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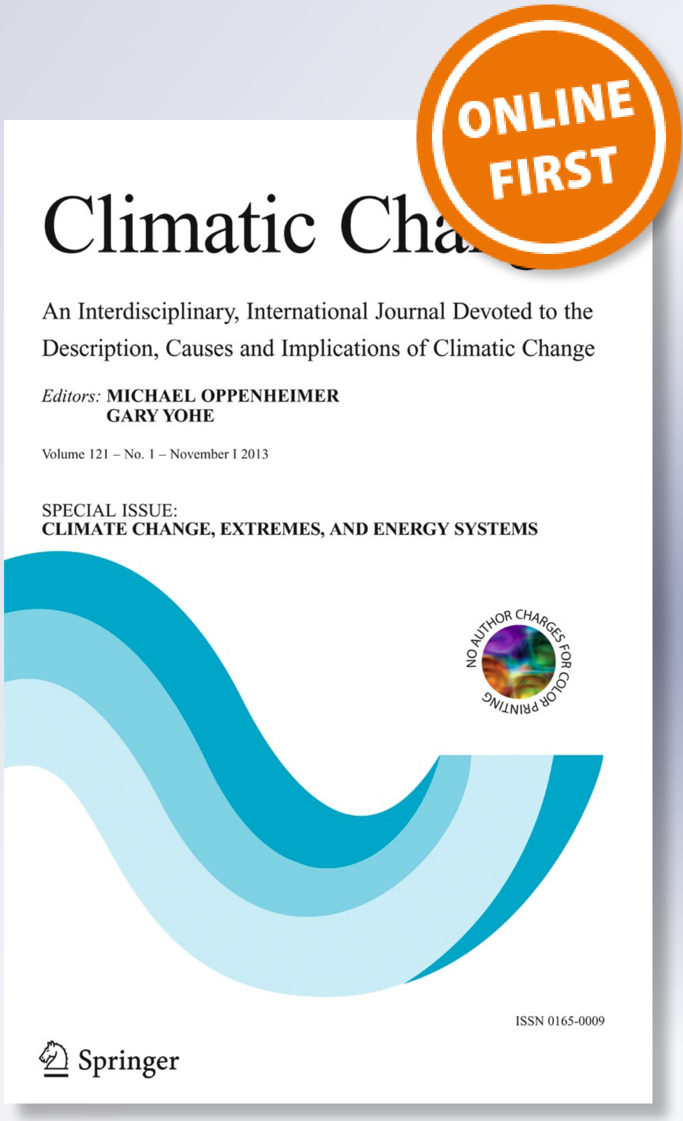

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Global energy security under different climate policies, GDP growth rates and fossil resource availabilities

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Abstract Energy security is one of the main drivers of energy policies. Understanding energy security implications of long-term scenarios is crucial for informed policy making, especially with respect to transformations of energy systems required to stabilize climate change. This paper evaluates energy security under several global energy scenarios, modeled in the REMIND and WITCH integrated assessment models. The paper examines the effects of long-term climate policies on energy security under different assumptions about GDP growth and fossil fuel availability. It uses a systematic energy security assessment framework and a set of global and regional indicators for risks associated with energy trade and resilience associated with diversity of energy options. The analysis shows that climate policies significantly reduce the risks and increase the resilience of energy systems in the first half of the century. Climate policies also make energy supply, energy mix, and energy trade less dependent upon assumptions of fossil resource availability and GDP growth, and thus more predictable than in the baseline scenarios.

This article is part of a Special Issue on "The Impact of Economic Growth and Fossil Fuel Availability on Climate Protection" with Guest Editors Elmar Kriegler, Ottmar Edenhofer, Ioanna Mouratiadou, Gunnar Luderer, and Jae Edmonds.

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1 Introduction

Understanding energy security implications of long-term climate stabilization scenarios is crucial for informed policy making. A few systematic studies in this area analyze oil and gas trade and availability (Turton and Barreto 2006; Rozenberg et al. 2010; McCollum et al. 2011), energy import dependency (McCollum et al. 2011; Bollen et al. 2010), or focus on a specific region (Costantini et al. 2007; Grubb et al. 2006). Riahi et al. (2012) explore the trade dynamics for different fuels and diversity of energy supply in energy end-use sectors. None of the published studies assessed long-term global energy security with respect to all energy sectors and under different assumptions of economic growth and fossil fuel availability.

