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Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices

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HIGHLIGHTS

- We explore energy security implications of long-term energy decarbonization scenarios.
- We define energy security as low vulnerability of vital energy systems.
- The trade-related risks are considerably lower in decarbonization scenarios.
- Diversity of energy systems is generally higher in the first half of the century.
- Vulnerability is lowest in scenarios with both high efficiency and renewable energy constraints.

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ABSTRACT

How would a low-carbon energy transformation affect energy security? This paper proposes a framework to evaluate energy security under long-term energy scenarios generated by integrated assessment models. Energy security is defined as low vulnerability of vital energy systems, delineated along geographic and sectoral boundaries. The proposed framework considers vulnerability as a combination of risks associated with inter-regional energy trade and resilience reflected in energy intensity and diversity of energy sources and technologies. We apply this framework to 43 scenarios generated by the MESSAGE model as part of the Global Energy Assessment, including one baseline scenario and 42 'low-carbon' scenarios where the global mean temperature increase is limited to 2°C over the pre-industrial level. By and large, low-carbon scenarios are associated with lower energy trade and higher diversity of energy options, especially in the transport sector. A few risks do emerge under low-carbon scenarios in the latter half of the century. They include potentially high trade in natural gas and hydrogen and low diversity of electricity sources. Trade is typically lower in scenarios which emphasize demand-side policies as well as non-tradable energy sources (nuclear and renewables) while diversity is higher in scenarios which limit the penetration of intermittent renewables.

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1. Introduction

A radical transformation of energy systems is required to reduce greenhouse gas emissions and avoid long-term consequences from global climate change. However, policy makers are typically more concerned with *immediate* (rather than long-term) and *national* (rather than global) effects of energy policies. One such immediate national issue is energy security. Thus, understanding energy security implications of climate mitigation policies is critically important for anticipating the degree of political support they are likely to command.

There are three main challenges to characterizing the energy security of low-carbon energy futures. First, there are scholarly disagreements on the meaning of and the ways to measure energy security. For example, there are debates on whether energy security includes economic, environmental and social considerations.[1] Other disagreements are over the most appropriate scale (national, regional, local, etc.) of analyzing energy security, the

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[1] For those scholars who consider environmental impacts of energy systems a "dimension" of energy security (Sovacool and Brown, 2010) the very question of the *relationship* between climate and energy security goals does not make sense, since in their view these goals are identical.

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extent to which energy security is a generic or context-dependent concept, the relative importance of various risks (geopolitical, technological, natural, economic) and the most appropriate methods of assessing energy security.

Second, even the existing academic and policy consensus on what energy security is and how it can be evaluated is not always possible to extend into long-term future scenarios. Most existing studies project present energy security concerns such as oil and gas trade and resource scarcity into the future (e.g. Turton and Barreto, 2006; Rozenberg et al., 2010; Costantini et al., 2007; Bollen et al., 2010). While these studies provide useful insights, they do not account for the fact that if energy systems undergo radical transformations (for example, if oil is no longer the dominant fuel in the transport sector), new energy security concerns (such as trade in biofuels) may replace current ones. Other studies provide a more generic approach to evaluating future energy security based on overall net import dependency (McCollum et al., 2011) or import dependency and diversity combined into a single indicator (McCollum et al., 2013). However, there is little evidence that real-life energy security policies are guided by such highly aggregated and generic indicators. Thus, an appropriate method to assess energy security implications of long-term climate policies should be both reflective of policy concerns and suitable for future energy systems that may be radically different from present ones.

Third, assessing long-term energy security requires a concrete, preferably quantitative, representation of a future, or a range of potential futures. Over the past several decades the development of Integrated Assessment Models (IAMs) (Leimbach et al., 2009; Rao and Riahi, 2006; van Vuuren et al., 2011; Manne and Richels, 2004; Bosetti et al., 2011) which present detailed quantitative descriptions of low-carbon futures has made this possible.

The purpose of this paper is to develop and apply a method for assessing energy security implications of low-carbon energy futures under different policy and technology choices. It overcomes the three limitations of present energy security studies by:

(a) formulating a coherent concept of energy security which both accurately reflects historic and current energy security policy concerns and yet is sufficiently generic to be applicable to energy systems which are radically different from present ones (Sections 2.1 and 2.2);
(b) translating this concept into a framework for assessing energy security under radical transformations of energy systems (Section 2.3);
(c) applying this assessment framework to the energy decarbonization pathways (described in Section 3) developed within the Global Energy Assessment (GEA, 2012) to assess energy security under various decarbonization scenarios (Section 4 presents the results Section 5 the discussion and Section 6 concludes with the policy implications).

2. Framework and indicators for evaluating future energy security

For the purposes of this analysis we define energy security as ‘low vulnerability of vital energy systems’. In line with the Global Energy Assessment (GEA) (Cherp et al., 2012) and other mainstream definitions of energy security (for an overview see Winzer (2012)), this definition is sufficiently flexible to be applicable in diverse situations, including in future energy systems which may be very different from present ones. Evaluating energy security in accordance with this definition involves (1) identifying vital energy systems including those which may emerge under future scenarios; (2) identifying vulnerabilities of such systems; and (3) developing, applying and interpreting indicators to characterize these vulnerabilities.

2.1. Vital energy systems

Energy security is about protecting energy systems whose failure may disrupt the functioning and stability of a society. Such *vital energy systems* can be defined in terms of their geographic boundaries (national, sub-national, regional or the world as a whole) or in terms of their sectoral boundaries (a primary energy source such as crude oil, an energy carrier such as electricity or an energy end-use such as transportation). Different combinations of geographic and sectoral boundaries yield a potentially large number of vital energy systems (e.g. “the global oil market“, “the European electricity network” or “transportation in China“) each of which can be the subject of an energy security assessment.

With respect to geographic boundaries, the current and historic focus of energy security policies has been national. This is logical, because historically nation states have been responsible for security in all areas and most energy policies are developed and implemented at the national level. At the same time, many contemporary energy security policies focus on regional or global energy systems rather than merely national ones. For example, the European Union's (EU) energy security policies address electricity systems in the EU and their integration with neighboring countries (European Parliament, 2006) as well as the Eurasian and global natural gas markets (European Union Council, 2004). Regional and global energy markets are also considered in energy security policies and policy-driven assessments in the UK (Wicks, 2009), Japan (Pant, 2006; Atsumi, 2007) and Australia (Australian Government Department of Resources Energy and Tourism, 2011, 2009). Concerns about the *global* oil market are clear from the presence and policies of international organizations such as the IEA and OPEC.

National, regional and global energy systems are likely to remain relevant to energy security in the future although their relative importance may change depending on the dynamics of energy trade and dependence. As explained in the next section, Integrated Assessment Models (IAMs) typically provide regional and global rather than national level resolution which restricts our energy security analysis to these two levels. However, the proposed framework can also be used for the analysis of national energy security if relevant data are available (for example, Jewell et al. (forthcoming) apply this framework to China, the EU, India and the US–major economies the size of global regions).

With respect to energy sectors, energy security studies typically focus on ‘security of supply’ comprised of primary energy sources. In particular, there is extensive literature on measuring security of oil supplies (see for example Gupta, 2008 and Greene, 2010). The IEA's Model of Short-term Energy Security (MOSES) evaluates oil, natural gas, coal, biomass, nuclear and hydropower supply as well as four energy carriers (biofuels and three types of oil products) (IEA, 2011; Jewell, 2011). There are a number of energy security studies which focus on electricity (Stirling, 1994; Grubb et al., 2006). Finally, a few studies focus on security of energy end-uses, sometimes called ‘energy services security’ (Jansen and Seebregts, 2009).

Projecting energy sectors into the future is less straightforward than projecting geographic boundaries of vital energy systems. In particular, key primary energy sources and energy carriers can change under radical energy transitions. For example, while oil lies at the heart of today's energy security concerns, over the long-term natural gas, electricity or biomass production could become central to ensuring energy security. Liquid energy carriers which today are mostly oil products could be replaced by biofuels,

Table 1
Vital energy systems used for evaluating energy security at present and for future energy scenarios.

	Geographic boundaries	Sectoral boundaries		
		Energy sources	Energy carriers	Energy end-uses
Present*	Sub-national, national, regional, global	Oil, natural gas, hydropower, nuclear, biomass, renewable energy sources (RES)	Oil products, biofuels, electricity	Transportation, industry, buildings, exports
Future	National**, regional, global	Oil, natural gas, hydropower**, nuclear**, biomass**, RES**	Oil products, synthetic fuels, hydrogen, electricity, biofuels	Transportation, industry, residential & commercial, exports**

Notes:
* As used in GEA (Cherp et al., 2012).
** Show energy systems which can potentially be evaluated but are not evaluated in this paper.

synthetic fuels[2], hydrogen or electricity. However, end-use sectors – transportation, industrial and residential & commercial – are unlikely to change in nature although their relative size and importance could. Thus, to evaluate future energy security we use generic categories of energy sources, energy carriers and energy end-uses. Table 1 compares these systems to the vital energy systems used in the analysis of present-day energy security in GEA (Cherp et al., 2012).

2.2. Vulnerabilities

The second step in constructing an energy security assessment framework is defining vulnerabilities of vital energy systems. As in the case of vital energy systems, vulnerabilities should be defined specifically enough to echo current and historical energy security concerns, yet generically enough to be applicable to future energy systems potentially very different from present ones.

Vulnerabilities of an energy system are a combination of its exposure to risks and resilience, i.e. its capacity to respond to disruptions. Some energy security assessments focus primarily on risks (e.g. APERC, 2007; Winzer, 2012), others focus primarily on resilience (e.g. Stirling, 1994, 2010) and some look at both risks and resilience (Kendell, 1998; Gupta, 2008; Jewell, 2011). Vulnerabilities may be physical (disruptions of energy flows) or economic (disruptive variations in energy prices and costs (see Keppler, 2007; Greene, 2010; Helm, 2002)) and may come in the form of shocks (rapidly unfolding short-term disruptions) or stresses (slowly approaching and longer-lasting phenomena) (Stirling, 2010; Cherp and Jewell, 2013).

The distinction between risks and resilience, physical and economic disruptions and shocks and stresses is relatively common in the literature, however, there is less agreement concerning more specific classification of vulnerabilities. The most widely proposed 'dimensions' of energy security cannot be used for the analysis of future energy security because of at least one of the following reasons:

1. They lack solid theoretic foundations and thus their use is limited to illustrating the current rather than conceptualizing potential future vulnerabilities. For example, the widely cited "four A's of energy security" – "Affordability, Availability, Accessibility, and Acceptability" – which are similar to the "five A's of health care" (Penchansky and Thomas, 1981), cannot be meaningfully used for assessing the vulnerability of energy carriers, energy end-uses or primary energy sources other than fossil fuels whose role in future energy systems may not be as important as today.
2. They are open to a wide variety of interpretations which makes quantification difficult. For example, the concept of 'affordability' (as well as a variety of related terms such as 'fair' or 'reasonable' prices) is for the most part used rhetorically and can be interpreted to mean stability of prices, competitiveness, low prices or even protection from energy poverty (Cherp and Jewell, 2013).[3]
3. They are too narrow and/or too data-intensive to be used for generic quantitative evaluations either in present-day or in future energy systems. This relates, for example to many of the over 300 indicators (ranging from "energy literacy of users" to "annual volume of sales from woodlots") for 20 dimensions of energy security proposed by Sovacool and Mukherjee (2011).

In this article we use a more universal way of structuring vulnerabilities which is based on generic 'perspectives' of energy security that have emerged over the last century (Table 2).

All three perspectives are likely to be relevant for analyzing energy security in the long-term although their nature may change as a result of low-carbon energy systems transformations. The sovereignty perspective has been around for over 100 years and is likely to persist in the future unless all types of polities and conflicting interests dissolve. At the same time, shifts in trade affecting national interdependencies and energy power balances would affect this perspective. Robustness concerns are not likely to subside but rather intensify as energy systems become more advanced, dynamic and integrated. Resilience is the most generic perspective since it does not depend on specific configurations of energy systems but rather reflects generic concerns arising from their exposure to complex and uncertain factors.

