coal. In the climate policy scenario, India's import dependence will be reduced and the diversity will be higher.

In the European Union, a developed region poor in fossil fuel resources, the main positive effect of climate policies would be decreasing import dependency and the rapid rise of diversity of energy options in the transport sector, occurring even under the StrPol scenario. Additionally, under certain assumptions the E.U. may have a possibility to export bioenergy in the second half of the century.

The U.S. is a developed economy with largest fossil fuel energy endowments. In the Baseline scenario it will import large volumes of oil in the 1st half of the century but is likely to export coal and natural gas and possibly even oil at the 2nd half of the century as the large global market will require extraction of its unconventional resources. Under climate policies the imports of oil will be smaller, but the possibility of large fossil fuel exports in the 2nd half of the century will also be eliminated, only partially compensated by the possibility to export bioenergy.

Table 8 Key trends in the main energy security concerns in major economies

	Trends in key energy security concerns	**Impact of long-term climate stabilization**
China	↑↑ **Imports** dramatically increase in the Baseline in most models, but stay stable or slightly decrease under the 450 scenario; ↓ **Exports** of coal may emerge in the Baseline* but not in the 450 scenario; ↑ **Extraction of oil exceeds reserves and resources,** but is 3-4 times less in the 450 scenario; ↑↑ **Diversity** stays low in the Baseline but increases under climate policies.	Generally strongly positive with some possibility of foregone coal export revenues
India	↑↑ **Imports** dramatically increase in the Baseline in most models, but only moderately increase under the 450 scenario; ↑↑ **Diversity** stays low in the Baseline but increases under climate policies, particularly the 450 scenario; ↑ **Extraction of coal** approaches the reserves and resources in the Baseline, but is 3-4 times less under the climate policies.	Strongly positive
EU	↑ **Imports** remain high in the Baseline in most models but decrease under climate policies; ↓ Modest **exports** of coal are possible under the Baseline* but decrease under climate policies; ↑ **Diversity** may decline in the Baseline but stays high under climate policies; ↑ **Extraction of oil** may exceed reserves and resources, but is 2-3 times less in the 450 scenario	Mostly positive even under the Copenhagen pledges
USA	→ **Imports** decline in all scenarios and all models depict the region as self-sufficient by the end of the century; ↓↓ Large **exports** of coal are possible under the Baseline; decrease under climate policies; ↑ **Diversity** may decline in the Baseline but stays high under climate policies;	Mixed: possible loss of export revenues but gains in diversity

Notes: The summary findings of the Table relate to all or most models unless indicated by *, which means that the result is only shown in one or two models
↑ - modest improvement as a result of climate policies compared to the Baseline;
↑↑ - significant improvement as a result of climate policies compared to the Baseline;
→ - no major impact of climate policies compared to the Baseline;
↓ - modest deterioration as a result of climate policies compared to the Baseline
↓↓ - significant deterioration as a result of climate policies compared to the Baseline.

Different models depict certain variations to these common themes of energy security in long-term scenarios (Table 9). Some of these variations concern the global level and some other are relevant to certain major economies. Of all the models, ReMIND indicates the largest global coal market in the Baseline scenario of ~120 EJ/year in 2050

growing to ~240 EJ/year by 2100 primarily supplied by the U.S. and largely consumed by China. ReMIND is based on the general storyline of co-operation and unrestricted international trade. Under such 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 with Lin and Liu's (2010) findings 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 major unfamiliar patterns of global energy interdependence. Notably, this massive coal trade disappears under the climate policy scenarios. 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 among models concerns the production and trade of bioenergy. Both IMAGE and ReMIND are different from other models in indicating a notable global bioenergy trade (which is still relatively small compared to both the current and future trade in fossil fuels) partially substituting coal trade under climate policies. 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 because of assumptions of peaking populations and higher agricultural yields.

The final notable difference between models from the energy security perspective concerns the diversity of energy sources used in the transport sector. These differences relate to (a) penetration of electrically-propelled vehicles; (b) penetration of biofuels; and (c) penetration of hydrogen-based technologies. In ReMIND and MESSAGE, climate policies result in a rapid rise in transport energy diversity because they trigger penetration of both electricity based on renewable energies and biofuel. TIAM-ECN has rather conservative assumptions on available biomass from sustainable resources and therefore models only modest changes in the transport sector before 2050. At the same time, TIAM-ECN [7] and IMAGE [8] model strong deployment of hydrogen in transport starting in 2050 so that transportation becomes dominated by hydrogen by the end of century. This means that 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 biofuels penetration in the transport sector. These differences between models depend on their assumptions concerning costs and learning curves of different technologies, availability of land resources and other factors which are discussed in detail in the literature describing the particular IAMs (referenced in section 2.4).