This article examines the implications of long-term climate policies (CPs) for energy security under different assumptions about GDP growth and fossil fuel availability. It uses the conceptualization of energy security developed in the Global Energy Assessment (GEA) (Cherp et al. 2012 and Riahi et al. 2012) as summarized by Cherp and Jewell (2013). This conceptualization is sufficiently specific to be meaningful in today's policy context and yet sufficiently generic to be applicable to energy systems which may be radically different from those at present. We apply indicators based on this framework to a set of global energy scenarios developed within two integrated assessment models (IAMs) - REMIND and WITCH - as part of RoSE multi-model ensemble comparison exercise (Kriegler et al. Submitted for publication in this issue).

2 Framework and indicators

2.1 The concept of energy security

Following the GEA (Cherp et al. 2012) and other mainstream definitions (see a summary in Winzer (2012)), we define energy security as "*low vulnerability of vital energy systems*". Vital energy systems can be delineated sectorally and/or geographically. In terms of energy sectors, these can be the total primary energy supply (PES), individual fuels, energy carriers, or end-uses. In terms of geographic boundaries, vital energy systems can be those of individual nations, regions, or the global system as a whole. Although the present-day energy security concerns are primarily articulated at the national level, most of the IAMs do not have the granularity necessary for assessment of national energy systems, except for very large economies. Therefore, in this assessment we address energy security of *global* and *regional* energy systems, focusing on the TPES, major fuels, carriers and end-uses as shown in Table 1. Due to space limitations, this analysis is primarily focused on global-level results.

Vulnerabilities of vital energy systems can be categorized in terms of the three perspectives on energy security (Cherp and Jewell 2011). The '**sovereignty**' perspective, with its roots in geopolitics, focuses on risks associated with foreign control over energy resources such as threats of trade embargoes or price manipulations. The '**robustness**' perspective, with its roots in natural science and engineering, focuses on technical and natural risks to energy systems such as aging of infrastructure and resource scarcity. The ability of energy systems to respond to diverse risks (including those that are less predictable and controllable such as political instability, terrorism and price volatility) is in the focus of the third '**resilience**' perspective on energy security with its roots in economics and complex systems science.

Our definition of energy security deals with both physical and economic vulnerabilities. With respect to the latter, energy security is concerned with competitive and stable rather than *low* prices (Cherp and Jewell 2013). However, competitiveness is a feature of institutional (market) arrangements and price stability is a short-term phenomenon and thus neither

Table 1 Energy security indicators used in this study

Energy systems	TPES	Primary fuels: oil, coal[b], gas[b]	Carriers: Liquids and electricity[c]
Global			
Sovereignty	Global[a] energy trade: absolute; Global[a] energy trade: share of PES (intensity)	Global[a] trade in fuel: absolute; Geographic diversity of the production of traded fuels	
Resilience	Diversity of energy sources in PES		Diversity of primary energy sources in carrier production
Regional			
Sovereignty	Net import dependency	Import dependency on a particular fuel	
Resilience	Diversity of energy sources in PES of the region		Diversity of fuels in carrier production

Extended definitions and formulas for all indicators are available online in Jewell et al. (2012) and in the SM

[a] Global trade is defined as trade between the model regions

[b] REMIND only

[c] The diversity of electricity production is calculated based on the PES mix used for electricity generation; the diversity of liquids is calculated based on the type of liquid fuels: oil, synthetic fuels and biofuels in the overall liquid fuel mix

can be directly represented in IAMs. Therefore we analyze long-term economic aspects of energy security through such proxies as import dependence and diversity of energy options. This analysis is limited because it does not cover the robustness perspective of energy security. Some aspects of robustness (e.g. topography of energy infrastructure, the volumes of strategic stocks or redundant capacities) are difficult to represent in IAMs, whereas some other (e.g. the scarcity of resources) are in principle possible to analyze, but are not included in the current paper due to space limitations (for such expanded analysis see Jewell et al. (2013b)).

2.2 Indicators

Table 1 lists the indicators used in this article representing vital energy systems (in columns) and perspectives on energy security (in rows). These indicators for evaluating energy security in IAMs (based on Jewell et al. (2013a)) are further explained in the Supplementary Material (SM). The sovereignty risks are reflected in trade-related indicators echoing the current energy security concerns associated with import dependence and geographically concentrated production of oil and gas (Cherp et al. 2012). Resilience of energy systems is represented by the diversity[1] of energy sources in the global or regional primary energy supply (PES) mix or used for the production of liquid fuels or electricity.

The selection of indicators was influenced by availability of data. We could not use indicators involving values which are either not reported or not represented in models such as trade in secondary energy (hydrogen and electricity), diversity of carriers in end-use sectors. For WITCH, only oil trade was analyzed because this model did not report trade in other fuels.