Shifting trade patterns, along with a growing reliance on renewable energy sources, would profoundly impact the geography of energy systems (network density, number and nature of connections and size of installations), which is at the heart of the robustness and resilience perspective. In some ways this transition would alleviate current concerns by, for example, avoiding choke points present in oil trade (Lehman Brothers, 2008). While a shift to renewables would mean increased deployment flexibility, both

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[2] Refers to liquefied coal and natural gas.

[3] The IEA remarks that "Energy insecurity stems from the welfare impact of either the physical unavailability of energy, or prices that are not competitive or overly volatile" (Lefèvre, 2007, 12). Extremely low energy prices are in many ways just as dangerous as high prices since they can lead to under-investment in resource extraction or infrastructure (Alhajji, 2008) as most recently evidenced by an electricity shortage in China during the summer of 2011 following caps on electricity prices.

Table 2
Three perspectives on energy security.
Source: Summarized from Cherp and Jewell (2011).

Perspective	Sovereignty	Robustness	Resilience
Historic roots	War-time oil supplies and the 1970s oil crises	Electricity blackouts and concerns about resource scarcity	Liberalization of energy systems
Key risks for energy systems	Intentional actions by malevolent actors	Predictable natural and technical factors	Diverse and partially unpredictable factors
Primary protection mechanisms	Control over energy systems and institutional arrangements to prevent disruptive actions	Upgrading infrastructure and switching to more abundant resources	Increasing the ability to withstand and recover from various disruptions
Parent discipline	Security studies, international relations, political science	Engineering, natural science	Economics, complex system science

in terms of location and size of generation, the hyper-scalability of renewable energy sources (Walker and Cass, 2007) also has a downside, potentially resulting in the emergence of trade patterns similar to those of oil or natural gas today.

Although the energy security assessment framework we propose is in principle sufficiently flexible to address all these evolving concerns, we could not quantitatively evaluate some of them in this article. This is due to limitations of the integrated assessment model (MESSAGE) that generated the scenario data for our analysis. Similar to most other IAMs, MESSAGE models energy mixes in and energy trade between 11 world regions but not the specific topography of energy infrastructure or the specific geography of energy trade. In particular, exact spatial locations of energy infrastructure are not modeled and neither are bilateral trade flows. Instead there is a global pool from or to which regions can buy or sell energy.[4] Thus, many interesting and important energy security concerns associated with spatial characteristics of energy flows and infrastructure could not be addressed by this analysis.

2.3. Indicators

Quantitative evaluations of energy security are used to compare energy security of different countries (Gupta, 2008; Gnansounou, 2008; International Energy Agency, 2011; Le Coq and Paltseva, 2009), or plot the evolution of energy security over time (Lefèvre, 2007; Löschel et al., 2010; Sovacool and Brown, 2010) including analyzing future energy security (Turton and Barreto, 2006; Costantini et al., 2007). All such evaluations use *indicators*: quantitative proxies of vulnerabilities of energy systems. Hundreds of energy security indicators have been proposed in dozens of scholarly articles and policy papers, but only a small number of them can be used for evaluating energy security under long-term energy scenarios. Indicators for evaluating future energy security should meet the following criteria:

1. They should be policy relevant to current and/or historical energy security concerns;
2. They should be sufficiently generic to be applicable to energy systems which are radically different from present ones;
3. They should be possible to calculate from available and meaningful data in the model or scenario which is being used to represent the future;
4. They should provide information which is additional to that provided by other indicators;
5. They should reflect key vulnerabilities of vital energy systems and clarify policy trade-offs.

Criteria (1) and (2) were already discussed in Section 2.2 and can be illustrated by our choice of indicators for the sovereignty perspective. Import dependency is commonly cited as a major driver of energy security policies and rhetoric (Kuzemko, 2011; Greene, 2010). The global proxy of this measure is interregional energy trade[5] (expressed as absolute volume and relative to the total primary energy supply (TPES)). The other sovereignty indicator we use is the geographic concentration of exports of a particular fuel or carrier as measured by the diversity of exporting regions contributing to the tradable share of an energy commodity (Lefèvre, 2010; Costantini et al., 2007). This reflects the current energy security concern associated with oil that it is only produced in a small number of countries and regions. To meet criteria (2) and (5), we apply these two indicators not only to oil and gas, which dominate energy trade today, but also to coal and "new-fuels" (hydrogen, biofuels and synthetic fuels) which could become important in the future.

The resilience perspective is particularly relevant to criterion (2) since the future is associated with many complexities and uncertainties. The most commonly used indicator for resilience is the Shannon-Wiener diversity index which was first applied to electricity systems (Stirling, 1994) and has been subsequently used in Jansen et al. (2004), O'Leary et al. (2007) and many other studies. Finally, energy intensity is a commonly used indicator of an economy's ability to deal with both physical and economic shocks and stresses (Gnansounou, 2008; Cherp et al., 2012).

A note should also be made about the indicators which we excluded because they did not meet one or more of the five criteria. Of all robustness indicators, very few can be meaningfully estimated in IAMs (i.e. they do not meet criterion 3). This is because most infrastructural attributes of energy systems are either not represented or are endogenously optimized (for example the replacement of power plants follows planned retirement ages which renders meaningless a key robustness concern such as ageing). Resource extraction compared with known reserves and resources is a robustness indicator which can in principle be analyzed in IAMs (Turton and Barreto, 2006; Kruyt et al., 2009). Due to space limitations we do not include this indicator in the present analysis but instead refer the reader to several related

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[4] Except with natural gas trade for which bilateral trade is depicted for certain regions.

[5] In many instances interregional energy trade represents realistic energy security concerns (e.g. EU and China energy imports). In some other cases more granular representation of energy trade between nations rather than simply between world regions would be preferable. However, energy trade between individual nations so far cannot be modeled in long-term energy scenarios.

Table 3
Indicators of long-term energy security.

Energy systems		**Perspectives**	
		Sovereignty	**Resilience**
Primary energy sources	**Total Primary Energy Supply (TPES)**	Global energy trade (absolute and relative to the TPES) and Net import dependence*	Diversity of TPES and Energy intensity
	Oil, gas, coal	Global fuel trade Regional diversity of fuel exports	
Carriers	**Hydrogen, synthetic fuels, electricity, biofuels**	Global trade in carrier Regional diversity of carrier exports	Diversity of primary energy sources used in carrier production
End-use sectors	**Transport, industry, residential & commercial**		Diversity of primary energy sources used in end-use sector

Notes: All indicator formulas are presented in the Appendix along with additional indicators which could be used in another study. All resilience indicators can be applied at both the global and regional level. Most sovereignty indicators can be applied at the global level except for net import dependence (marked with *) which is applied at the regional level.

studies exploring similar sets of de-carbonization scenarios (Jewell et al., forthcoming; McCollum et al., in press). Finally, some indicators were excluded because they did not meet criteria 4; for example costs of imports and import dependence of specific end-use sectors did not provide information additional to the more generic import dependence indicator.

3. Methods and scenarios

We use the indicators developed in Section 2 and summarized in Table 3 to evaluate energy security under a set of de-carbonization scenarios generated by the MESSAGE IAM (Rao and Riahi, 2006; Messner and Strubegger, 1995; Riahi et al., 2007) in the framework of the GEA (Riahi et al., 2012). We compare the energy security under these transformational scenarios – further referred to as “low-carbon scenarios” –to the energy security under a Baseline (counterfactual) scenario also from the GEA. Since these scenarios provide detailed quantification of future developments of the energy system for various energy supply and demand-side configurations, we are able to apply each indicator to either the energy system as a whole (for example we measure the energy intensity for the economy as a whole) or a set of energy subsystems (for example, regional diversity of fuel or carrier exports for each globally traded fuel or carrier—seven in all: oil, gas, coal, hydrogen, electricity, synthetic fuels and biofuels). This application of the framework illustrates how the objective of measuring energy security can be combined with the concept of vital energy systems in order to provide a rigorous and robust evaluation of energy security under de-carbonization scenarios.

In all low-carbon scenarios the increase in the global mean temperature is stabilized with 50% probability to 2°C above pre-industrial levels by 2100 under medium GDP and population growth projections (in other words GHG concentration is stabilized at 450 ppme). This requires massive changes in both supply- and demand-side energy technologies so that the greenhouse gas (GHG) emissions from energy systems decline over the 21st century in stark contrast to the Baseline scenario as shown in Fig. 1. The exact nature of these changes varies among the low-carbon scenarios depending on the supply- and demand-side configurations as described below.[6]

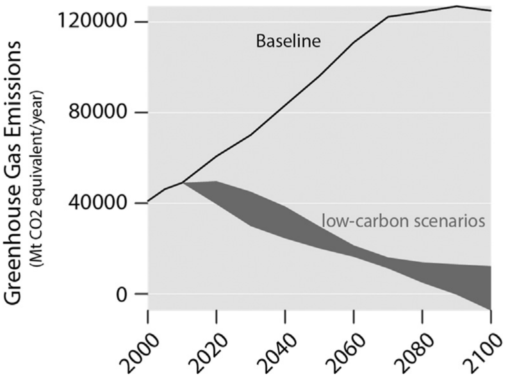

Fig. 1. Annual GHG emissions in the Baseline and low-carbon scenarios.

There are three dimensions of technological and policy choices which potentially affect energy security in the low-carbon scenarios. The first dimension concerns energy demand, where the low-carbon scenarios fall into three groups:

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

Fig. 2 shows energy intensity in the three groups of scenarios. Under a given GDP assumption, higher energy intensity translates into higher demand while lower intensity translates into lower demand.

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

- Limited renewable energy sources (limitRES) scenarios where intermittent solar and wind energies make up no more than 20% of final energy consumption;
- Limited bioenergy (limitBE) scenarios with bioenergy limited to no more than 50% of the estimated global potential;

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[6] This article highlights the main characteristics of low-carbon scenarios with a focus on energy-system changes which are particularly relevant to energy security. More extensive documentation can be found in the GEA report (Riahi et al., 2012) and the GEA web-database (http://www.iiasa.ac.at/web-apps/ene/geadb).

Table 4
Low-carbon scenarios of energy transitions analyzed in this article.

	Supply		**Mix**		**Efficiency**	
	Advanced transport	**Conventional transport**	**Advanced transport**	**Conventional transport**	**Advanced transport**	**Conventional transport**
Full portfolio of supply options	SupplyATR Full	SupplyCTR Full	Mix ATR Full	MixCTR Full	EfficiencyATR Full	EfficiencyCTR Full
Limited renewable energy sources	SupplyATR limitRES	–	MixATR limitRES	MixCTR limitRES	EfficiencyATR limitRES	EfficiencyCTR limitRES
Limited bioenergy	Supply ATR limitBE	–	MixATR limitBE	MixCTR limitBE	EfficiencyATR limitBE	EfficiencyCTR limitBE
Limited RES & Limited bioenergy	–	–	–	–	EfficiencyATR limitRES & limitBE	EfficiencyCTR limitRES & limitBE
Nuclear phaseout (noNUC)	SupplyATR noNUC	SupplyCTR noNUC	MixATR noNUC	MixCTR noNUS	EfficiencyATR noNUC	EfficiencyCTR noNUC
No carbon capture and storage	–	–	MixATR noCCS	MixCTR noCCS	EfficiencyATR noCCS	EfficiencyATR noCCS
Nuclear phaseout & No carbon capture and storage	–	–	–	–	EfficiencyATR noNUC & noCCS	EfficiencyCTR noNUC & noCCS
No bioenergy CCS*	SupplyATR noBECCS	–	MixATR noBECCS	–	EfficiencyATR noBECCS	EfficiencyCTR noBECCS
No additional carbon sinks beyond the baseline*	SupplyATR noSinks	–	MixATR noSinks	MixCTR noSinks	EfficiencyATR noSinks	EfficiencyCTR noSinks
No bioCCS & No sinks & Limited BE*	–	–	–	–	EfficiencyATR noBECCS & noSinks & limitBE	EfficiencyCTR noBECCS & noSinks & limitBE

Note:

* These type of constraints had only a small effect on energy security and while included in the analysis are not specifically mentioned in the paper. Cells marked with "-" denote scenarios where the low-carbon energy transformation was found infeasible under the given combination of energy demand and supply-side restrictions.