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[7] In TIAM-ECN, there are only only exogenous technology cost reductions and no endogenous learning curves. The reason that hydrogen becomes so dominant in the transport sector is due to the assumption that hydrogen cars becomes cheaper then electric ones because there is a larger potential for cost reduction of fuel cells than batteries.

[8] In IMAGE hydrogen can be produced using 7 different production routes based on fossil fuels, nuclear power or renewables. Over time, the competitiveness of hydrogen in end-use increases as a result of decreases in production costs and an expansion in transport networks. Also driven by increasing oil prices, in the second half of the century, hydrogen becomes very competitive in the transport sector

Table 9 Most significant 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
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	IMAGE & MESSAGE	More rapid rise in transport diversity under climate policies than under the Baseline
	GCAM, ReMIND & TIAM-ECN	Rise of transport energy diversity in the Baseline similar to the rise under the 450 scenario

The overall findings in this paper are robust across two additional climate policy cases. In addition to the StrPol case with ambitious Copenhagen targets, we evaluated the RefPol scenario associated with the lower end of Copenhagen pledges (weak policy) projected for the rest of the century. The results of this analysis were largely similar to the StrPol case except that changes in comparison to the Baseline are slightly less pronounced and happen later. We also evaluated long-term stabilization at 500 ppm but, similar to the RefPol/StrPol case found that the results do not differ significantly from the ones in the 450 scenario.

5 Conclusions

This paper aimed to explore the energy security of major economies (China, the E.U., India and the U.S.) under long-term scenarios including both the Baseline, the projection of the present climate commitments for the rest of the century, and more ambitious climate policies guided by the 2 degrees climate stabilization targets. The development of energy systems in these scenarios was modeled in six Integrated Assessment Models: IMAGE, MESSAGE, ReMIND, TIAM-ECN and WITCH. Our analysis of energy security followed the energy security assessment framework developed in the Global Energy Assessment which includes systematic identification of vital energy systems and assessment of their vulnerabilities from three perspectives: sovereignty, robustness and resilience.

Our results indicate that the main present-day energy security concern - the over-dependence of the transport sector on just one fuel, oil, with limited global reserves extensive global trade, and high import dependency of the majority of countries - is likely to become more serious under the Baseline development of the energy system. In addition, other energy security concerns, such as high dependence on imported coal and natural gas are likely to become more serious in the major economies. The known resources of oil will be significantly depleted both at the global level and in China, India and the E.U. which may result in price volatility and growing anxiety and tensions between nations.

Under climate policy scenarios, these concerns will be largely alleviated as global trade and import dependence will decline, 'safety buffers' of non-renewables will be left in the ground, and the diversity of energy options, especially in the most vulnerable transport sector, will increase, though many models also indicate increasing transportation

diversity under the Baseline. The most notable and lasting effects would be under stricter more ambitious climate policies. Our analysis did not identify any significant energy security concern similar in scale and nature to the present concerns associated with the oil sector, which may emerge under climate policies, despite the emergence of many new energy systems and global energy flows.

Some of the energy security benefits and potential risks of climate policies depend on modeling assumptions. For example, the smaller global trade will mean not only the welcoming decrease in import dependency, but also, under certain assumptions, foregone opportunities to export coal from China and all fossil fuels from the U.S. in the 2nd half of the century. Another concern is the potential domination of solar energy in the electricity sector and biofuels in the transport sector under some modeling assumptions in the 2nd half of the century.

In addition to being dependent on modeling assumptions, the analysis of future energy security using IAMs naturally has some limitations. In particular, as we explain in the Methodology section, energy security is not only about the magnitude and probabilities of risks to energy systems, but also their ability to recover from major disruptions. We evaluate a static proxy of that ability: the diversity of energy options, but IAMs cannot tell us how energy systems will respond to actual disruptions. This is because IAMs are not designed to deal with discontinuities such as political and economic instabilities, which may arise as a result of disruptions of vital energy systems. Nevertheless, we believe our analysis clearly outlines potential vulnerabilities of energy systems under different scenarios.