[1] Calculated by the Shannon-Wiener diversity index as proposed by (Stirling 1994) and subsequently used by O'Leary et al. (2007), Gupta (2008), Jansen and Seebregts (2009) and many other studies.

Table 2 Scenarios used for the analysis of energy security

Climate policies	Default (medium GDP and fossil resources)	GDP growth(medium fossil fuel availability)		Fossil resources availability (medium GDP growth)		
		Fast	Slow	High	Low	Low oil
Baseline	BAU DEF	BAU FS Gr	BAU SL Gr	BAU HI Fos	BAU LO Fos	BAU LO Oil
WEAK-POL (projection of existing commitments)	WEAK-POL DEF	WEAK-POL FS Gr	WEAK-POL SL Gr			
450 ppme stabilization	450 DEF	450 FS Gr	450 SL Gr	450 HI Fos	450 LO Fos	450 LO Oil
550 ppme stabilization	550 DEF	550 FS Gr	550 SL Gr	550 HI Fos	550 LO Fos	550 LO Oil

Detailed assumptions for different scenarios are provided in Kriegler et al. (Submitted for publication in this issue) and Luderer et al. (Submitted for publication in this issue)

2.3 Scenarios

Table 2 lists and illustrates the differences between 21 scenarios analyzed in this paper. The first difference is with respect to the presence and stringency of climate policies. Six Baseline scenarios do not contain any climate policy measures. Three WEAK-POL scenarios project the currently existing climate mitigation commitments (Luderer et al. Submitted for publication in this issue). The 450 and 550 scenarios model climate policies compatible with constraining the GHG concentrations in the atmosphere at 450 ppm CO_2eq and 550 ppm CO_2eq respectively. The second difference is in their assumptions concerning GDP growth and fossil fuel availability. The four DEF scenarios represent medium assumptions about both factors. The 4 FS Gr and 4 SL Gr scenarios represent fast GDP growth and slow GDP growth assumptions respectively (with medium fossil fuel availability). The 3 HI Fos and 3 LO Fos scenarios represent high and low fossil fuel availability (with medium GDP growth). Finally, the 3 LO Oil scenarios represent medium assumptions on gas and coal availability and GDP growth and low assumptions on oil availability. A detailed description of the scenarios and their assumptions is provided by Kriegler et al. (Submitted for publication in this issue).

3 Results

3.1 Effects of climate policies on energy security

3.1.1 Sovereignty risks (trade)

In the baseline scenario BAU DEF, REMIND models a rapidly rising gas and coal trade due to rising demand in developing economies (Fig. 1) and, as a result an up to 5-fold increase in the global energy trade by the end of the century (Figure S-1 in SM). Oil trade increases by 50 % in the BAU DEF scenario in both REMIND and WITCH[2] (Fig. 1).

[2] Since WITCH only reported oil trade, the total PES trade equals oil trade in WITCH.

Both models show radically lower energy trade under the 450 scenarios: in REMIND it is almost 4.5 times less compared to BAU DEF, and in WITCH it declines almost to zero. The drop in energy trade in REMIND is due to a decrease of coal 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. The 550 scenarios also result in reduction of trade, although to a lesser extent than the 450 scenarios. The WEAK-POL scenarios do not lead to notable differences in global energy trade.

The share of tradable energy in TPES ('trade intensity', Figure S-2 in the SM) declines to much lower levels in CPs than in Baseline scenarios in both models. In REMIND, the present trade intensity of some 25 % increases to 40 % in the Baseline, but drops to some 10-15 % in the 450 DEF scenario or stays at approximately the same level of 25 % in the 550 DEF scenario. In WITCH, where only oil is traded, the present global trade intensity of some 20 % remains virtually unchanged in the Baseline scenario and drops to zero under the CP scenarios. The decline in trade intensity occurs due to declining shares of tradable fuels (oil, coal and gas) in the energy mix under CPs.

CPs reduce oil imports of most regions. At the same time, CPs constraint the use of unconventional oil resources and coal- and gas-to-liquid technologies. This may on the one hand, increase the share of imported oil in some regions and some periods of time and on the other hand somewhat sustain oil export revenues of traditional exporters of conventional oil such as the Middle East. Of course, all these developments would occur against the background of declining importance of oil in the energy system (Figure S-3 in the SM).

