Energy security indicators for use in integrated assessment models

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Abstract

How would a low-carbon energy transformation affect energy security, a top policy priority for most countries? This paper proposes a new framework for evaluating 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 scenarios and 42 'low-carbon' scenarios where the global mean temperature increase is limited to 2ºC 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 emerging under low-carbon scenarios by 2100 include potentially high trade in natural gas and hydrogen as well as low diversity of electricity sources. Trade is typically lower in scenarios emphasizing demand-side policies as well as non-tradable energy sources (nuclear and renewables) while diversity is higher in scenarios limiting the penetration of certain renewables.

1 Introduction

The IEA executive director was recently asked in an interview "What are the concerns of [Energy] Ministers". Her response? "It's always about energy security. Always."

While policy-makers are focused on energy security, climate scientists warn that if energy systems are not radically transformed society may face catastrophic consequences from climate change. Would such transformations be a threat to energy security? Answering this question will be important to gain the political support needed for a low-carbon energy transition.

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

Secondly, 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. Energy security concerns, which are closely linked to present configurations of energy systems, are sometimes projected into the future. For example, Turton and Barretto (2006a) analyze the impact climate policies has on domestic oil and gas resources and Rozenberg et al. (2010) analyze the interplay between global oil scarcity and climate policies. Costantini et al (2007) explore European dependence on

[1] For those scholars who consider environmental impacts 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.

imported fossil fuels under different scenarios. Another approach has been to model the interaction between climate change, air pollution, and "energy security" (measured by oil and gas import dependency) (Bollen, Hers, and van der Zwaan 2010), overall net import dependency (McCollum, Krey, and Riahi 2011), or import dependency and diversity combined into a single indicator (McCollum et al. n.d.) over the 21st century. While these approaches provide useful insights into potential interactions between some aspects of energy security and climate change mitigation they mostly focus on present concerns: oil and gas imports, long-term fossil-fuel availability, and overall energy dependence. However, if energy systems undergo radical transformations (for example, if oil is no longer the dominant fuel in the transport sector), the present concerns might subside, and new ones may emerge. Therefore, a method for assessing future energy security should be suitable for energy systems that are radically different from current ones.

Thirdly, 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 (Bosetti et al. 2011; Kim et al. 2006; Leimbach et al. 2009; Loulou, Goldstein, and Noble 2004; Manne and Richels 2004; Rao and Riahi 2006; van Vuuren et al. 2011) which present detailed quantitative description of low-carbon futures has made this possible.

The purpose of this paper is to develop and illustrate a method for assessing energy security implications of low-carbon energy futures. It overcomes the three limitations of the 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;

(b) translating this concept into a framework for assessing energy security under radical transformations of energy systems;

(c) applying this assessment framework to the energy decarbonization pathways developed within the Global Energy Assessment (GEA) (GEA 2012) to assess energy security under various decarbonization scenarios.

We start by describing a framework for assessing energy security under radical de-carbonization scenarios in Section 2. In Section 3 we describe the scenarios to which we apply this framework. Sections 0 and 5 presents the results and a discussion of this energy security analysis under low-carbon scenarios. The Conclusion summarizes the main findings and lays a pathway for future work.

2 Framework and indicators for evaluating future energy security

A framework for evaluating energy security in long-term scenarios needs to start with defining energy security. This definition should be specific enough to reflect the current energy security concerns and at the same time generic enough to reflect potential vulnerabilities of future energy systems, which may be fundamentally different from today's. We use a definition provided by Cherp and Jewell (2011b) based on a review of the historic and current scholarly and policy literature: energy security is a *low risk of disruptions of vital energy systems*.

Evaluating future energy security in light of this definition involves (1) identifying *vital energy systems* including those which may emerge under future scenarios; (2) identifying *vulnerabilities* of such systems potentially leading to their disruptions in the future; and (3) developing *indicators* to characterize these vulnerabilities. These three steps are explained in the following three subsections.