The analysis which we conducted can be further expanded with respect to the energy concerns investigated (e.g. reliance of particular sectors on imported energy) and the economies that it covers (e.g. major energy exporters such as the Middle East and the former Soviet Union). New methods of assessing energy security which are both relevant to current policy concerns and applicable to energy systems which may emerge in the distant future are always needed. The results of such energy security analysis can be used not only in policy-making but also in developing more accurate long-term models of energy systems by accounting for energy security driven motivations of nation-states and other policy actors. Economic and climate implications of such policies as compared to free trade will need to be assessed as well.

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Supplementary Material

Additional explanations for the energy security analysis

This appendix contains a description and formula for all the indicators discussed in the paper (listed in Table 10).

Table 10 Indicators of energy security in long-term energy transformation scenarios

| Indicator	Definition (unit)	Formula
Global energy trade[a]	Total interregional trade (EJ)	$$Global\ energy\ trade = \sum s_i$$ where s_i is the sum of each traded fuel or carrier
Net energy imports[a]	Total energy imports into a country minus the energy exports (EJ)	$$Net\ imports = \sum i_i - e_i$$ where i_i is the imports of each imported fuel or carrier and e_i is the exports of each exported fuel or carrier
Net import dependency[a]	Net energy imports divided by total PES (%)	$$Net\ import\ dependence = \frac{\sum i_i - e_i}{TPES}$$ where i_i is the imports of each imported fuel or carrier and e_i is the exports of each exported fuel or carrier and $TPES$ is the total primary energy supply
Diversity of energy sources in total primary energy supply (TPES)	Shannon-Wiener diversity index (unitless)	$$Diversity\ index = -\sum p_i * \ln(p_i)$$ where p_i is the share of the energy source *i* in the TPES
Diversity of energy sources in electricty	Shannon-Wiener diversity index (unitless)	$$Diversity\ index = -\sum p_i * \ln(p_i)$$ where p_i is the share of the energy source *i* in the electricity mix
Diversity of energy sources in transport	Shannon-Wiener diversity index (unitless)	$$Diversity\ index = -\sum p_i * \ln(p_i)$$ where p_i is the share of each energy source *i* in the transport sector
Cumulative extraction	Total energy resources extracted (EJ)	$$Cumulative\ extraction = e_{2100} - e_{2010}$$ where e_t is extraction in year t

Note: [a]Can be calculated either for one year or cumulatively over several years. Both are done in this article..

Global energy trade is the sum of all net exports for each globally-traded fuel or carrier. In this paper that includes: crude oil, oil products, natural gas, coal, biomass, biofuels, electricity, hydrogen and synfuels (liquefied coal and natural gas). Uranium trade, which is modeled in IMAGE and ReMIND was excluded from the calculation of global energy trade since uranium supply is not the main energy security issue related to nuclear energy (see Section 3.1.1). 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.[9]

Regionally, net energy imports is the sum of all imports minus the sum of all exports for all fuels and carriers. We 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.

For diversity, we use the Shannon-Weiner diversity index (SWDI) which is calculated using the formula in the table (Shannon & Weaver, 1963).[10] The diversity represents diversity between the following sources: coal, oil, gas, bioenergy, nuclear energy, hydropower, wind, solar, and geothermal.

Figure 10 The diversity of sources used in transportation in Electricity and Transport with their respective SWDI's
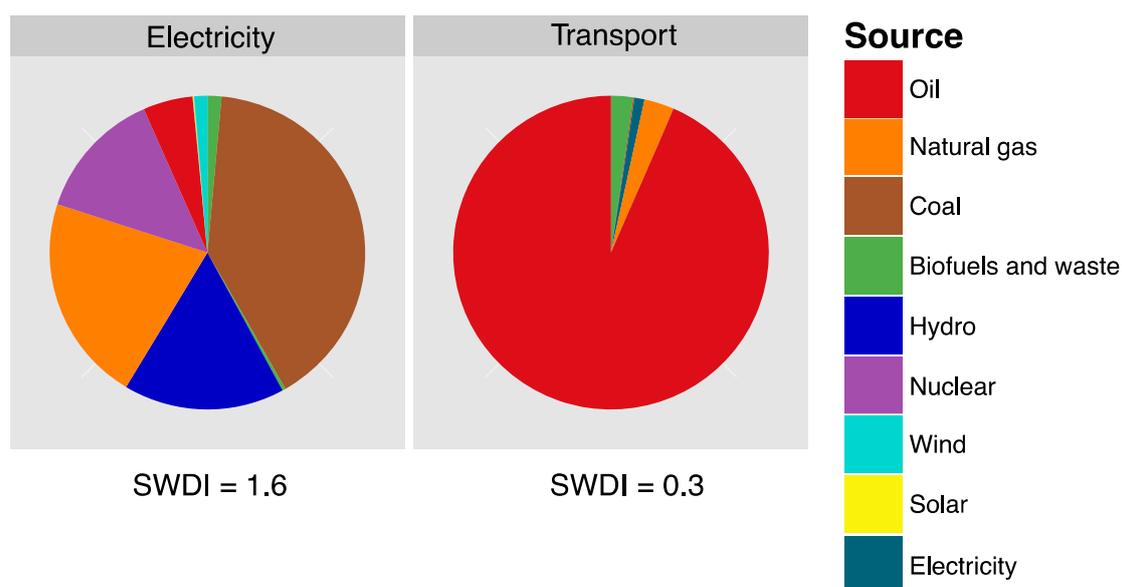
Note: Data are from (International Energy Agency, 2012b)