3.1.2 Resilience (diversity)

The overall diversity of TPES follows a distinctly different pattern in CPs and the Baseline scenarios (Fig. 2 and Figure S-4 in the SM). Under the 450 DEF scenario, TPES diversity rises at a higher rate than in the Baseline at the beginning of the century when low-carbon and traditional technologies co-exist. At the end of the century, however, low-carbon technologies domination either slows or reverses this trend so that the CP and Baseline scenarios converge (in REMIND this is also due to the rise in diversity under the Baseline).

The diversity of electricity production also behaves differently under CPs and in the Baseline (Fig. 2 and Figure S-4 in the SM). In the Baseline scenarios, it stays virtually unchanged in WITCH while in REMIND it initially declines and then rises. In both models the diversity of electricity production in the CP scenarios rises (the faster the stricter are CPs) in the first half of the century, exceeding that of the Baseline. In REMIND this rise is followed by a rapid decline below the Baseline, as renewable energies, particularly solar, start to dominate electricity production. In WITCH there is no comparable decline in diversity of electricity production because the penetration of renewable energies is constrained by an economic penalty, which is exponentially increasing with the increasing share of renewables in the electricity mix based on Hoogwijk et al. (2007) (Figure S-5 in the SM).

In case of liquids (Fig. 2 and Figures S-4 and S-6 in the SM), in REMIND, the diversity of the liquid production mix - which includes biofuels, coal-derived synfuels and oil products - steadily increases from the initially very low level throughout the century in all scenarios. Until the middle of the century this increase is faster in the 450 scenarios, but in the last third of the century it slows down or even slightly reverses eventually becoming lower than in the Baseline due to lower share of synfuels and increasing domination of biofuels.

In WITCH, the diversity of liquid fuels in the Baseline scenarios does not change much staying at very low levels throughout the century because these remain based on oil products (gas-to-liquids and coal-to-liquids technologies are not available in WITCH). In the stricter

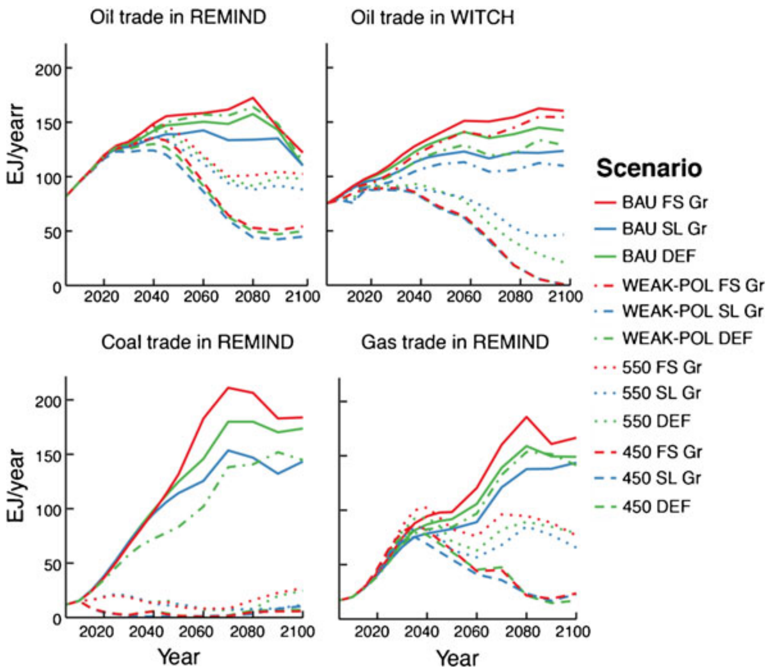

Fig. 1 Global energy trade in Baseline and CP scenarios under different economic growth assumptions. For definition of scenarios see Table 1. Only oil trade is modeled in WITCH. REMIND only models medium GDP growth assumptions for the WEAK-POL policy scenario.

CP scenarios, the diversity of liquids rapidly rises in the first part of the century when biofuels are introduced and then equally rapidly declines below the Baseline and even below the present already low levels in the 450 DEF scenario. In the 550 DEF scenario (see Figure S-4 in the SM), this decline occurs later and is not as pronounced. The rise and decline in diversity of fuels in WITCH is due to the rapid introduction of biofuels, which initially balance and then substitute oil in liquid fuels.

In both models there are regional differences in the diversity of energy systems. In general, the energy mix in different regions diverges more under CPs than under the Baseline (illustrated for WITCH by Figure S-7 in the SM). This is because in the Baseline 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 CPs, fossil fuels are phased out, there is less global energy trade and each region seems to gravitate to its own unique energy mix based on its resource endowments and demand dynamics.