2.1 Vital energy systems

Energy security policies naturally focus on protecting energy systems whose failure may disrupt the functioning and stability of a society.[2] There are two ways to draw boundaries of such '*vital*' energy systems. First, they can be geographic. Thus, one could in principle speak of energy security of a nation, a sub-national region, a regional or political alliance, or the world as a whole. Second, it is possible to focus on security of a primary energy source (crude oil, natural gas, coal, hydro energy, etc.), energy carrier (oil products, electricity, etc.) or energy end-use (transport, industry, etc.). Various combinations of geographic and sector choices define a number of energy systems: "the global oil market", "European electricity network", "transportation in China", etc. For assessing long-term energy security it is necessary to identify energy systems which will be vital for the functioning of societies in the future.

With respect to geographic boundaries, the current and historic focus of energy security policies is primarily 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 energy security policies address electricity systems in the European Union and their integration with neighboring countries (European Parliament 2006) as well as the Eurasian and global natural gas markets (Council 2004). Regional and global energy markets are also considered in energy security policies and policy-driven assessments in the UK (Wicks 2009), Japan ((Atsumi 2007; Mansoz 2010; Pant 2006)) and Australia (RET 2009, 2011). Concerns about global oil markets 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 regional and global energy integration. As explained in the next section, Integrated Assessment Models (IAMs) typically provide regional and global rather than national level data which restricts energy security analysis to global and regional systems. Nevertheless, if detailed long-term scenarios are developed for national energy systems, the proposed framework can also be applied at the national level.

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 hydro energy supply (IEA 2011; Jewell 2011). Energy security policies of many European countries focus on natural gas. Another common focus is on energy carriers: for example MOSES deals with three types of oil products (Jewell 2011); a number of energy security studies (e.g. Stirling 1994, Grubb 2006) focus on electricity which is also a focus of many countries energy security policies (Lilliestam et al 2012). Finally, there is an emerging literature on security of energy end-uses, sometimes called 'energy services' (e.g. Jansen

[2] More exactly, policies usually protect functioning and stability of political systems generating these policies.

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 attention, over the long-term natural gas, electricity, or biomass production could become central to ensuring energy security. Liquid carriers which at present are primarily oil products may be replaced by biofuels, synthetic fuels[3], hydrogen or electricity. Thus, to evaluate future energy security we use generic categories of energy sources and energy carriers instead of looking only at today's predominant sources and carriers. At the same time, end-use sectors — transportation, industrial, residential & commercial— are unlikely to change in nature although their relative size and importance could change in future societies. Thus we use the same energy end-use sectors which are used for evaluating current energy security.

The vital energy systems used for evaluation of future energy security at present and in the future are listed in Table 1.

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, hydro, nuclear, biomass, RES	Oil products, biofuels, electricity	Transportation, industry, buildings, exports
Future	National* Regional Global	Oil, natural gas, hydro*, nuclear*, biomass* & RES*	Oil products, synthetic fuels, hydrogen, electricity, biofuels	Transportation, industry, buildings, exports*

Notes: *show energy systems which can potentially be evaluated but were not evaluated in this paper.

There are two final remarks to be made about using the concept of vital energy systems for evaluating future energy security. First in relation to energy security, the concept of a vital energy system implies a set of interacting elements which can substituted for each other in case of a disruption but cannot be equally easily substituted by elements from outside the system. For example, when we identify a national electricity system as a unit of evaluation we assume that increasing generation at one national power plant can substitute for a failure of another one, but that increasing power production in another country cannot make up for such loss and neither can the disruption be remediated by, say, increasing oil imports or refinery output. Such assumptions are only partially correct at present (consider for example electricity imports or disconnected regional grids within one and the same nation) and their validity in the future may be put into further question. For example, we do not know to which extent

[3] Refers to liquefied coal and natural gas.

global fuel markets or regional energy systems will be integrated and thus how valid it is to think of them as 'systems'. Despite these uncertainties, for effective energy security policy making vital energy systems should be clearly delineated. In other words it is better to have an imperfect representation of vital energy systems than to have no distinction at all.