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[9] Country-to-country oil trade in 2010 was about 110 EJ while in the models in this paper, oil trade was between 68 EJ and 83 EJ (British Petroleum, 2009). Thus, interregional trade currently accounts for about 60%-75% of all oil trade.
[10] The Herfindahl-Hirschmann index has also been used in the literature as a measure of diversity (Grubb et al., 2006; Jewell, 2011; 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 which is used (Stirling, 1998). In a study which compared the results of both indices no difference was found (Grubb et al., 2006).

Additional information on the trade dynamics

Figure 11 shows the cumulative global trade in the three scenarios over the first half of the century (top) and over the whole century (bottom). As discussed in Sections 3.1.1 and 3.2, the impact of climate policies on trade (and import dependence) is small in the first half of the century but increases in the second half.

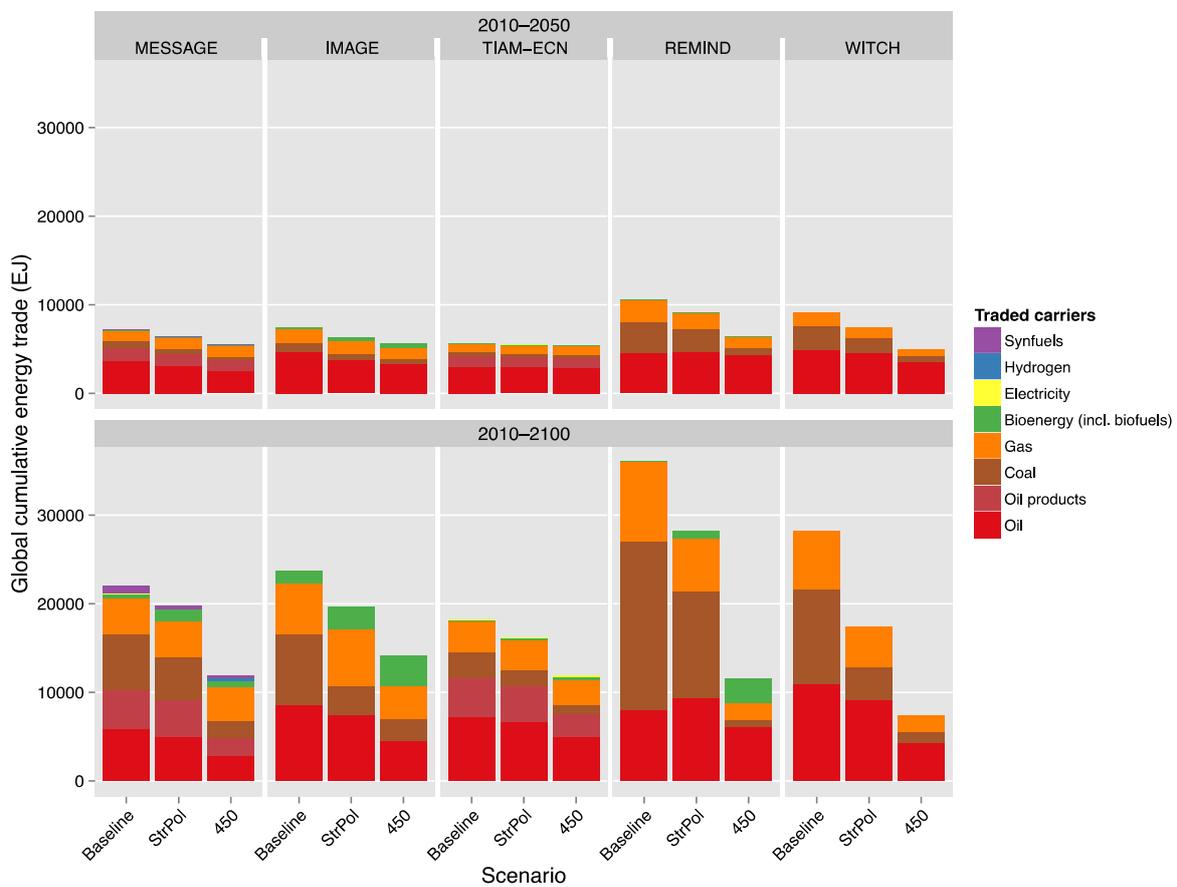*Figure 11 Cumulative trade at the global level from 2010-2050 (top) and from 2010-2100 (bottom)*