3.2 Effects of GDP growth assumptions on energy security under different climate policies

Higher GDP growth assumptions result in higher global energy trade in the Baseline, but barely affect the trade under CP scenarios (Fig. 1). This is because (a) the total energy consumption is less affected by GDP growth in CP scenarios due to the lower energy intensity (especially in WITCH) and (b) because the economic growth under CPs is primarily fueled by non-tradable renewable energy sources.

The diversity of energy options is not significantly affected by GDP growth assumptions in any of the scenarios (Fig. 2). An exception is diversity of electricity and liquids under

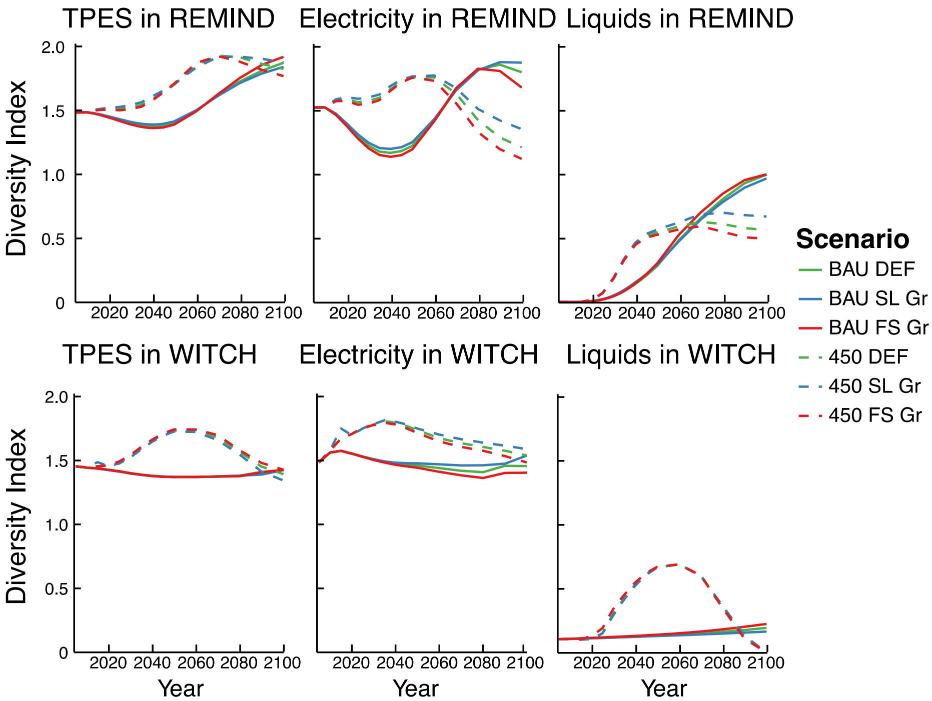

Fig. 2 Diversity of TPES, electricity and liquids in the Baseline and the 450 scenarios under different GDP growth assumptions

strict CPs in REMIND in the 2nd half of the century, when faster economic growth leads to more notable decline of diversity. This occurs because faster growth is supported by solar energy and biofuels which more rapidly penetrate electricity and liquids fuels, further accelerating the pattern already induced by climate policies as described in the previous section.

3.3 Effect of fossil fuels availability assumptions on energy security under different climate policies

In both models, the Baseline scenarios are dominated by fossil fuels. However, lower fossil fuel availability results in a higher share of bioenergy in WITCH (up to 25-27 % in BAU LO Fos as compared to negligible amounts under BAU HI Fos in 2100) and a higher share of renewable energies in REMIND (up to 40 % under BAU LO Fos as compared to some 16 % in 2100 under BAU HI Fos). Under CPs, the total energy supply and the energy mix are much less significantly affected by fossil fuel availability assumptions.

In the Baseline scenarios, higher availability of fossil fuels generally results in higher volumes of trade in these fuels, especially in the longer term. Lower availability of oil also results in higher trade in coal and gas, which substitute for oil in REMIND (Fig. 3). Thus, the overall global energy trade in the Baseline remains high even under low oil availability assumptions.

In the strict CP scenarios, the availability of fossil fuels does not affect the global oil or coal trade. However, low fossil fuel availability results in higher gas trade under CPs, especially earlier in the century. This occurs because the endowments of import regions are lowered disproportionately to those of export regions. At the same time, even under the lowest resource assumption, the trade in any fuel in the Baseline scenario is higher than the trade under any of the CP scenarios.