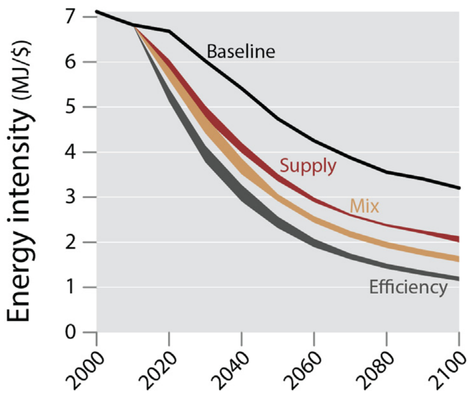

Fig. 2. Energy intensity in the Baseline and low-carbon scenarios.

- Nuclear phaseout (noNUC) scenarios where no additional nuclear capacity is built after 2020 and all nuclear power is phased out by 2060;[7]
- No carbon capture and storage (noCCS) scenario with no development of carbon capture and storage (CCS);
- No bioenergy CCS (noBECCS) scenarios where CCS technologies are not applied in conjunction with biomass combustion;
- No carbon sinks beyond the baseline scenarios where additional (non-energy) carbon sinks are not created.

The third dimension of choices within the low-carbon scenarios concerns the configuration of transport systems, namely:

- Conventional transportation (CTR) scenarios with transport systems relying primarily on liquid fuels;
- Advanced transportation (ATR) scenarios with transport systems increasingly relying on electric and hydrogen propulsion of vehicles.

Not all combinations of demand, supply and transport constraints are present among low-carbon scenarios. "Efficiency" scenarios allow for climate goals to be reached with a broader range of supply-side constraints (e.g. a combination of limitRES and limitBE or noNUC and noCCS). "Supply" scenarios allow for relatively few supply-side constraints (e.g. nuclear phaseout combined with no development of CCS is not possible). Similarly, "ATR" allows for more flexibility in the energy system and can meet 2°C stabilization under a wider range of energy supply restrictions. The full list of scenarios is presented in Table 4.

Different levels of energy demand and alternative assumptions about possible restrictions for supply-side technologies have major implications for the future portfolio of energy options. The GEA scenarios depict many possible evolutions of the energy system, exploring alternative routes of low-carbon energy transitions. Some scenarios are for example characterized by a relatively high contribution of renewables while others emphasize carbon capture and storage or nuclear energy. Energy technologies in the transport sector are also varied ranging from advanced electrification to continuous reliance on liquid fuels. Primary energy portfolios of the low-carbon scenarios for which we conduct our energy security analysis are shown in Fig. 3. For a more detailed discussion of the GEA scenarios, see Riahi et al., (2012).

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[7] This assumes a 40-year life-span for nuclear power plants.

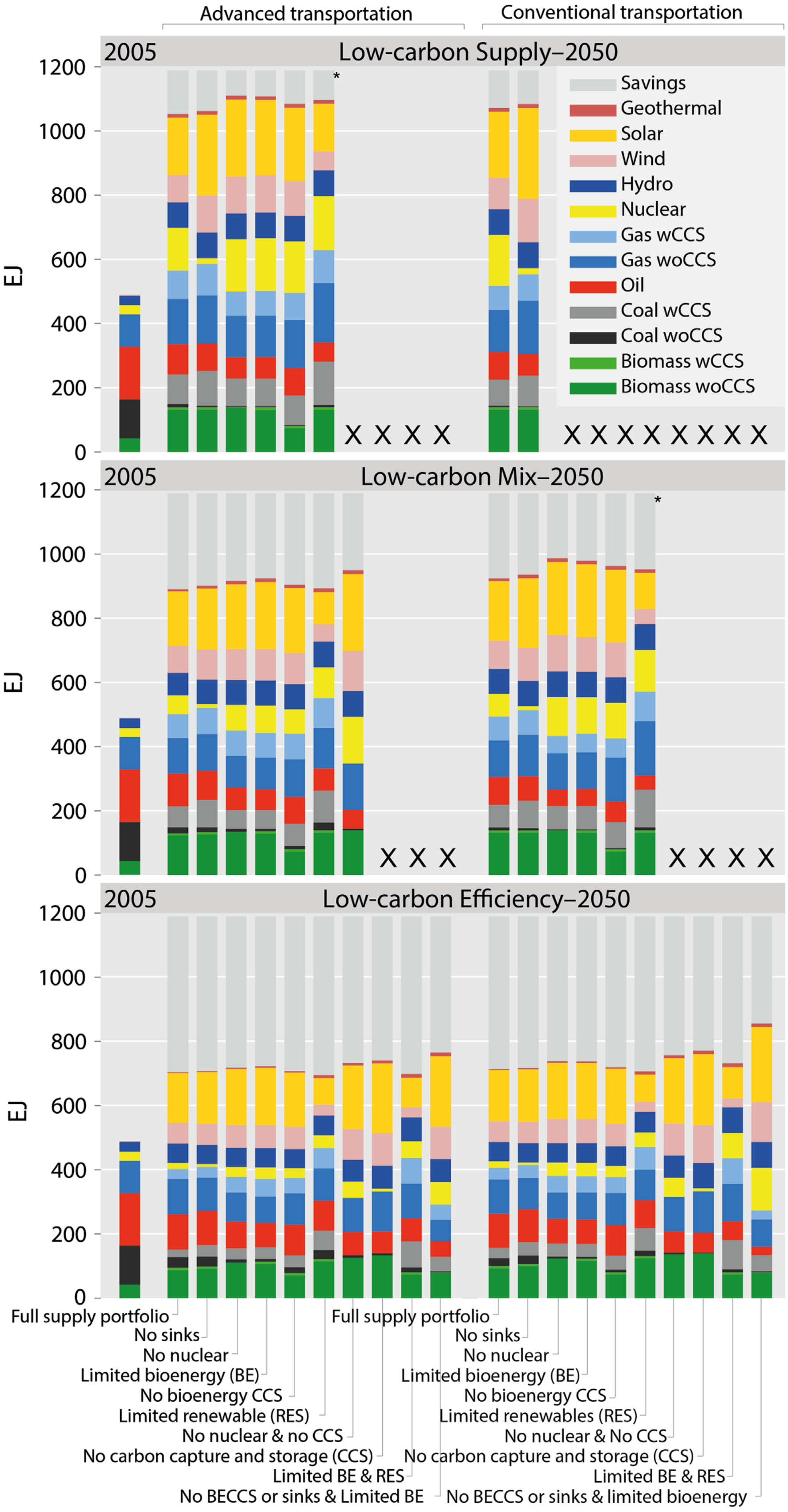

Fig. 3. Composition of the global TPES in 2005 and 2050 for low-carbon GEA scenarios. *Note*: figure modified from Riahi et al., (2012). 'X's indicate infeasible pathways.

4. Results

This section presents the results of assessing energy security in the GEA energy scenarios listed in Table 4 using the indicators listed in Table 3.

4.1. Sovereignty

4.1.1. Global energy trade

In the Baseline scenario, with a higher level of demand and a high reliance on fossil fuels, global energy trade rises dramatically from the current 100 EJ/year to over 400 EJ/year by 2100. The levels of trade in the low-carbon scenarios are much lower, ranging from 40 EJ/year to 240 EJ/year by 2100. Trade initially rises in all low-carbon scenarios and declines in the second half of the century in certain Efficiency and Mix scenarios (Fig. 4). The lower level of trade in low-carbon scenarios is explained by (a) generally lower energy supply and use (especially in the Efficiency scenarios) and (b) a higher share of non-tradable energies (renewables and nuclear)[8] in the energy mix.

The impact of technology and policy choices on the levels of global energy trade is illustrated in Fig. 5. In general, the volume of trade correlates with the overall level of energy demand: under other equal assumptions, trade in Supply scenarios is higher than in Mix scenarios which is in turn higher than in Efficiency scenarios since higher overall demand increases the demand for tradable fuels.

In all Supply scenarios, energy trade increases to about one and a half times current levels by 2030. In Supply scenarios with no nuclear or with limited renewables trade continues to rise for the rest of the century. This is because when domestic sources (nuclear energy and renewables) are limited, the energy system is forced to use more globally-traded fuels. In all other supply scenarios, where the share of non-tradable energies (nuclear and renewables) in the energy mix is much higher, energy trade plateaus at ~100–140 EJ/year by 2100.

In all Mix scenarios, global energy trade rises to ~120–130 EJ/year by 2030. Subsequently the highest trade is in scenarios in which conventional transport is combined with limitations on renewables; these constraints require more tradable fuels in the energy system since the transport system continues to be dependent on liquid fuels and there are limitations on domestic sources. In contrast, the lowest trade is under advanced transport with no limitations on nuclear or renewables, especially combined with limitations on CCS. All of these supply choices lead to higher shares of non-tradable sources and electricity as a carrier in the energy mix.

In the majority of Efficiency scenarios, the initial moderate rise in energy trade is followed by a decline below the current levels by the end of the century. In Efficiency scenarios with limited renewables, energy trade does not decline and when limited renewables are combined with conventional transport and limited bioenergy the trade actually rises by the end of the century to about two and a half times the current level because of continued dependence on traded energy.

In summary, the higher the demand, the more easily the rise of energy trade is triggered by additional constraints:

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

Energy trade intensity (shown in Fig. 6) rises in the Baseline scenario from the current 20% to 25% by 2030 before leveling off at ~20%. In contrast, in all low-carbon scenarios, trade intensity peaks at a lower level and declines after 2030. Unlike trade volumes, trade intensity does not notably vary across Supply, Mix and Efficiency scenarios: though Efficiency scenarios are generally associated with lower trade volumes the overall energy demand is also lower which results in similar trade intensity to Supply and Mix scenarios.

At the same time, trade intensity is affected by supply-side constraints. In scenarios with no limitations on renewables, trade intensity declines to 1–10% by the end of the century. When renewables are limited, this decline is less pronounced (11–15% by the end of the century) since the world is pushed to using more tradable fuels. If limiting renewables is combined with conventional transport and limited bioenergy, the trade intensity of the low-carbon scenario is only marginally lower than that observed in the Baseline since the transport system continues to be dominated by liquids but is unable to take full advantage of domestic biofuels.

4.1.2. Regional energy balances

A detailed analysis of regional energy security in low-carbon scenarios is beyond the scope of this article. Instead we present selected data to illustrate how the global picture may be reflected at the regional level.

Though in general regional import dependencies follow global trends they are also influenced by a region's resource availability and pace of economic development. Fig. 7 shows the import dependency of Western Europe and South Asia and the exports of the Middle East and North Africa region. Import dependency of both importing regions is lower than in the Baseline and is generally higher in scenarios with limited renewables since for both of these regions, their main domestic energy source is renewables. At the same time, the import dependency of Western Europe either declines or stays similar to the current level whereas in South Asia it initially peaks and in some scenarios stays above the current levels. While net energy exports from the Middle East and North Africa dramatically fall in all low-carbon scenarios and in the Baseline, the annual export volumes from this region initially rise before leveling off at current levels in the latter half of the century.