The second point is that vital energy systems are not independent from each other. End-use sectors depend on carriers which in turn depend on fuels. Thus vulnerabilities "propagate" through energy systems. An example is today's transport system which almost exclusively relies on oil produced in an increasingly limited number of countries and thus is relatively insecure. Most of these connections are left out in the present analysis of future energy scenarios. However, there is an emerging literature on taking a systems-approach to energy security which can eventually be exploited in evaluating future energy security as well (Cherp et al. 2012; Hughes 2012; Jewell 2011).

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, the vulnerabilities should be defined specifically enough to echo the current and historic energy security concerns and yet generically enough to be applicable to future energy systems potentially very different from the present ones.

The existing scholarly literature does not converge on a single classification of vulnerabilities which is partially explained by the highly contextual nature of energy security (Chester 2009). Most of the proposed 'dimensions' of energy security cannot be used for the analysis of future energy security at least one of the following reasons:

(a) They are too closely tied to present configurations of energy systems and energy security concerns. For example, the widely cited "four A's of energy security" - "Affordability, Availability, Accessibility, and Acceptability" – (first published by APERC (2007), later used by Kruyt (2009) and Hughes (2012)) cannot be meaningfully used with respect to 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.
(b) They are open to a wide variety of interpretations which makes quantification difficult. For example, the concept of 'affordability' is for the most part used rhetorically and can be interpreted to mean "stability of prices", "competitiveness", or protection from "energy poverty".[4]
(c) 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).

This paper uses a more universal way of structuring vulnerabilities which is based on generic 'perspectives' of energy security which have emerged over the last century as shown in Table 2.

[4] 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." (British Petroleum 2009; 2009; Lefèvre 2007). 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

Perspective	Sovereignty	Robustness	Resilience
Historic roots	War-time oil supplies and the 1970s oil crises	Electricity blackouts, concerns about resource scarcity	Liberalization of energy systems.
Key risks for energy systems	Intentional actions by malevolent agents	Predictable natural and technical factors	Diverse and partially unpredictable factors
Primary protection mechanisms	Control over energy systems. Institutional arrangements preventing 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 analysis

Source: Summarized from (Cherp and Jewell 2011b)

All three perspectives are likely to be relevant for analyzing energy security in the long-term. 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. 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, it does not depend on specific configurations of energy systems but rather reflects generic concerns arising from their exposure to complex and uncertain factors. In so far as the future is associated with such complexities and uncertainties the importance of the resilience perspective for analyzing future energy systems cannot be underestimated.

2.3 Indicators

Quantitative evaluations of energy security are used to compare energy security of different countries (Gnansounou 2008; Gupta 2008; IEA 2011; Le Coq and Paltseva 2009), plot the evolution of energy security over time (Lefèvre 2010) or to analyze aspects of future energy security (Costantini et al. 2007; Turton and Barreto 2006a). 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 are relevant to evaluating energy security under de-carbonization scenarios. Indicators of energy security should be systematically derived from an energy security assessment framework so that they reflect key vulnerabilities of vital energy systems(Cherp and Jewell 2011a, in press).

This study uses energy security indicators based on the framework outlined in the previous two subsections. Ideally, the indicators should cover all three energy security perspectives with respect to all energy systems potentially vital in the 21st century. However, not all such indicators are possible to calculate in IAMs. The indicators used in this study are listed in Table 3.