Figure 12 shows the Energy imports for China in 2010, 2050, and 2100. While today, the country is mostly self-sufficient, most models depict growing import dependence under both the Baseline and climate policy, though this import dependence is generally higher under the Baseline scenario. A notable exception is China's energy exports in the Baseline in MESSAGE.

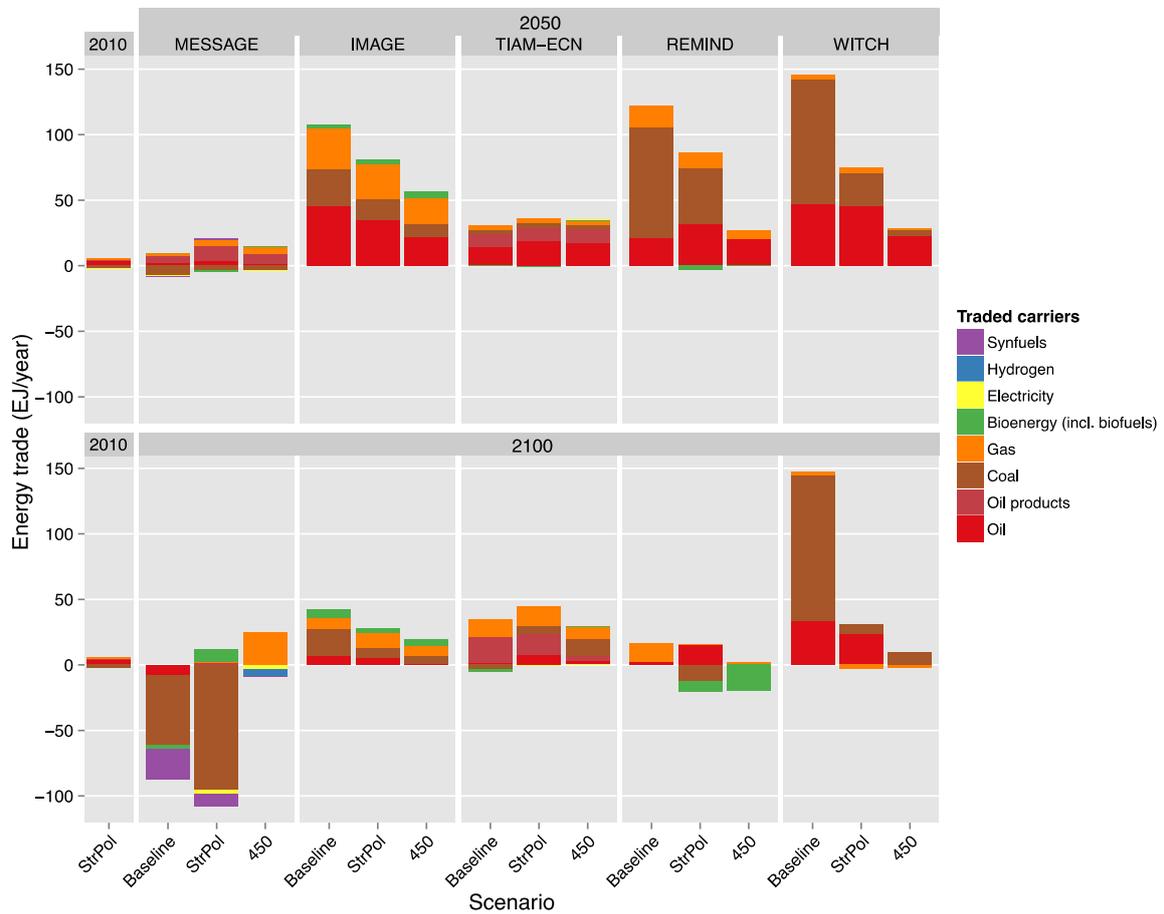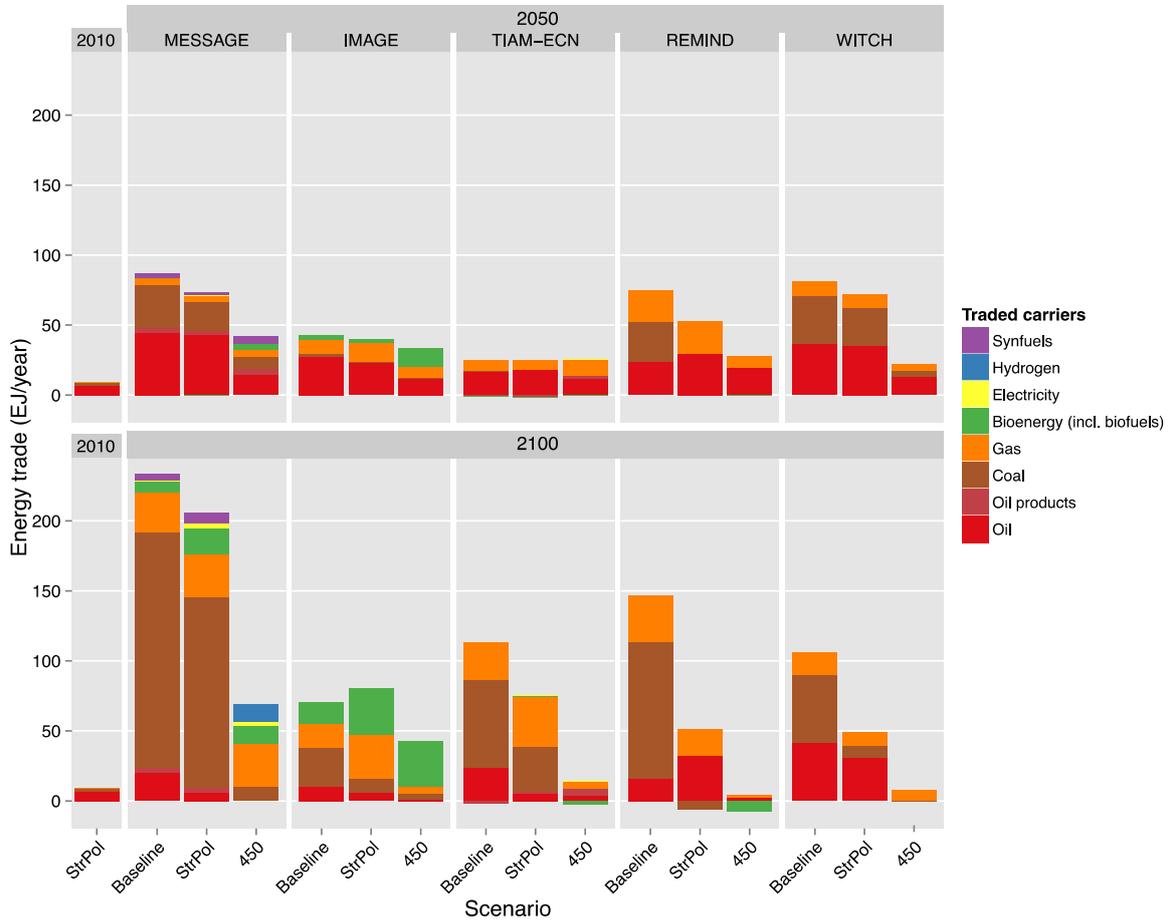*Figure 12 Energy imports and exports in China in 2010, 2050 and 2100*

Figure 13 shows annual energy imports in India in 2010, 2050, and 2100. The country experiences a massive growth in annual energy imports but this increase is generally smaller under climate policies.