In the Baseline scenarios in REMIND, lower resource availability generally results in higher diversity of energy options (Fig. 4). This occurs because alternative energy options are introduced to replace scarce fossil fuels. The only exception is diversity of electricity at the end of the century, which is lower in the BAU LO Fos scenario because solar energy starts dominating electricity generation much like in the CP scenarios. In WITCH, low fossil fuel availability increases the diversity of liquids in Baseline scenarios due to substitution of oil products by biofuels, but otherwise resource availability has no distinct effect on diversity.

In CP 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 is liquid fuels in REMIND which become more diverse under low fossil availability, because scarcity of oil results in substitution of this dominating fuel by biofuels (Figure S-6 in SM).

4 Discussion

Our analysis shows that in the Baseline scenarios the global trade in fossil fuels would rapidly rise. At the same time, alternatives to oil in the transport sector are introduced slowly,

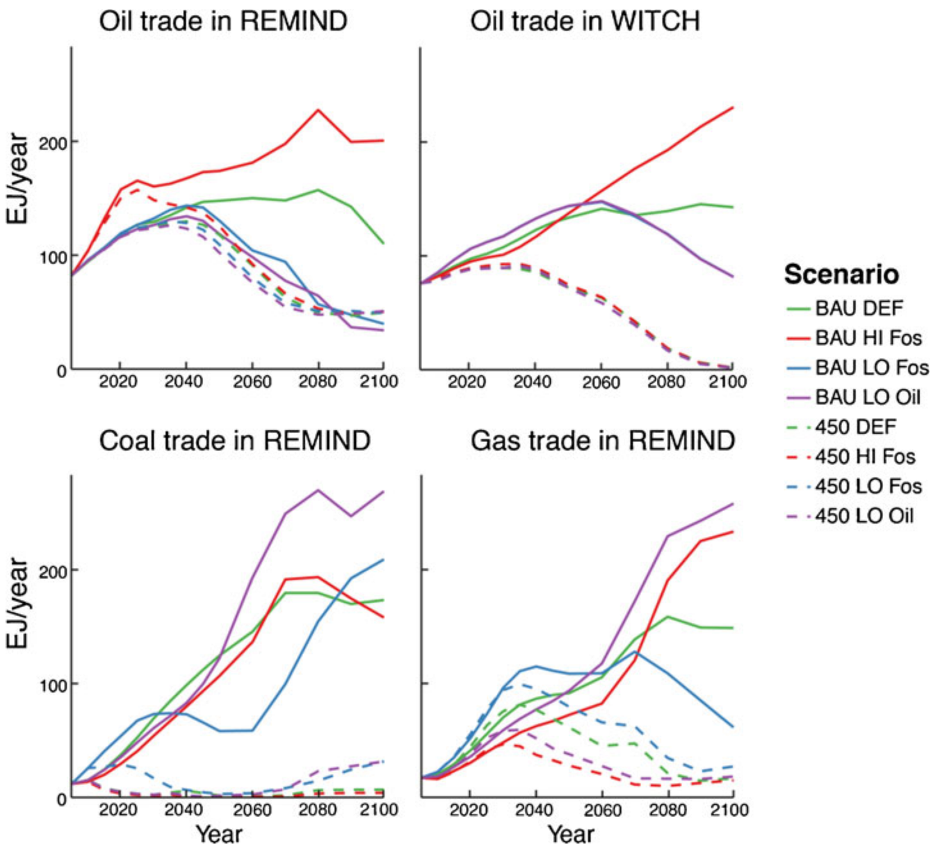

Fig. 3 Global energy trade in individual fuels depending on fossil fuel availability in REMIND and WITCH