Table 3. Indicators of long-term energy security

Energy systems		Perspectives: Sovereignty	Perspectives: Resilience
Primary energy sources	Total Primary Energy Supply (TPES)	Global energy trade (absolute and relative to the total TPES) Net import dependency*	Diversity of TPES Energy intensity
	Oil, gas, coal, biofuels	Global fuel trade *[Fuel import dependency]**	
		Regional diversity of fuel production	
Carriers	Hydrogen, electricity	Global trade in carrier *[Reliance on imported fuels in carrier production]**	Diversity of PES used in carrier production
		Regional diversity of carrier production	
End-use sectors	Transport, industry, residential and commercial	*[Reliance on imported fuels in end-use sector]**	Diversity of PES used in the end-use sector *[Energy intensity of end-use sector]*

Notes: All indicator formulas are presented in the Appendix. Indicators not reported in this paper are in italics. All resilience indicators can be applied at both the global and regional level. *Regional level sovereignty indicator

This study uses the most widespread metric of sovereignty: import dependency. The global equivalent of this measure is the interregional energy trade[5] (expressed as absolute volume and relative to the total primary energy supply (TPES)). The other sovereignty indicator is the geographic concentration of production of a particular fuel or carrier as measured by the diversity of producing regions contributing to the tradable share of the energy commodity (Lefèvre 2007; 2010). This reflects the current energy security concerns associated with fuels such as oil, which are only produced in a small number of countries and regions.

With respect to resilience, we use two equally widespread indicators: diversity and energy intensity. The argument for using the Shannon-Wiener diversity index for measuring energy security was first applied to electricity systems and presented in (Stirling 1994); it has been

[5] This analysis focuses on inter-regional energy trade. In many instances such energy trade well 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 regions would be preferable. However, energy trade between individual nations so far cannot be modeled in long-term energy scenarios.

subsequently used in (Jansen, van Arkel, and Boots 2004; O'Leary et al. 2007) and many other studies. Energy intensity has also been used in many studies of energy security such as (Gnansounou 2008; Hughes 2012; and Jansen 2009).

In summary, this study is based on 3 common and widely used metrics: import dependency, diversity[6], and energy intensity. The novelty of our approach is that in line with the framework that focuses on 'vital energy systems' we utilize these indicators in relation to multiple energy systems delimited by various geographic and sectoral boundaries. That means that all in all we use 20 global indicators and 5 indicators for each of the 11 regions.

A separate note should be made concerning robustness indicators. Many such indicators have been proposed and used for the studies of present-day energy security. These include reserves or resources -to-production (R/P) ratio, rates of demand growth, reliability of electricity and heating supply and aging of energy infrastructure, spare storage capacities, and number of import entry points (Cherp et al. 2012; Jewell 2011; Winzer 2012).Only some of these indicators can be meaningfully estimated in most of the IAMs. For example, the reliability of electricity supply and the age of power plants can be empirically observed at present but their behavior of the future is endogenously optimized meaning the replacement of power plants follows planned retirement ages and lifetime extensions are not represented. Nevertheless, long-term robustness indicators can be productively used in exploring the interaction between climate policies and energy security as further explained in the Conclusions.