4.1.3. Trade in individual fuels

Fig. 8 illustrates the trade in fossil fuels, which currently makes up the bulk of the global energy trade. The most striking difference between the Baseline and low-carbon scenarios is in relation to oil trade. Whereas in the Baseline scenario, oil trade steadily rises and more than doubles by the end of the century, in low-carbon scenarios it peaks around 2030 and then rapidly declines as oil is phased out of the energy system in order to decarbonize.

Natural gas trade rises in both the Baseline and low-carbon scenarios in the first half of the century. In the second half of the century, the trade in the Baseline continues to rise reaching over

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[8] Nuclear energy is generated from uranium resources and enriched fuel, both of which are traded, however these were excluded for both theoretical and practical reasons. Since refueling a nuclear power plant typically provides fuel for two to three years (Nelson and Sprecher, 2008) and nuclear fuel can even be stockpiled for up to ten years (IAEA, 2007), most countries use nuclear energy as a way to curtail risks from imported fossil fuels. Practically, MESSAGE does not depict trade in either raw uranium and to the best of our knowledge no global IAM depicts trade in either enriched nuclear fuel or nuclear power plant components, which are the biggest energy security issues for nuclear power (Cherp et al., 2012).

100 EJ/year (more than oil trade at present). At the same time the low-carbon scenarios diverge falling roughly into three groups:

(a) In one Supply and one Mix scenario with limitations on renewables, gas trade increases to levels comparable to the Baseline and exceeding present-day oil trade volumes. In these scenarios, with limited renewables, natural gas continues to be a critical part of the energy system until the end of the century (marked with dark gray lines in Fig. 8).

(b) In several scenarios, gas trade plateaus (with some gradual growth or decline) at levels below the present volumes of oil trade and below the Baseline. These scenarios are: Supply combined with nuclear phase-out (leading to gas being used in electricity); Supply or Mix combined with conventional transport (leading to the use of gas-to-liquids in transport); Mix or Efficiency combined with limited renewables (leading to a lack of alternatives to gas); and Efficiency combined with conventional transport and limited bioenergy (leading to gas liquids being used in transportation instead of biofuels).

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

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

In addition to traditionally traded fossil fuels, some scenarios include significant trade in “new” fuels and carriers: biofuels, synthetic fossil fuels, and hydrogen (Fig. 9). In the Baseline scenario the trade in biofuels rises after 2040 to ca 20 EJ/year by the end of the century. In low-carbon scenarios, trade in biofuels increases to comparable levels (earlier in the century), but less so in scenarios where the production of bioenergy is limited since this in turn limits the extent of biofuel use. In all scenarios the levels of trade in biofuels are two to ten times lower than the volumes of oil trade at present. The trade in synthetic fuels (liquids produced from coal or gas) in the Baseline scenario rises over 40 EJ/year but stays below 12 EJ/year in all low-carbon scenarios.

In contrast to synthetic fuels, hydrogen trade is present in some low-carbon scenarios, but not in the Baseline scenario. Towards the end of the century, trade in hydrogen rises to levels comparable to oil trade today in Supply scenarios with advanced transport or a phaseout of nuclear energy. For the advanced transport scenarios this is because these scenarios assume a higher potential for fuel cell technologies which when combined with high demand drives up hydrogen trade. For the nuclear phaseout scenarios, this is because limitations on nuclear energy limit the number of regions where it is economically feasible to produce hydrogen, for which there is high demand around the world.

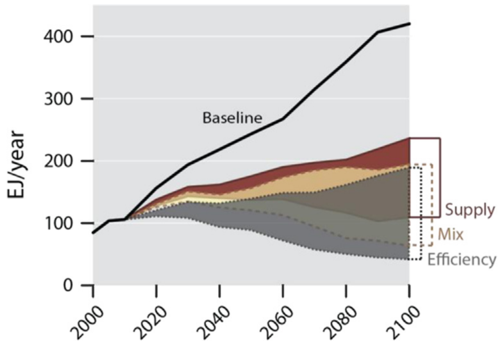

Fig. 4. Global energy trade in the Baseline and low-carbon scenarios.

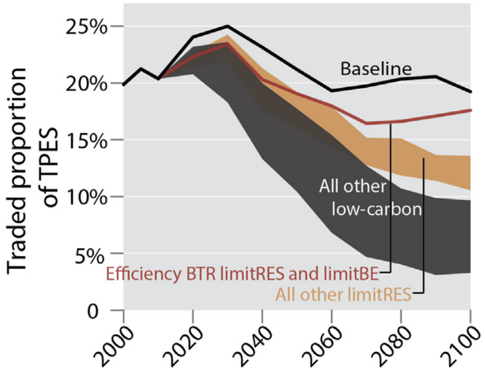

Fig. 6. Global trade intensity.

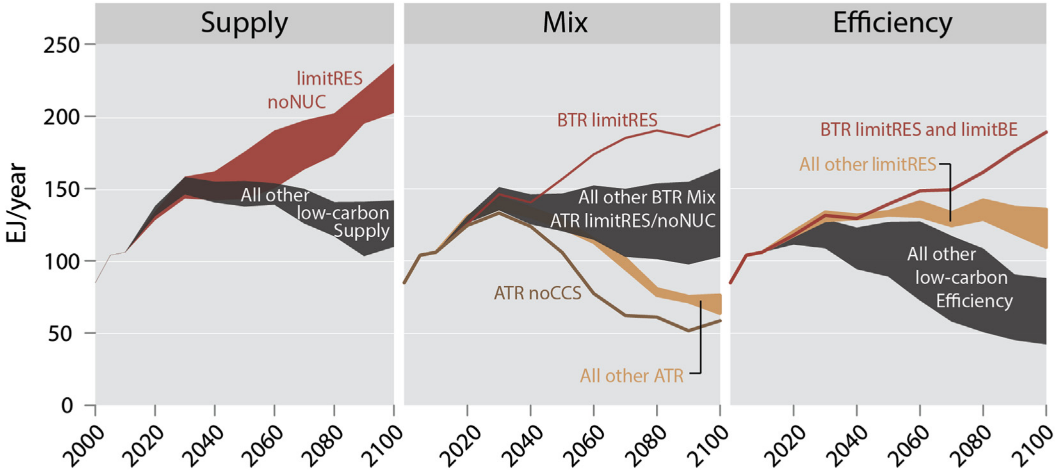

Fig. 5. Global energy trade and choices within the low-carbon scenarios.

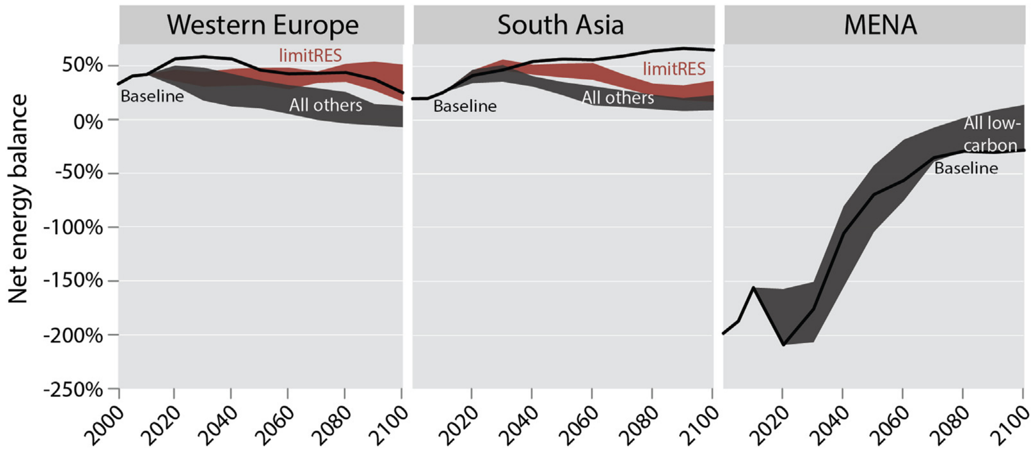

Fig. 7. Net energy balance of selected regions.

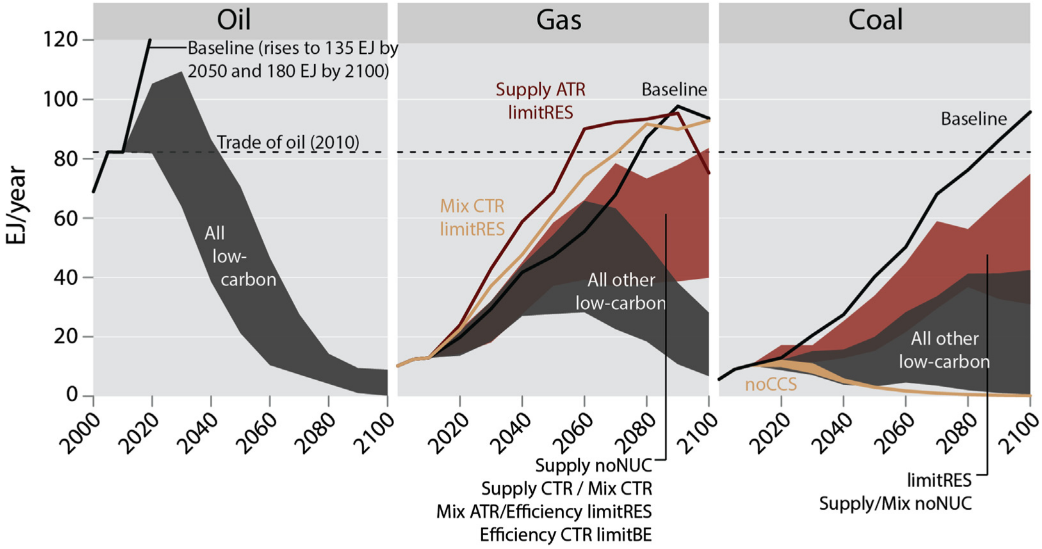

Fig. 8. Global trade in fossil fuels.

High volumes of trade may be especially risky if the fuel in question is primarily produced in a limited number of regions. Fig. 10 illustrates the geographic concentration of exports of tradable gas, coal and hydrogen (i.e. the fuels which are highly traded in some low-carbon scenarios).

In the case of limited renewables and other scenarios associated with higher gas trade (groups (a) and (b) in the explanation to Fig. 8 described on page 7) natural gas is indeed produced in fewer and fewer regions. This is because natural gas resources are unevenly distributed and large volumes of extraction inevitably lead to increasing geographic concentration of exports. In fact, in these scenarios (as well as in the Baseline) gas exports may become far more geographically concentrated than oil exports today.

Fig. 10 also illustrates that the geographic diversity of coal exports remains high even in scenarios with higher coal trade. The same is true with respect to biofuels (not shown on the Figure). This is because coal and bioenergy resources as well as the capacity to produce hydrogen are more evenly distributed around the world than natural gas or oil resources. The geographic diversity of hydrogen exports remains high under most scenarios but not all. Under supply scenarios with no nuclear development, the geographic diversity of hydrogen exports dips to that of oil's today. This is because the limitations on nuclear limit where it is economically-feasible to produce hydrogen.

4.2. *Resilience*

4.2.1. *Energy intensity*

Fig. 2 illustrates that energy intensity in low-carbon declines at a much faster rate than in the Baseline. This decline in energy intensity means gains in energy security as economies become less sensitive to energy price fluctuations.[9]

4.2.2. *Diversity of primary energy supply*

Fig. 11 illustrates the diversity of energy sources in the total primary energy supply (TPES), electricity generation and the transport sector. The diversity of TPES and electricity show largely similar trends: in the Baseline scenario it slowly but steadily rises whereas in low-carbon scenarios it rapidly rises between now and 2030 or 2040 and then either declines (to levels below the

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[9] Energy intensity is an endogenous variable in these low-carbon scenarios and therefore its decline is essentially programmed in the model rather than being an independent outcome of pursuing climate protection targets.