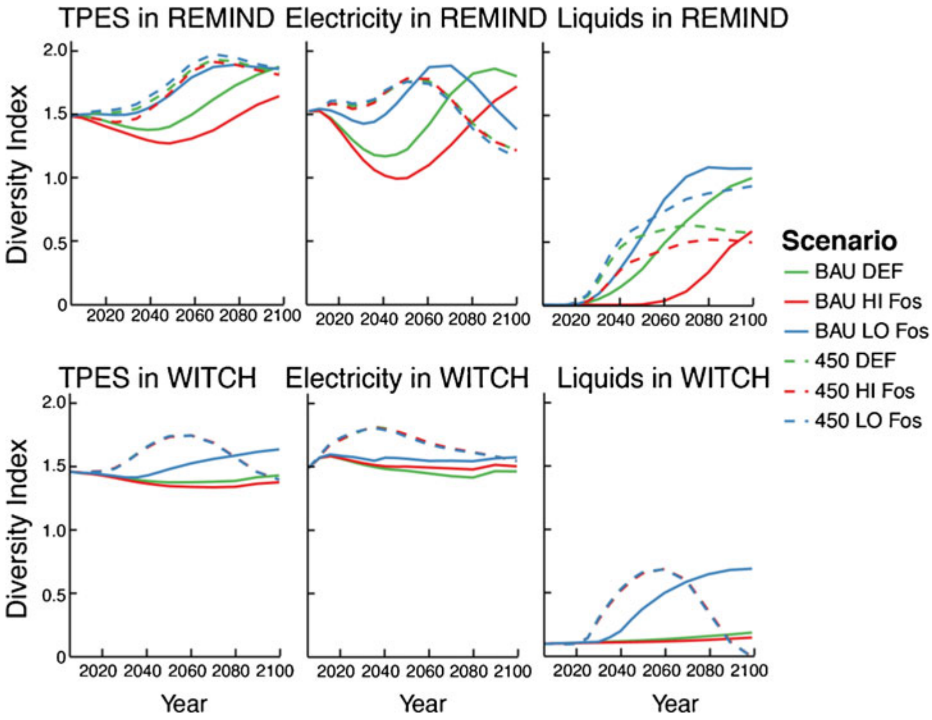

Fig. 4 Diversity of TPES, electricity and liquids in the Baseline and the 450 scenarios under different assumptions about fossil fuel availability

which means that disruptions of the global oil trade (including price fluctuations) would seriously affect this vital system essential for all modern societies.

Climate mitigation policies would radically lower the trade in fossil fuels as compared to the Baseline because of the lower energy demand and because the energy mix would be dominated by non-tradable renewable energy. The resilience of energy systems as reflected in their diversity would also be higher around the middle of the century when low-carbon and fossil energy sources coexist (Fig. 5, the top two graphs).

The overall energy trade in the 450 scenarios does not significantly depend on the GDP growth or fossil resources availability assumptions. In contrast, in the Baseline scenarios the trade in fossil fuels is highly sensitive to their availability (varying by as much as two times) and to economic growth assumptions (varying by as much as some 40 %). The diversity of energy systems under CPs is also not strongly affected by any of these assumptions. Thus, in CP scenarios, the vulnerability of energy systems is not only lower but also less uncertain than in the Baseline.

At the same time, climate policies may entail certain risks for energy security. For example, if unconventional oil resources are not exploited more regions would need to import oil. However, this would occur against the background of decreasing importance of oil and thus constitute a progressively declining risk. Climate policies may also result in dropping energy export revenues although these risks may be not so profound for conventional oil exporters (due to limitations on unconventional fossils and on coal- and gas-to-oil substitutes). The effect of climate policies on oil exports is described by Bauer et al. (2013) and (see also results for other these and other models in Jewell (2013, 131–141)).

With respect to diversity, climate policies may result in deep penetration of solar energy in the electricity sector and biofuels in the liquid fuels sector, particularly under high economic growth and low fossil fuel resource assumptions. This may reduce the diversity of these vital energy systems by the end of the century as shown in Fig. 5 (the bottom two graphs). By 2100, the diversity of electricity and liquids under CPs in REMIND may become lower than in the Baseline and, in the case of electricity, lower than at present. Such decrease in diversity may be especially pronounced in certain regions which will be using their domestic resources rather than relying on the global mix of tradable fuels as at present.

Although the two models present generally similar trends, there are certain differences between WITCH and REMIND as far as energy security is concerned. WITCH portrays a