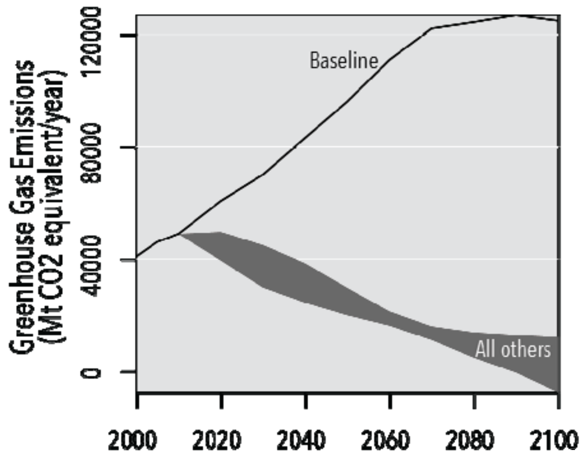
3 Scenarios

The energy security assessment framework and indicators presented in the previous section can be used to analyze energy security in quantitative scenarios of energy systems development. To illustrate the application of the framework we use it to assess energy security implications of energy scenarios in which dangerous climate change is mitigated over the course of the 21st century. One set of such transformational scenarios was recently generated by the MESSAGE IAM (Messner and Strubegger 1995; Rao and Riahi 2006; Riahi, Grubler, and Nakicenovic 2007) in the framework of GEA (Riahi et al. 2012). These transformational scenarios — further referred to as "low-carbon scenarios" — have been compared to the Baseline (counterfactual) scenario also constructed within the GEA and modeling the evolution of the energy system in the absence of carbon constraints. The low-carbon scenarios provide a detailed quantification of future developments of the energy system for various energy supply and demand-side configurations. In all low-carbon scenarios the increase in the global mean temperature is stabilized with 50% probability to 2ºC above pre-industrial levels by 2100 under medium GDP and population growth projections. 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 Figure 1. The exact nature of these changes varies among the low-carbon scenarios depending on the supply and demand-side

[6] The diversity metric is applied to both the geographic distribution of production of energy commodities (as a sovereignty indicator) and the diversity of energy sources in the overall energy mix or used for production of a particular carrier or in an end-use sector (as a resilience indicator).

configurations as described below.[7] We apply the framework described in the previous section to explore the energy security implications of low-carbon energy futures.

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



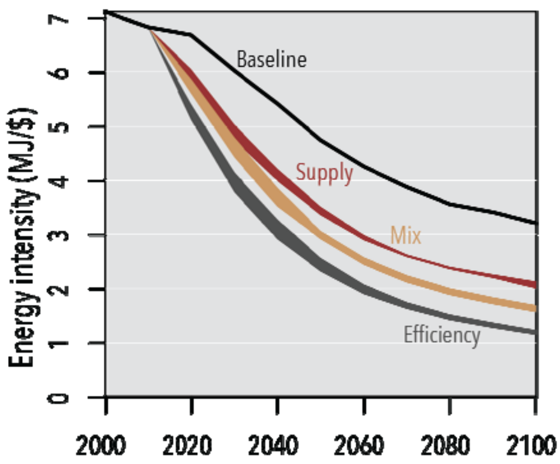
There are three dimensions of technological and policy choices which potentially affect energy security in the low-carbon scenarios. The first dimension concerns energy demand, where the low-carbon scenarios fall into three groups

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

Figure 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.

[7] This paper 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); additionally, quantitative results are publicly available at the GEA web-database (http://www.iiasa.ac.at/web-apps/ene/geadb).

Figure 2 Energy intensity in the Baseline and low-carbon scenarios



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

- "Limited RES" scenarios where intermittent solar and wind energies make up no more than 20% of final energy consumption;
- "Limited BE" scenarios with bioenergy limited to no more than 50% of the estimated global potential;
- "No-NUC" scenarios where no additional nuclear capacity is built after 2020 and all nuclear power is phased out by 2060[8];
- "No-CCS" scenarios with no development of carbon capture and storage (CCS).
- “No bioenergy CCS” scenarios where CCS technologies are not applied in conjunction with biomass combustion;
- “No carbon sinks beyond the baseline” scenarios where additional (non-energy) carbon sinks are not created.

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

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

Not all combinations of demand, supply and transport constraints are present among low-carbon scenarios. "Efficiency" scenarios allow for climate goals to be reached with a broader range of supply-side constraints, (e.g. a combination of limited RES+limited BE or NoNUC + NoCCS. "Supply"

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

scenarios allow only for selected supply-side constraints (e.g. NoNUC+NoCCS is not possible). The full list of scenarios is presented in Table 4.