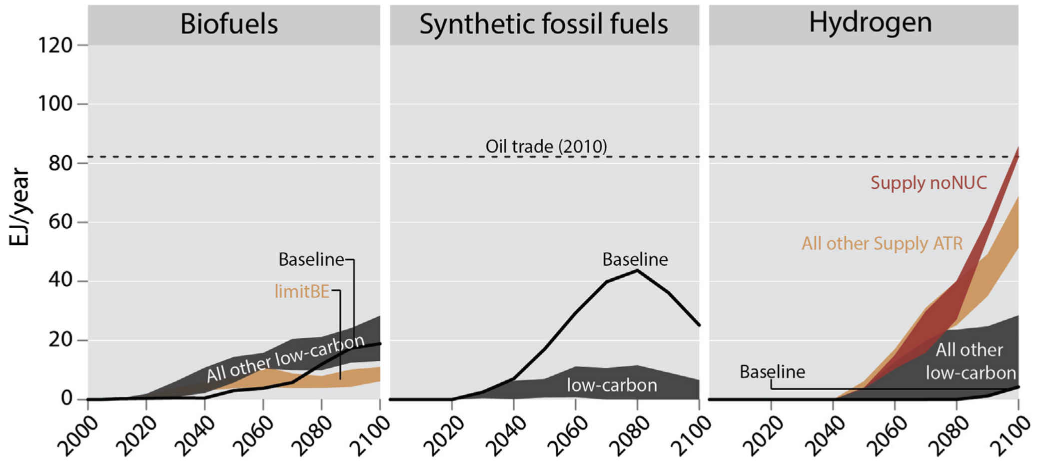

Fig. 9. Global trade in “new” fuels and carriers.

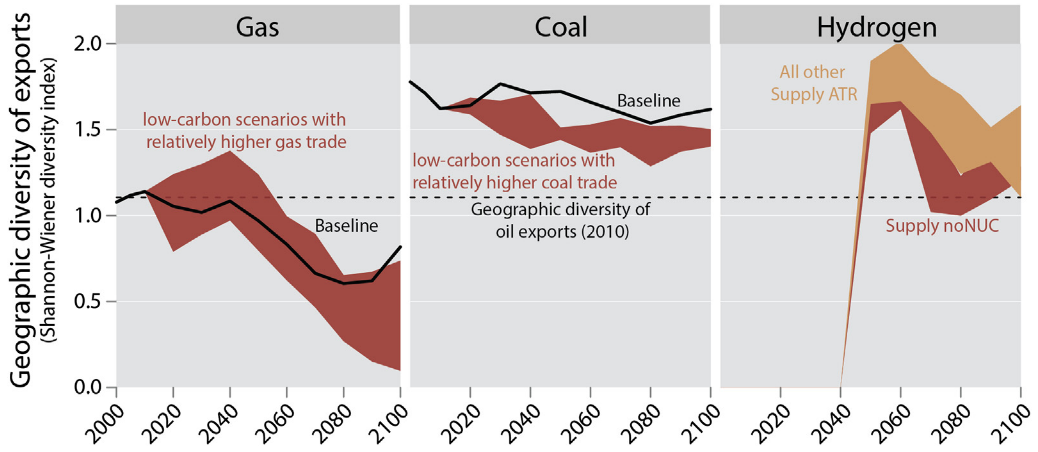

Fig. 10. Geographic diversity of supply of fuels with the highest global trade (depicted in Figs. 8 and 9).

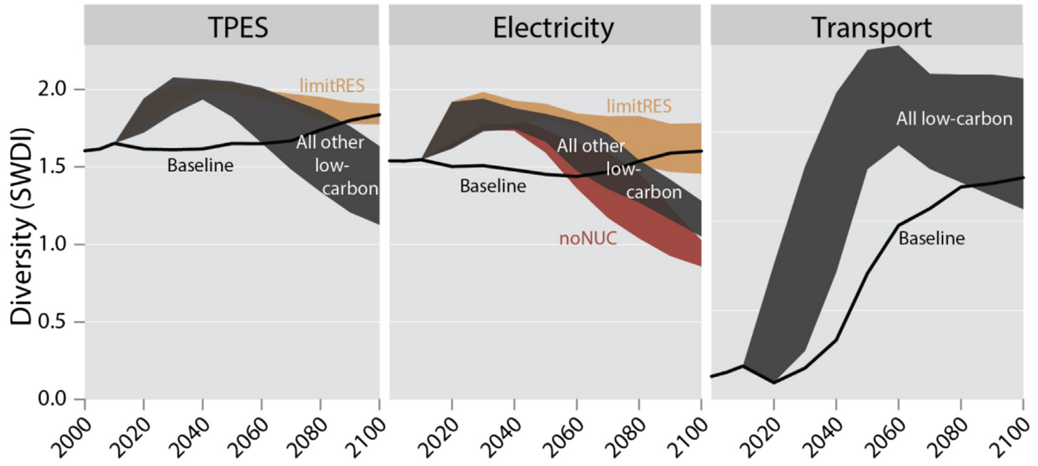

Fig. 11. Diversity of TPES, Electricity and Transport sector.

Baseline and the present value) or stays at an elevated level depending upon supply options. The mid-century peak in diversity in low-carbon scenarios occurs when “old“ and “new“ energy technologies coexist, it starts declining as the low-carbon energy sources replace carbon-intensive ones.

In scenarios with limited penetration of renewables, the diversity of TPES and electricity generation is comparable to the baseline development and generally higher than today's diversity by the end of the century. This is because with limitations on renewables, no energy source is able to dominate the energy mix. In contrast, in scenarios with a phaseout of nuclear energy the diversity of electricity production declines to significantly lower levels than both the Baseline and the present value.

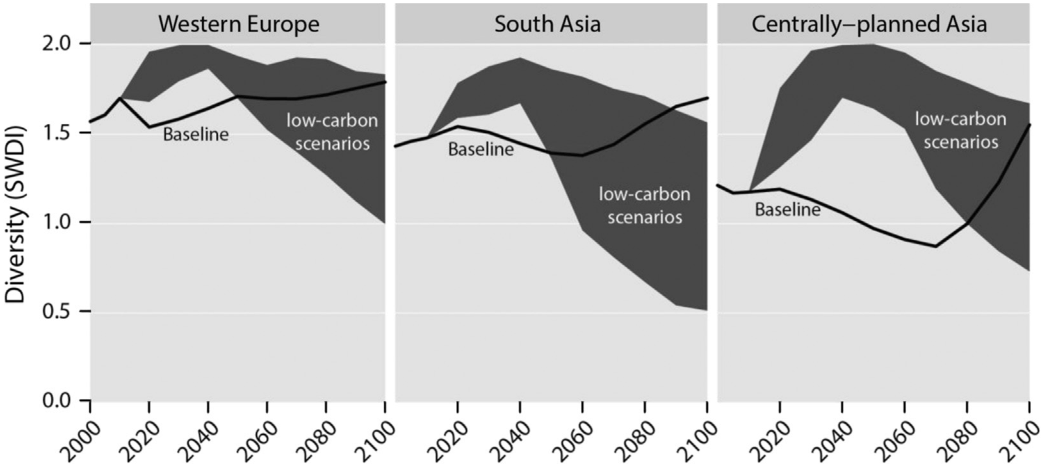

Fig. 12. Regional diversity of TPES.

The low diversity of energy sources used in transport is one of the main energy security concerns at present (Cherp et al., 2012). Diversity in this sector rises much more rapidly and stays higher for most of the century in low-carbon scenarios than in the Baseline. In other end-use sectors (industry as well as residential and commercial) the diversity of energy sources does not change significantly in either the Baseline or low-carbon scenarios.

In summary, the diversity of energy options in the medium-term (20–50 years) is higher in low-carbon scenarios than in the Baseline. In the longer term, the diversity of some low-carbon scenarios drops below the diversity of the Baseline because of the dominance of renewables, particularly in scenarios where renewables are not limited or where nuclear energy is.

4.2.3. *Diversity of energy supply at the regional level*

Fig. 12 shows TPES diversity in Western Europe, South Asia (dominated by India) and Centrally-planned Asia (dominated by China). It illustrates that whereas the three representative regions generally repeat the global pattern (compare with Fig. 11, first graph), there are certain regional differences. For example the rise-decline pattern is more profound in the region which is dominated by rapidly developing China (Centrally-planned Asia). Diversity also reaches lower levels in populous South Asia with limited energy options.

5. Discussion

This section discusses how the long-term evolution of energy security in low-carbon scenarios depends on policy and technology choices.

5.1. *Energy security in low-carbon scenarios*

Table 5 lists selected energy security indicators in 2010, 2050 and 2100 in low-carbon scenarios and the Baseline.

By 2050, low-carbon scenarios perform better than the Baseline with respect to all energy security indicators except natural gas trade, which is higher in some scenarios. Especially notable are the decrease in oil trade and the increase in diversity of energy used for transport and electricity production.

By 2100, the picture becomes more nuanced. The overall energy trade and oil trade are both lower in low-carbon scenarios. However, in some low-carbon scenarios the levels of gas trade reach the level of oil trade today and its production becomes even more geographically concentrated than for oil today. Thus, while oil ceases to be a major energy security issue, natural gas trade could acquire insecure patterns resembling those of the global oil market today. It should be noted, however, that natural gas does not dominate any of the end-use sectors to the extent that oil dominates the transport sector today, therefore even relatively high trade and concentration of natural gas production would be a lower energy security risk compared to the risks associated with present oil trade, particularly since the overall energy use in these high-trade scenarios would be much higher than at present. The diversity of energy sources in electricity generation and the overall TPES is also lower in some low-carbon scenarios than in the Baseline and at present. Both higher trade in natural gas and lower diversity of energy systems is associated with certain policy and technology choices assumed in some low-carbon scenarios as further explored in the next sub-section.

5.2. *Impact of policy and technology choices on energy security in low-carbon scenarios*

Potential long-term energy security concerns within low-carbon scenarios highlighted in the previous section are triggered by different combinations of demand and supply choices (Fig. 13):

- Higher gas and/or hydrogen trade is observed in Supply scenarios with limited renewables or nuclear energy phase-out;
- Lower diversity of electricity and TPES production is observed in scenarios with unlimited renewables, particularly combined with advanced transport and limitations on nuclear energy.

Both effects are more pronounced in Supply and Mix scenarios, particularly when nuclear energy is phased out. Fig. 13 shows that only a limited number of scenarios are not located in “dangerous” corners where either trade is very high or diversity is very low. The relatively “secure” scenarios are Efficiency with limitations on renewables where both high diversity and lower energy trade can be assured simultaneously.

5.3. *Compound energy security indices*

This paper uses relatively straightforward methods of presenting energy security indicators for vital energy systems including trade-offs between different dimensions of energy security (e.g. on Fig. 13). In many cases, however, such a direct presentation of

Table 5
Selected energy security indicators in 2010, 2050 and 2100 in GEA pathways and the Baseline scenario.

Indicator	2010	2050		2100	
		Low-carbon	Baseline	Low-carbon	Baseline
total interregional trade	106 EJ	89–175 EJ	243 EJ	42–227 EJ	420 EJ
total interregional trade intensity	20%	10%–19%	21%	3%–18%	19%
Oil trade	82 EJ	21–71 EJ	135 EJ	0–8 EJ	179 EJ
Gas trade	9.4 EJ	28–68 EJ	47 EJ	7–98 EJ	94 EJ
Coal trade	1.1	0.8–1.1*	1.0	0.1–0.7*	0.8
Hydrogen trade	10 EJ	3–34 EJ	40 EJ	0–75 EJ	96 EJ
Geographic diversity of gas exports	1.6	1.4–1.5*	1.7	1.4–1.5*	1.6
Geographic diversity of coal exports	–	0–6 EJ	–	5–86 EJ	4
Geographic diversity of hydrogen exports	–	1.5–1.9*	–	1.1–1.6*	0
Electricity diversity	1.5	1.6–1.9	1.5	0.9–1.8	1.6
TPES diversity	1.7	1.8–2.1	1.7	1.1–1.9	1.8
Transport diversity	0.2	1.3–2.0	0.7	1.1–1.8	1.2

* Only reports geographic diversity of exports for scenarios with high trade in that fuel or carrier (see Fig. 10).