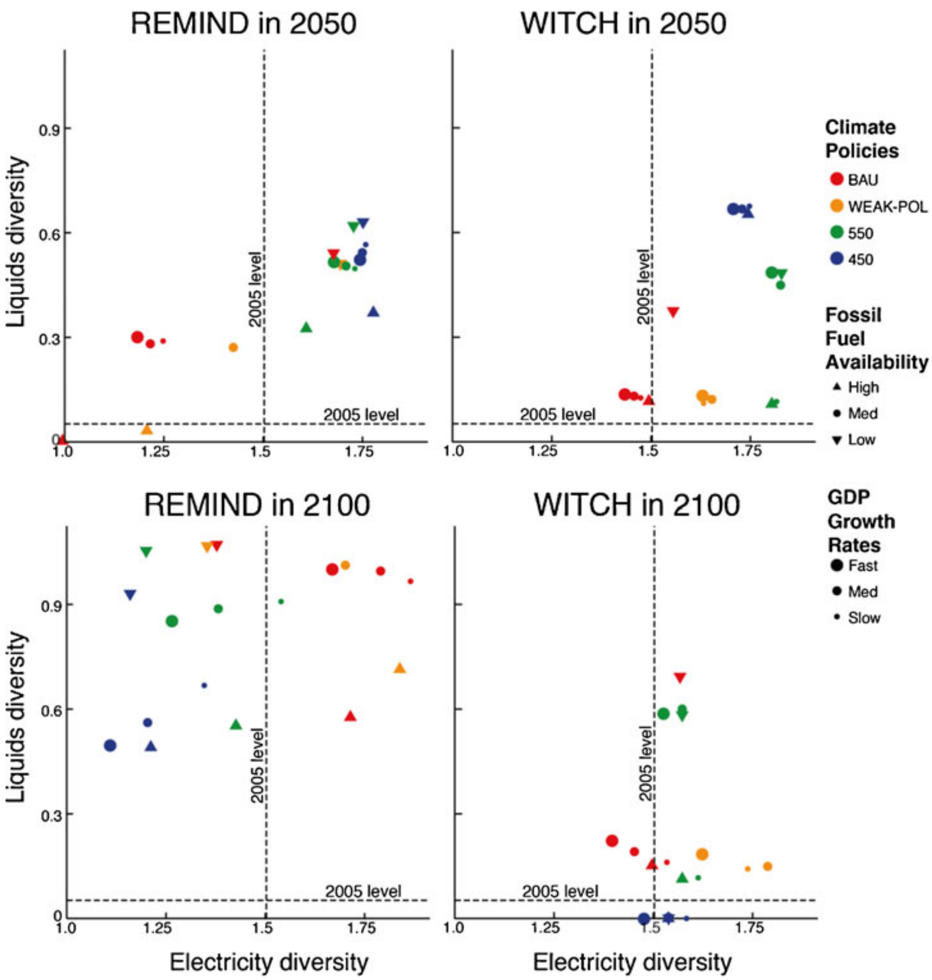

Fig. 5 Diversity of energy sources used in electricity and liquid fuels in 2050 and 2100 under different scenarios. The data points indicate the diversity of primary energy sources used for electricity generation and production of liquid fuels in 2050 (the top two graphs) and in 2100 (the bottom two graphs). The colors of the data points correspond to the strength of the climate policy, the shapes – to fossil fuel availability, and the sizes – to GDP growth assumptions. The dotted lines show the 2005 levels of diversity of liquid fuels and electricity. Any data point to the left of the vertical line or to the bottom of the horizontal line reflects potential insecurity

world where only oil is globally traded and thus exposure to trade risks is lower (especially under climate policies where oil is phased out) than in REMIND which is based on free and flexible trade assumptions and where gas and coal trade may exceed the present oil trade. On the other hand, WITCH does not allow a rapid increase of solar energy in electricity production or using synthetic fuels in liquids due to its more severe constraints on penetration of energy technologies. This makes the diversity of the electricity sector under strict CPs higher in WITCH and the diversity of liquids higher in REMIND.[3]

5 Conclusions

This article aimed to evaluate energy security in long-term scenarios with different stringency of climate policies and different assumptions about fossil resources availability and GDP growth. Our results show that climate policies would generally enhance energy security through reducing energy trade and increasing the diversity of energy options. At the same time, the exclusion of non-conventional fossil fuels as well as the potential domination of the electricity sector by solar energy and of liquid fuels by bioenergy may somewhat increase vulnerabilities of energy systems.

The limitation of this conclusion is that we analyse only trade in fossil fuels, whereas it is entirely plausible that bioenergy, synthetic fuels, hydrogen and even electricity may become globally traded on a large scale in the future. Nevertheless, analysis by Jewell et al. (2013a,b) indicates that this trade in 'new' fuels is unlikely to exceed the current levels of oil trade.

Another limitation is that this analysis is primary focused on the global level, whereas many of the current energy security concerns are most apparent at the *national* level. Though IAMs do not typically have the national-level granularity, future research should explore the applicability of these results to national energy security concerns starting with major economies.

The two models, REMIND and WITCH, considered in this analysis portray two different worlds of the future: one with higher global energy interdependence and high penetration of solar energy and one with high regional specialization, a more diverse electricity sector and dominance of bioenergy in liquid fuels. As emphasized in other studies (Jewell 2013, 165–166) these differences in long-term energy security profiles may reflect not only different modeling approaches, but may actually signal trade-offs between energy trade and diversity as shaped by different technology choices. There are many pathways to low-carbon future and energy security may be a consideration in choosing which of these paths are more feasible and desirable.

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[3] Kriegler et al. (this issue) provide a detailed explanation of the technological capabilities of the two models.

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