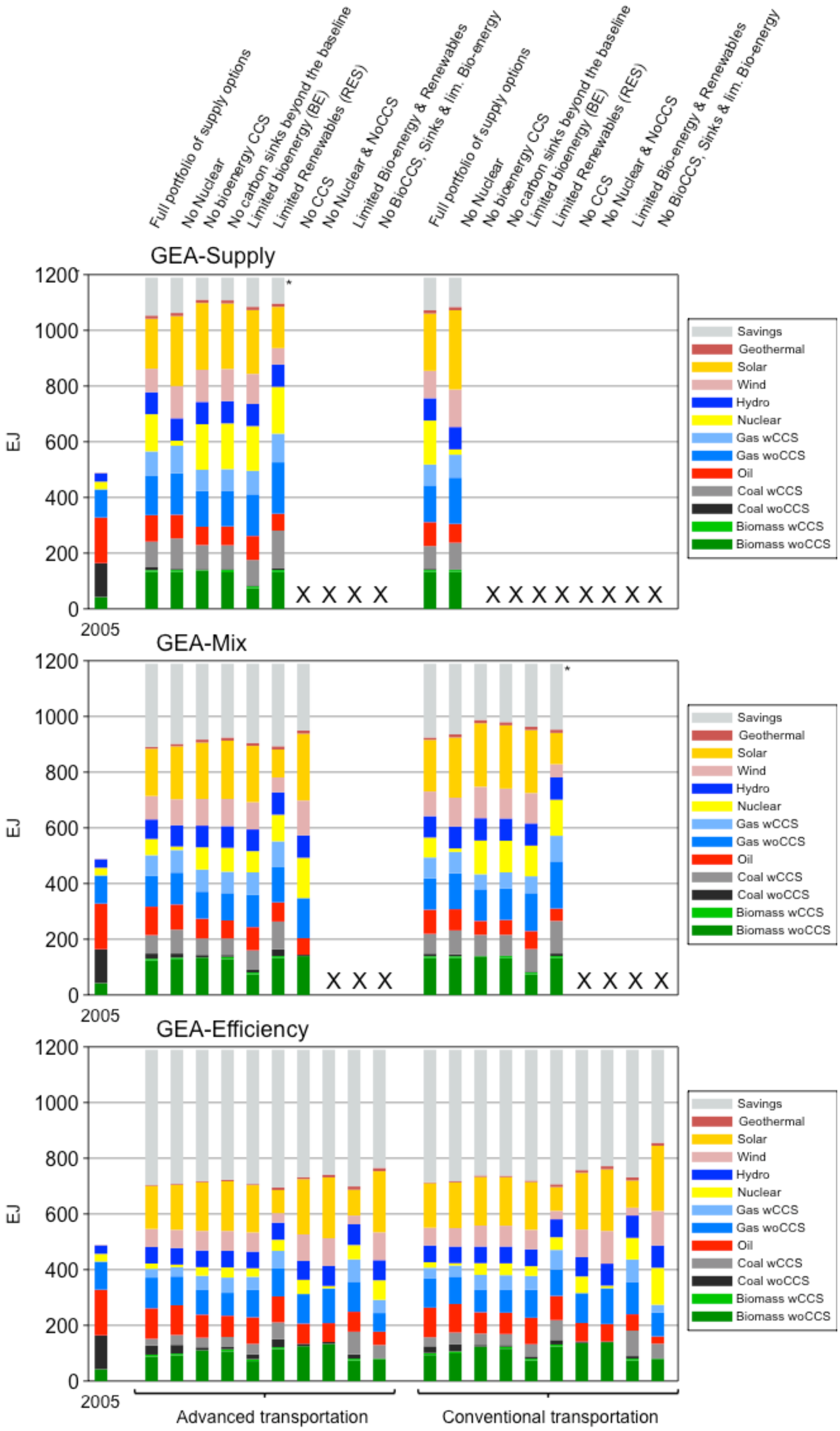
Table 4 Low-carbon scenarios of energy transitions analyzed in this paper