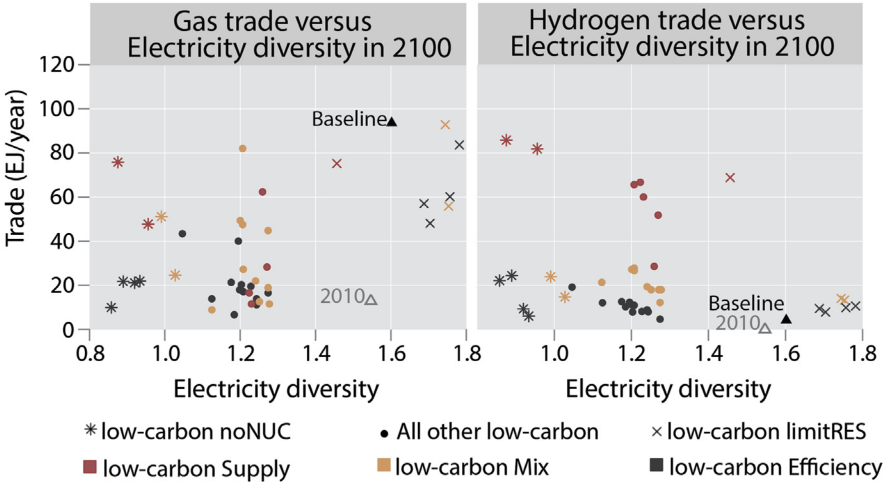

Fig. 13. Diversity of electricity production, trade in gas and hydrogen in low-carbon scenarios. The lower right corner represents the most 'secure' situations with low trade and high diversity, whereas the upper left corner shows the 'danger zone' with high trade and low diversity.

multiple indicators may be insufficient to communicate the results of an energy security assessment. While it is necessary to use multiple indicators to portray an integrated picture of energy security, too much data can also lead to confusion, especially if indicators tell different stories. Thus, energy security studies often use compound indices - calculated from several different indicators - to reduce the amount of data and increase the accessibility of the results of an energy security assessment. However, most of the compound indices in the literature (e.g. Gupta, 2008; Scheepers et al., 2007) cannot be used to analyze energy security in long-term scenarios because of the data and assumptions they use.

One notable exception is the compound index based on the modified Shannon-Wiener diversity index which 'penalizes' energy sources for being imported (see the formula in the Appendix). This indicator was used in connection with long-term future energy security studies, including in Riahi et al. (2012) and McCollum et al. (2013). It was based on a more complex index originally proposed by Jansen et al. (2004) (who also suggested penalizing sources coming from unstable countries or scarce resources).

While this index shows the potential for aggregation, it has several limitations. It is useful when diversity and import dependency are within a moderate range of values and correlate with each other. In such situations the compound diversity index reduces the number of variables that need to be considered in the assessment and may be useful for monetization or other such calculations. However, this index can obscure the policy trade-offs where diversity and import dependency tell different stories. In particular, this index fails to account for the fuel diversity of imports. For example if a country's energy system imports all of its energy, this compound diversity index will always be zero regardless of the how many sources it depends on.[10]

Thus, any aggregation must strike a very delicate balance between on the one hand reducing the amount of data and on the other hand staying true to the systems, vulnerabilities, and priorities of policy makers. Cherp and Jewell (2013) consider situations and methods for appropriately aggregating indicators as well as suggest alternative approaches to making sense of multiple indicators. For the purposes of this paper other approaches for presenting several indicators proved to be more suitable than aggregated indices.

6. Conclusions and policy implications

Mitigating dangerous climate change requires unprecedented policy commitment to transforming energy systems. The purpose of

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[10] A country may rely only on imported natural gas or it may rely on imported natural gas, coal, oil, and bioenergy. While these two situations are by common sense drastically different, the compound diversity index does not distinguish them.

this article is to evaluate one major factor that influences such commitment: the energy security implications of de-carbonization. To achieve this aim, we propose a systematic energy security assessment framework that is sufficiently specific to be policy relevant and yet sufficiently generic to be applicable to energy systems radically different from the present ones, given all the uncertainties associated with possible configurations of such systems.

Our energy security assessment framework is based on the fact that policy-relevant energy security concerns focus on distinct and concrete vital energy systems rather than vague and abstract 'energy' as a whole. Under different energy scenarios some of today's vital energy systems would persist and evolve (e.g. generation of electricity and transport energy use), some could disappear (e.g. oil and its products) and some might emerge or radically expand (e.g. global markets for natural gas, biofuels and hydrogen). By evaluating vulnerabilities of both existing and potentially new energy systems this article portrays energy futures in the familiar light of policy-relevant energy security concerns.

We consider vulnerabilities of each of the vital energy systems as a combination of *risks* associated with energy trade and *resilience* represented by the diversity of energy options and energy intensity. This approach reflects two policy perspectives of energy security which have existed for most of the history of modern energy systems: 'sovereignty'—focused on the degree of domestic control over energy systems and 'resilience'—focused on the capacity of energy systems to respond to disruptions. We also note the third, 'robustness', perspective on energy security, but due to data and space limitations do not evaluate the robustness of future energy systems in this paper. We select indicators of vulnerabilities of future vital energy systems according to their policy relevance and data availability and apply these indicators to over 40 energy transformation scenarios developed within the Global Energy Assessment.

All in all, our results indicate that energy systems in low-carbon scenarios have lower trade and higher diversity than in the Baseline scenario. These gains are most profound in the mid-term perspective (by 2050) although most of them persist through 2100. In particular, present-day energy security risks associated with global oil trade rapidly subside and eventually disappear under low-carbon scenarios.

Both these results and the proposed energy security assessment framework have several novel policy implications. First, the finding that long-term de-carbonization has considerable energy security benefits should bring the global energy security and climate mitigation agendas closer together. While several previous studies have explored the energy security implications of climate mitigation policies for certain regions (Costantini et al., 2007; Criqui and Mima, 2012; Shukla and Dhar, 2011) or sectors (Grubb et al., 2006; Rozenberg et al., 2010), our paper explores and re-affirms these earlier findings more systematically and comprehensively. In particular, we contrast the very rapid rise of global energy trade and import dependence in the Baseline with the decline or stagnation of trade and imports in climate stabilization scenarios. While previous studies almost exclusively focus on fossil fuels (particularly oil) trade we show that future trade in all other fuels is unlikely to cause as serious energy security concerns as oil causes today.

Second, we identify several potential vulnerabilities of certain energy systems in some scenarios, particularly by the end of the century. With respect to sovereignty, this is a potentially large trade in gas and hydrogen[11] and with respect to resilience this is low diversity of electricity generation options. We show that policy focus on energy efficiency *and* on limiting potential domination of solar energy make it possible to avoid both of these concerns simultaneously. These findings can inform long-term technology choices and policies.

Third, we indicate that energy security benefits of de-carbonization, apparent at the global scale, may not be equal for all countries and regions, a factor potentially defining national support for the global climate regime. This is consistent with other findings that climate policies lead to divergence between regional energy systems (Cherp et al., in Press). Although regional and national energy security implications of climate mitigation policies need to be studied separately, we do provide initial insights into this topic. In particular, we show that while exports of oil from Middle East and North Africa (MENA), decline in the climate stabilization scenarios, this decline is generally similar to the one expected in the Baseline. Because this initial observation contrasts the conventional wisdom that MENA would be a major loser of the global climate regime, it should be investigated in more details using a range of models and assumptions on fossil fuel resource availability (see a meta-review of literature on this topic in Jewell, (2013)).

Our study can also be used in *national* energy security assessments, which are increasingly being used to guide national energy policies, to characterize the global context within which national energy futures may develop (Australian Government Department of Resources Energy and Tourism, 2011; Wicks, 2009). In addition, the systematic, rigorous and yet flexible framework proposed here may be used by national policy makers to identify and assess energy security implications of different policy options and scenarios.

The analysis presented in this article also opens an extensive research agenda. First of all, our results come from one modeling framework and one set of assumptions. Evaluating energy security in other models and under different assumptions would help to validate both the framework and the findings of our research. Second, the results should be obtained for the national rather than the global level, possibly starting with major economies (China, EU, India and the US) which are more easily represented in IAMs. Third, it is important to explore the 'robustness' perspective on energy security for example by studying 'buffers' such as remaining resources and spare electricity generation capacity. Finally, detailed understanding of energy security concerns may allow introducing relevant constraints in energy models and thus producing more policy-realistic depictions of possible futures.

Acknowledgements

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Appendix. Formulas for Indicators

This appendix contains a description of all the indicators discussed in the paper and listed in Table 6.

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[11] As discussed above, although significant, this trade will be less of an energy security concern than oil trade today because no end-use sector will depend upon gas to the extent the transport sector depends on oil today.

Table 6
Indicators of energy security in long-term energy transformation scenarios.

Indicator	Energy security concern(s)	Unit	Definition (formula)[*]	Sector	Geography
Sovereignty indicators					
Global energy trade (absolute)	Disruption of trade flows by various factors	Ej/year	Total flows of trade between regions in a given year	TPES, oil, gas, coal, hydrogen, biomass, synfuels, electricity, uranium, oil products, other fuels and carriers	Global
Global energy trade (intensity)	Same as above	Share (0–1)	Global energy trade divided by global energy supply	As above (only **TPES** used in this article)	Global
Geographic diversity of exports	Same as above	Non-dimensional	SWDI or HHI	As above	Global
Net import dependency	Regional vulnerability to trade disruptions by various factors	share (0–1)	Net energy imports divided by total PES or total primary energy of a given source	As above (only **TPES** used in this article)	Regional
Cost of energy imports in relation to GDP	Regional vulnerability to trade disruptions by various factors	Share (0–1)	Energy import value divided by GDP	TPES or a particularly vulnerable fuel	Regional
Cost of energy exports in relation to GDP	Regional vulnerability to disruptions of energy exports	Share (0–1)	Energy export value divided by GDP	TPES	Regional
Carriers dependence on imported fuels	Vulnerability of carriers to trade disruptions	Share (0–1)	Share of energy carriers produced from imported sources divided by the total energy carrier	Electricity, hydrogen, and other carriers	Regional
End-use sectors dependence on imported fuels	Vulnerability of end-use sectors to trade disruptions	Share (0–1)	Share of end-use sectors produced from imported fuels	Transportation, industry, residential and commercial	Regional
Resilience indicators					
Energy intensity	Overall vulnerability to energy supply and price shocks	MJ/$ GDP	TPES divided by GDP	**TPES**	Global or Regional
Diversity of energy sources in primary energy supply (PES)	Overall vulnerability to various primary energy source disruptions	Non-dimensional	SWDI or HHI	**TPES**	Global or Regional
Diversity of primary energy sources in carriers	Carrier vulnerability to various primary energy source disruptions	Non-dimensional	SWDI or HHI	**Electricity**, hydrogen, liquid fuels, and other carriers	Global or Regional
Diversity of primary energy sources in end-use sectors	End-use vulnerability to various primary energy source disruptions	Non-dimensional	SWDI or HHI	**Transportation**, industrial, residential and commercial	Global or Regional
End-use sector diversity of carriers	as above	Non-dimensional	SWDI or HHI	Transportation, industrial, residential and commercial	Global or Regional
Robustness indicators					
Reserves or Resource to production ratios	Vulnerability to energy shocks	Years	Reserves or resources divided by production rates	Oil, gas, and coal	Global or Regional
Average age of infrastructure	Reliability of energy conversion and transmission	Years in relation to projected life-time	The age of all infrastructural facilities	Electricity transmission and generation; potentially other carriers or fuels	Global or regional
Spare capacities for electricity generation	Reliability of electricity generation	%	Installed capacity divided by the critical or average load	Electricity	Regional
Rate of energy sector growth	Burden on energy systems associated with fast growth	%/year	The growth in energy supply (or use) in fuel, carrier or end-use	End-uses, carriers, sectors	Global or regional
Rate of energy export revenue decline	Instability associated with fast decline of energy export revenues	%/year	The change in energy export revenues year on year	Energy exports	Regional
Compound indicators					
Compound diversity index	Combined diversity and sovereignty concerns	Non-dimensional	Modified SWDI[*]	TPES	Regional

Bold text represents the indicators used or energy systems addressed in this article.