Figure 13 Energy imports in India in 2010, 2050 and 2100

In Figure 14 we show the annual energy imports and exports figures for the European Union. Gas imports are high for this region in the medium-term regardless of climate policies in most models. However, over the long term, the 450 scenario significantly curtails energy imports to the E.U.

Figure 14 Energy imports and exports for the European Union in 2010, 2050 and 2100
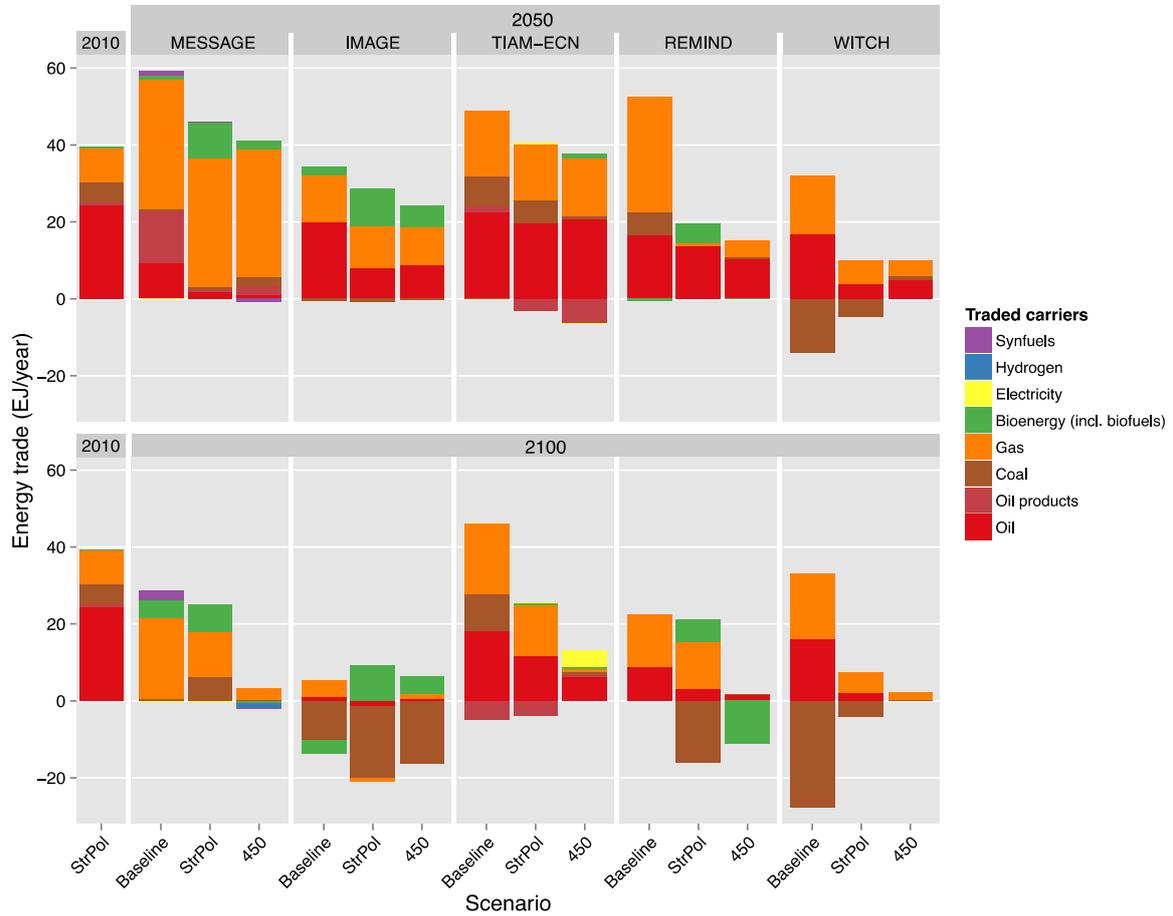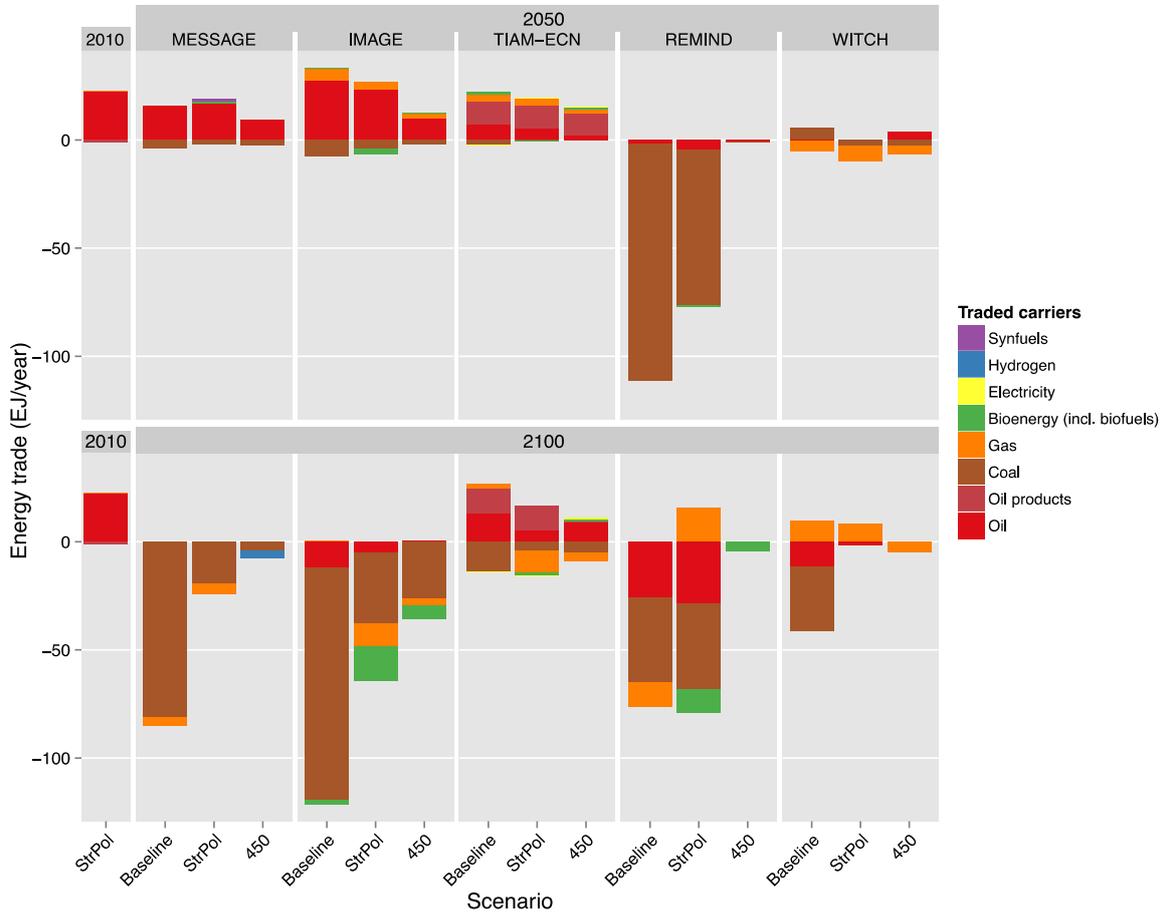