[*] See the formulas and the explanation in the main text.

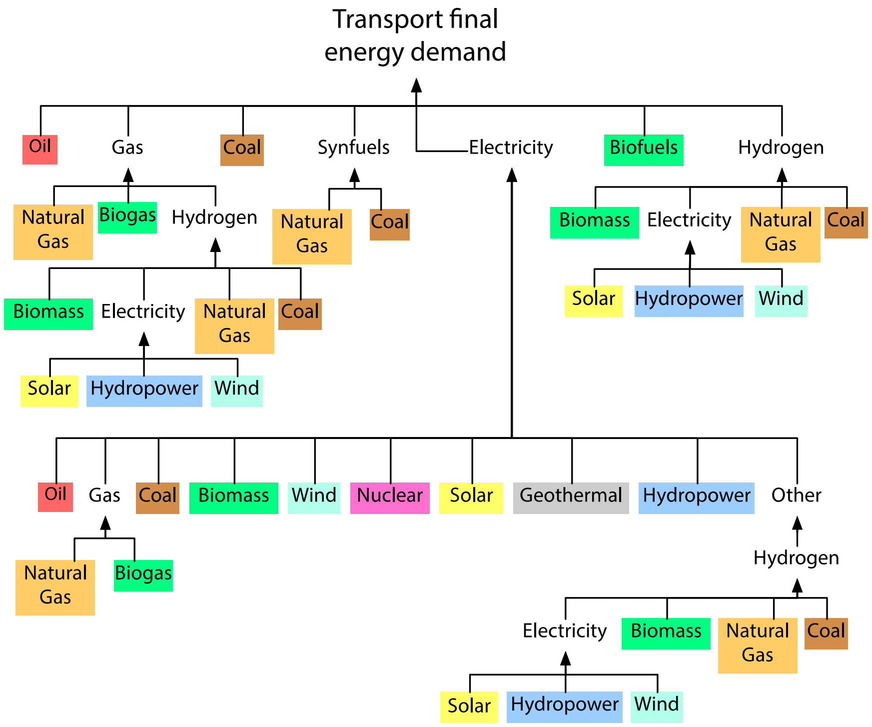

Fig. 14. Proportional allocation of primary energy sources for transportation.

Energy trade

Global energy trade is the sum of all net exports for each globally-traded fuel or carrier. This paper analyses trade in oil, gas, coal, electricity, hydrogen, biofuels, electricity and fossil synfuels. Other fuels and carriers, e.g. uranium or specific types of bio-liquids could also be analyzed. Global energy trade is the sum of all global fuel trade. This value only accounts for interregional trade which is likely to be a large part of country-to-country trade.[12]

Trade intensity is calculated by dividing the total volume of energy trade (or the volume of trade for a carrier or a fuel) by the total primary energy supply (or the total supply for a carrier or a fuel). In this study, we use the substitution equivalent but it could be done using another primary energy accounting method as well. The important thing is to use the same primary energy accounting method to compare different scenarios.

On the regional level, net-import dependence is the difference between exports and imports divided by the regional TPES. Similarly, fuel import dependency or carrier import dependency is the net-imports divided by the primary energy supply of that source. A symmetrical indicator can be calculated for energy exports. Import and export indicators can be expressed (a) as absolute volumes of traded energy (aggregated or by individual fuel or carrier); (b) as shares of a traded energy/fuel/carrier in its overall regional supply; (c) as costs of a traded energy/fuel/carrier expressed in absolute terms or as a share of regional GDP.

Another regional trade indicator is the reliance on imported fuels in carrier production or end-use sectors. This can be calculated by decomposing the end-use sectors into their globally-traded fuels and carriers (similar to the primary energy source decomposition in Fig. 14 below) and sum the net-imports for each globally-traded fuel or carrier. This indicator could capture concerns such as the high import dependence of the transportation sector in most countries which dominates the energy security landscape today (Cherp et al., 2012).

The final energy trade indicator is the geographic diversity of exports for each globally-traded fuel or carrier. The regional exports for each globally-traded fuel or carrier is calculated by dividing a region's net-exports of a fuel or carrier by the total volume of trade for the respective fuel or carrier. Then the SWDI index (see next section) is calculated for the distribution between energy exporting regions.

Diversity

For diversity, we use the Shannon-Wiener diversity index (SWDI) which is calculated as

$$SWDI = \Sigma_i \, p_i \ln(p_i)$$

where p_i is the share of the primary energy source i in the TPES. The Herfindahl-Hirschmann index[13] (HHI) has also been used in the literature as a measure of diversity (Neff, 1997; Jewell, 2011; International Energy Agency, 2011; Grubb et al., 2006). Stirling (1998) 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 and Grubb et al. (2006) found no difference in their conclusions when comparing results from the SWDI and the HHI.

Much more important than the question of *which* diversity index is the issue of the diversity of *what*. The most meaningful analysis of diversity is one that measures the diversity of energy options within a vital energy system. The term "system" means that it consists of resources, infrastructure, technologies, markets and other elements connected to each other stronger than they are connected to the outside world. From an energy security angle, it means that in the case of a disruption, the elements within a

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[12] Country-to-country oil trade in 2005 was about 110EJ (British Petroleum, 2009) compared to 83EJ of the interregional trade in the MESSAGE model for this year. Thus, interregional trade currently accounts for about 75% of all oil trade.

[13] Herfindahl Hirschmann index $= \Sigma_i p_i$.

system can replace each other but the elements outside the system cannot (Cherp and Jewell, 2013). Indeed diversity indices were first proposed to measure the diversity of sources in an electricity system (Stirling, 1994) which are readily-substitutable; that is, there is no difference between electricity produced from a gas-fired power plant or a concentrated solar power system.

In this article, we present the diversity of TPES as well as the diversity of energy sources used for electricity generation and transport. The TPES diversity was calculated based on the proportion each primary energy source contributed to the TPES (using the substitution equivalent primary energy accounting method). The SWDI for electricity reflects the diversity of fuel sources used for electricity generation. Such an index can also be used for other carriers such as synfuels, liquid fuels in general or hydrogen. The SWDI is calculated for end-uses based on the diversity of primary energy sources by proportionally allocating different energy carriers to their respective sources (see Fig. 13). This proportional allocation needs to be tailored for the specific configuration of the energy system, actual or modeled. The way we apply the end-use diversity index accounts for disruptions which would occur at the primary energy level. It's also possible to measure the diversity of carriers (e.g. electricity vs. liquid fuels) used in an end-use sector.

We also apply the SWDI to the geographic diversity of exports. Measuring the geographic diversity of supply (or geographic concentration of supply) has been done in Jewell, (2011), Costantini et al. (2007) and Lefèvre (2007).[14] The geographic diversity of supply uses the same formula as the diversity of TPES, electricity and transportation, but p_i is the share of a given energy source from region i in the total interregional trade of that energy source or carrier.

As discussed in Section 5.3, some studies have used a compound diversity index (CDI) on the regional level to combine the import dependency and diversity on the regional level according to the following formula:

$$CDI = \Sigma_i \left\{ \left(1 - m_i \left(1 - \frac{S_i^m}{S_i^{m,max}}\right) \right) (p_i \ln(p_i)) \right\}$$

where, p_i is the share of the primary energy source i in the TPES; m_i is the share of imports of net imports in primary energy supply of resource i; and S_i^m is the Shannon diversity index of import flows of resource i and $S_i^{m,max}$ is the maximum possible value of the Shannon index if all regions exported an equal amount.

Energy intensity

Energy intensity is the amount of energy used per dollar of GDP or value-added (in this paper MJ/US2005$). In this study it is a unique indicator because it is partially-exogenous to the GEA-modeling framework. Thus while we calculated the other energy security indicators ex-post, we tested the effect energy intensity has on other aspects of energy security.

Robustness indicators

Robustness indicators include resource scarcity, the rate of demand growth, aging and reliability of infrastructure, the presence of spare capacity, strategic stocks and resource buffers. As we explain in the main text it is often difficult to meaningfully represent these variables in Integrated Assessment Models because they are not depicted in a model, are exogenous or are endogenously optimized. Nevertheless they can be used for exploring the relationship between different aspects of energy security as well as between energy security and climate mitigation measures as is done for example in Turton and Barreto (2006). Other robustness indicators which have been suggested in the literature on current energy security concerns include: rates of demand growth, reliability of electricity and heating supply, energy infrastructure age, spare storage capacities and number of import entry points (Cherp et al., 2012; Jewell, 2011; Winzer, 2012).

References

APERC (Asia Pacific Energy Research Centre), 2007. A Quest for Energy Security in the 21st Century: Resources and Constraints. Institute of Energy Economics, Japan, available at: http://aperc.ieej.or.jp/file/2010/9/26/APERC_2007_A_Quest_for_Energy_Security.pdf.

Alhajji, A.F., 2008. What is energy security? Definitions and concepts. Oil, Gas & Energy Law Intell. 6 (3).

Atsumi, Masahiro, 2007. Japanese energy security revisited. Asia-Pac. Rev. 14 (1), 28–43, http://dx.doi.org/10.1080/13439000701330353.

Australian Government Department of Resources Energy and Tourism, 2009. National Energy Security Assessment 2009. Commonwealth of Australia, available at: http://www.aip.com.au/pdf/National-Energy-Security-Assessment-2009.pdf.

Australian Government Department of Resources Energy and Tourism, 2011. National Energy Security Assessment 2011. Canberra, AU, Commonwealth of Australia, available at: http://www.aip.com.au/pdf/National-Energy-Security-Assessment-2011.pdf.

Bollen, Johannes, Hers, Sebastiaan, Bob van der, zwaan, 2010. An integrated assessment of climate change, air pollution, and energy security policy. Energy Policy 38 (8), 4021–4030, http://dx.doi.org/10.1016/j.enpol.2010.03.026.

Bosetti, Valentina, Carraro, Carlo, Duval, Romain, Tavoni, Massimo, 2011. What should we expect from innovation? A model-based assessment of the environmental and mitigation cost implications of climate-related R&D. Energy Econ. 33 (6), 1313–1320, http://dx.doi.org/10.1016/j.eneco.2011.02.010.

British Petroleum, 2009. BP Statistical Review of World Energy June 2009. London: British Petroleum.

Cherp, Aleh, Jewell, Jessica, 2011. The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration. Curr. Opin. Environ. Sustainability 3 (4), 202–212, http://dx.doi.org/10.1016/j.cosust.2011.07.001.

Cherp, Aleh, Jewell, Jessica, 2013.Energy security assessment framework and three case-studies, in: Dyer, H., Trombetta, M.J. (Eds.), International Handbook of Energy Security. Edward Elgar Publish- ing, Cheltenham,UK and Northampton, MA, pp.231–277.

Cherp, Aleh, Adenikinju, A, Goldthau, Andreas, Hughes, Larry, Jansen, Jaap C., Jewell, Jessica, Olshanskaya, Marina, et al., 2012. Chapter-5 Energy and Security, in Global Energy Assessment: Toward a More Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, 325–384.

Cherp, Aleh, Jessica Jewell, Vadim Vinichenko, Nico Bauer, and Enrica De Cian. in press. "Global Energy Security Under Different Climate Policies, GDP Growth Rates and Fossil Resource Availabilities." Climatic Change. http://dx.doi.org/10.1007/s10584-013-0950-x.