Figure 15 shows the annual energy trade for the U.S. for 2010, 2050 and 2100. Under the Baseline scenarios, the U.S. becomes a net exporter in most models. However, climate policies prevent the U.S. from taking full advantage of their energy resources.

Figure 15 Energy trade in the U.S. in 2010, 2050 and 2100

Additional information on reserves and resources assumptions in models

Table 11 summarizes the sources for reserves and resources for the six different models included in this study. When known reserves and resources are depleted (which are the listed in Table 4 and Table 6) newer resources become available at higher costs. Exploration costs are generally included in the price of these newer resources and productivity gains are assumed overtime.

Table 11 Reserve and resource assumptions in the six models

Model	Source of reserves and resource assumptions	Unconventional resource prices
GCAM	(Rogner, 1997)	From (Rogner, 1997)
IMAGE	(Rogner, 1997) with updates from USGS (2000) for oil and gas and BGR (2004) for coal	From (Rogner, 1997)
MESSAGE	(Rogner, 1997)	Based on (Rogner, 1997), updated to 2005 prices for unconventional resources
ReMIND	(Rogner et al., 2012) with updates from BGR and USGS	(Rogner et al., 2012)
TIAM-ECN	(Remme, Blesl, & Fahl, 2007) which synthesizes data from BGR (2006), USGS (2000), BP (2006), and WEC (2004)	Based on (Remme et al., 2007), updated to 2007 prices
WITCH	(Rogner et al., 2012)	Based on (Rogner et al., 2012), updated to current market prices except for gas in the U.S.