Costantini, Valeria, Gracceva, Francesco, Markandya, Anil, Vicini, Giorgio, 2007. Security of energy supply: comparing scenarios from a European perspective. Energy Policy 35 (1), 210–226, http://dx.doi.org/10.1016/j.enpol.2005.11.002.

Criqui, Patrick, Mima, Silvana, 2012. European climate—energy security nexus a model based scenario analysis. Energy Policy 41, 827–842, http://dx.doi.org/10.1016/j.enpol.2011.11.061.

European Parliament, 2006. Directive 2005/89/EC of the European Parliament and of the Council of 18 January 2006 concerning measures to safeguard security of electricity supply and infrastructure investment. Off. J. Eur. Union, 22–27. (February 2).

European Union Council, 2004. Council directive 2004/67/EC of 26 April 2004 concerning measures to safeguard security of natural gas supply. Off. J. Eur. Union, 92–96. (April 29).

GEA, 2012: Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Gnansounou, Edgard, 2008. Assessing the energy vulnerability: case of industrialised countries. Energy Policy 36 (10), 3734–3744, http://dx.doi.org/10.1016/j.enpol.2008.07.004.

Greene, David L., 2010. Measuring energy security: can the United States achieve oil independence? Energy Policy 38, 1614–1621, http://dx.doi.org/10.1016/j.enpol.2009.01.041.

Grubb, Michael, Butler, Lucy, Twomey, Paul, 2006. Diversity and security in UK electricity generation: the influence of low-carbon objectives. Energy Policy 34 (18), 4050–4062, http://dx.doi.org/10.1016/j.enpol.2005.09.004.

Gupta, Eshita, 2008. Oil vulnerability index of oil-importing countries. Energy Policy 36 (3), 1195–1211, http://dx.doi.org/10.1016/j.enpol.2007.11.011.

Helm, D., 2002. Energy policy: security of supply, sustainability and competition. Energy Policy 30, 173–184.

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[14] In these publications, the authors use the HHI index, however, as discussed at the beginning of the section, which diversity index to use does not generally change the conclusions and some authors prefer the SWDI on theoretical grounds.

IAEA (International Atomic Energy Agency), 2007. Considerations to Launch a Nuclear Power Programme, International Atomic Energy Agency. Vienna.

IEA (International Energy Agency), 2011. Measuring Short-Term Energy Security. OECD/IEA, Paris.

Jansen, Jaap C., Seebregts, Ad J., 2009. Long-term energy services security: what is it and how can it be measured and valued? Energy Policy 38 (4), 1654–1664, http://dx.doi.org/10.1016/j.enpol.2009.02.047.

Jansen, J.C,vanArkel,W.G., Boots, M.G., 2004. Designing indicators of long-term energy supply security. Energy Research Centre of the Netherlands (ECN), available at: http://www.ecn.nl/docs/library/report/2004/c04007.pdf.

Jewell, Jessica, 2011. The IEA Model of Short-Term Energy Security (MOSES). : primary energy sources and secondary fuels. OECD/ IEA, Paris.

Jewell, Jessica, 2013. Energy Security and Climate Change Mitigation. the interaction in long-term global scenarios. Doctoral dissertation, Department of Environmental Sciences and Policy, Central European University, Budapest.

Jewell, Jessica, Cherp, Aleh, Vinichenko, Vadim, Bauer, Nico, Kober, Tom, McCollum, Davivd, van Vuuren, Detlef P, van der Zwaan, Bob, forthcoming. Energy security of China, India, the E.U. and the U.S. under long-term scenarios: results from six IAMs. accepted to Climate Change Economics.

Kendell, James M., 1998. Measures of Oil Import Dependence. U.S. Energy Information Agency, Washington, DC, available at: http://www.eia.doe.gov/oiaf/archive/issues98/oimport.html.

Keppler, Jan Horst, 2007. Energy supply security and nuclear energy: concepts, indicators, policies, background study in the context of the NDD security of supply project.

Kruyt, B, van Vuuren, Detlef P, De Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy 37 (6), 2166–2181, http://dx.doi.org/10.1016/j.enpol.2009.02.006.

Kuzemko, Caroline, 2011. UK Energy governance in the twenty-first century: unravelling the ties that bind. Doctoral dissertation, Politics and International Studies, University of Warwick, Coventry.

Le Coq, Chloé, Paltseva, Elena, 2009. Measuring the security of external energy supply in the European Union. Energy Policy 37 (11), 4474–4481, http://dx.doi.org/10.1016/j.enpol.2009.05.069.

Lefèvre, Nicolas. 2007. Energy security and climate policy: assessing interactions. OECD/IEA, Paris.

Lefèvre, Nicolas, 2010. Measuring the energy security implications of fossil fuel resource concentration. Energy Policy 38 (4), 1635–1644, http://dx.doi.org/10.1016/j.enpol.2009.02.003.

Lehman Brothers, 2008. Global Oil Choke Points. New York, January 18.

Leimbach, Marian, Nico, Bauer, Baumstark, Lavinia, Edenhofer, Ottmar, 2009. Mitigation costs in a globalized world: climate policy analysis with REMIND-R. Environ. Model. Assess. 15 (3), 155–173, http://dx.doi.org/10.1007/s10666-009-9204-8.

Löschel, Andreas, Ulf, Moslener, Rübbelke, Dirk T.G., 2010. Indicators of energy security in industrialised countries. Energy Policy 38 (4), 1665–1671, http://dx.doi.org/10.1016/j.enpol.2009.03.061.

Manne, Alan S., Richard G. Richels. 2004. MERGE: an Integrated Assessment Model for Global Climate Change, available at: http://www.cepe.ethz.ch/education/EnergyPolicy/GERAD1.pdf.

McCollum, David, Nico Bauer, Katherine Calvin, Alban Kitous, and Keywan Riahi. In press. “Fossil Resource and Energy Security Dynamics in Conventional and Carbon-Constrained Worlds.” Climatic Change. http://dx.doi.org/10.1007/s10584-013-0939-5.

McCollum, David L., Krey, Volker, Riahi, Keywan, 2011. An integrated approach to energy sustainability. Nat. Climate Change 1 (9), 428–429, http://dx.doi.org/10.1038/nclimate1297.

McCollum, David L, Krey, Volker, Riahi, Keywan, Kolp, Peter, Grubler, Arnulf, Makowski, Marek, Nakicenovic, Nebojsa, 2013. Climate policies can help resolve energy security and air pollution challenges. Clim. Change , http://dx.doi.org/10.1007/s10584-013-0710-y. (February 19).

Messner, S., Strubegger, M., 1995. User's Guide for MESSAGE III, Working Pater WP-95-069. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Neff, T., 1997. Improving energy security in Pacific Asia: diversification and risk reduction for fossil and nuclear fuels. Project Commissioned by the Pacific Asia Regional Energy Security (PARES) Massachusetts Institute of Technology Center Int. Stud. (December).

Nelson, Paul, Christopher M. Sprecher. 2008. What Determines the Extent of National Reliance on Civil Nuclear Power? Nuclear Security Science & Policy Institute, College Station, TX, NSSPI-08-014. available at: http://nsspi.tamu.edu/media/36556/p21_pub1.pdf.

O'Leary, Fergal, Morgan Bazilian, Martin Howley, Brian O Gallachoir. 2007. Security of Supply in Ireland. Energy Policy Statistical Support Unit. available at: http://www.seai.ie/Publications/Statistics_Publications/EPSSU_Publications/Energy_Security_in_Ireland/SEI_EPSSU_Security_of_Supply_Third_Report.pdf.

Pant, Girijesh, 2006. Energy security in Asia: the necessity of interdependence. Strategic Anal. 31 (3), 523–542, http://dx.doi.org/10.1080/09700160701432037.

Penchansky, R.R., Thomas, J.W., 1981. The concept of access: definition and relationship to consumer satisfaction. Med. Care 19 (2), 127–140.

Rao, S., Riahi, Keywan, 2006. The role of non-CO_2 greenhouse gases in climate change mitigation: long-term scenarios for the 21st century. Energy J. 27 (3), 177–200.

Riahi, Keywan, Grubler, Arnulf, Nakicenovic, Nebojsa, 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol. Forecasting Soc. Change 74 (7), 887–935, http://dx.doi.org/10.1016/j.techfore.2006.05.026.

Riahi, Keywan, Dententener, Frank, Gielen, Dolf, Grubler, Arnulf, Jewell, Jessica, Klimot, Zbigniew, Krey,Volker, et al., 2012. Chapter 17 – Energy pathways for sustainable development, in Global Energy Assessment: Toward a More Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, 1203–1306.

Rozenberg, Julie, Hallegatte, Stéphane, Vogt-Schilb, Adrien, Sassi, Olivier, Guivarch, Céline, Waisman, Henri, Hourcade, Jean-Charles, 2010. Climate policies as a Hedge against the uncertainty on future oil supply. Clim. Change 101 (3-4), 663–668, http://dx.doi.org/10.1007/s10584-010-9868-8.

Scheepers, M., Seebregts, Ad J., de Jong, J., Maters, H., 2007, EU Standards for Energy Security of Supply: updates on the crisis capability index and the supply/demand index quantification for EU-27. ECN/Clingendael International Energy Programme, The Hague and Petten, NL. available at: ftp://ftp.ecn.nl/pub/www/library/report/2007/e07004.pdf.

Shukla, P R, Dhar, Subash, 2011. Climate agreements and India: aligning options and opportunities on a new track. Int. Environ. Agreements: Polit., Law Econ. 11 (3), 229–243, http://dx.doi.org/10.1007/s10784-011-9158-6.

Sovacool, Benjamin K, and Marilyn A Brown. 2010. “Competing Dimensions of Energy Security: an International Perspective.” Annual Review of Environment and Resources 35 (1) (November 21): 77–108. http://dx.doi.org/10.1146/annurev-environ-042509-143035.

Sovacool, Benjamin K, Mukherjee, Ishani, 2011. Conceptualizing and measuring energy security: a synthesized approach. Energy 36 (8), 5343–5355, http://dx.doi.org/10.1016/j.energy.2011.06.043.

Stirling, Andy, 1994. Diversity and ignorance in electricity supply investment: addressing the solution rather than the problem. Energy Policy 22 (3), 195–216, http://dx.doi.org/10.1016/0301-4215(94)90159-7.

Stirling, Andy. 1998. On the Economics and Analysis of Diversity. Science Policy Research Unit (SPRU), University of Sussex, Brighton. Electronic Working Papers Series, Paper 28(December 18):1–156.

Stirling, Andy, 2010. Multicriteria diversity analysis a novel heuristic framework for appraising energy portfolios. Energy Policy 38 (4), 1622–1634, http://dx.doi.org/10.1016/j.enpol.2009.02.023.

Turton, Hal, Barreto, Leonardo, 2006. Long-term security of energy supply and climate change. Energy Policy 34 (15), 2232–2250, http://dx.doi.org/10.1016/j.enpol.2005.03.016.

van Vuuren, Detlef P, Stehfest, Elke, Elzen, Michel G.J., Kram, Tom, Vliet, Jasper, Deetman, Sebastiaan, Isaac, Morna, et al., 2011. RCP2.6: exploring the possibility to keep global mean temperature increase below 2 °C. Clim. Change 109 (1-2), 95–116, http://dx.doi.org/10.1007/s10584-011-0152-3.

Walker, Gordon, Cass, Noel, 2007. Carbon reduction, ‘the public’ and renewable energy: engaging with socio-technical configurations. Area 39 (4), 458–469.

Wicks, Malcom.2009. Energy Security: a National Challenge in a Changing World. London, available at: http://www.igd.com/Documents/Industry%20Reports/Energy/Energy%20Security%20a%20national%20challenge%20in%20a%20changing%20world%202009.pdf.

Winzer, Christian, 2012. Conceptualizing energy security. Energy Policy 46 (C), 36–48, http://dx.doi.org/10.1016/j.enpol.2012.02.067.