	Supply		Mix		Efficiency	
	Advanced transport (ATR)	Conventional transport (CTR)	Advanced transport (ATR)	Conventional transport (CTR)	Advanced transport (ATR)	Conventional transport (CTR)
Full portfolio of supply options	SupplyATR Full	SupplyCTR Full	MixATR Full	MixCTR Full	EfficiencyATR Full	EfficiencyCTR Full
Limited renewable energy sources (RES)	SupplyATR Limit RES	-	MixATR Limit RES	MixCTR Limit RES	EfficiencyATR Limit RES	EfficiencyCTR Limit RES
Limited bioenergy (BE)	Supply ATR Limit BE	-	MixATR Limit BE	MixCTR Limit BE	EfficiencyATR Limit BE	EfficiencyCTR Limit BE
Limited RES & Limited bioenergy	-	-	-	-	EfficiencyATR Limit RES & Limit BE	EfficiencyCTR Limit RES & Limit BE
No Nuclear (NoNUC)	SupplyATR NoNUC	SupplyCTR NoNUC	MixATR NoNUC	MixCTR NoNUC	EfficiencyATR NoNUC	EfficiencyCTR NoNUC
No carbon capture and storage (NoCCS)	-	-	MixATR NoCCS	MixCTR NoCCS	EfficiencyATR NoCCS	EfficiencyATR NoCCS
No Nuclear & No carbon capture and storage	-	-	-	-	EfficiencyATR NoNUC & NoCCS	EfficiencyCTR NoNUC & NoCCS
No bioenergy CCS* (NoBCCS)	SupplyATR NoBCCS	-	MixATR NoBCCS	-	EfficiencyATR NoBCCS	EfficiencyCTR NoBCCS
No carbon sinks beyond the baseline* (NoSinks)	SupplyATR NoSinks	-	MixATR NoSinks	MixCTR NoSInks	EfficiencyATR NoSinks	EfficiencyCTR NoSinks
No bioCCS & No sinks & Limited BE*	-	-	-	-	EfficiencyATR NoBCCS & NoSink & Limit BE	EfficiencyCTR NoBCCS & NoSink & Limit BE

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

The different levels of energy demand and alternative assumptions about possible restrictions for supply-side technologies have major implications for the future portfolio of energy options. The GEA scenarios depict many possible evolutions of the energy system, exploring alternative routes of low-carbon energy transitions. Some scenarios are for example characterized by a relatively high contribution of renewables while others emphasize carbon capture and storage or nuclear energy. 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 Figure 3. For a more detailed discussion of the GEA scenarios, see (Riahi et al. 2012).

Figure 3 Composition of the global TPES in 2005 and 2050 for low-carbon scenarios



Note: 'X's indicate infeasible pathways.

4 Results

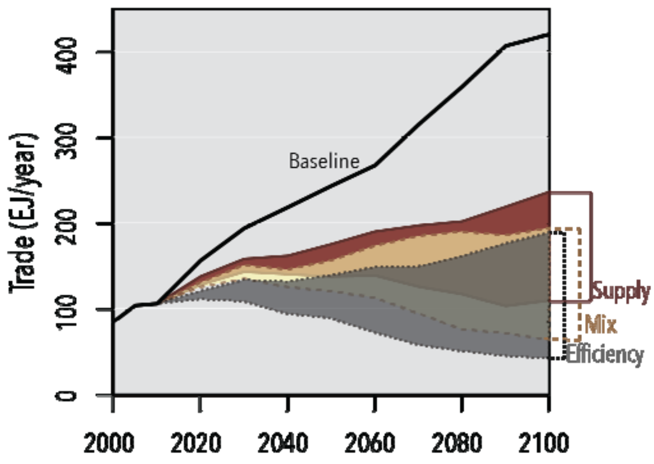
This section presents the results of assessing energy security in GEA energy scenarios listed in Table 4 using indicators listed in Table 3.

4.1 Sovereignty

4.1.1 Global energy trade

In the Baseline scenario, with the higher level of demand and a high reliance on fossil fuels (which are easy to trade), the global energy trade rises dramatically from the current 80EJ/year to over 400 EJ/year by 2100. The levels of trade in the low-carbon scenarios are much lower, ranging from 40 EJ/year to 240 EJ/year by 2100. The trade initially rises in all low-carbon scenarios, and declines in the second half of the century in certain Efficiency and Mix scenarios (Figure 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) in the energy mix.

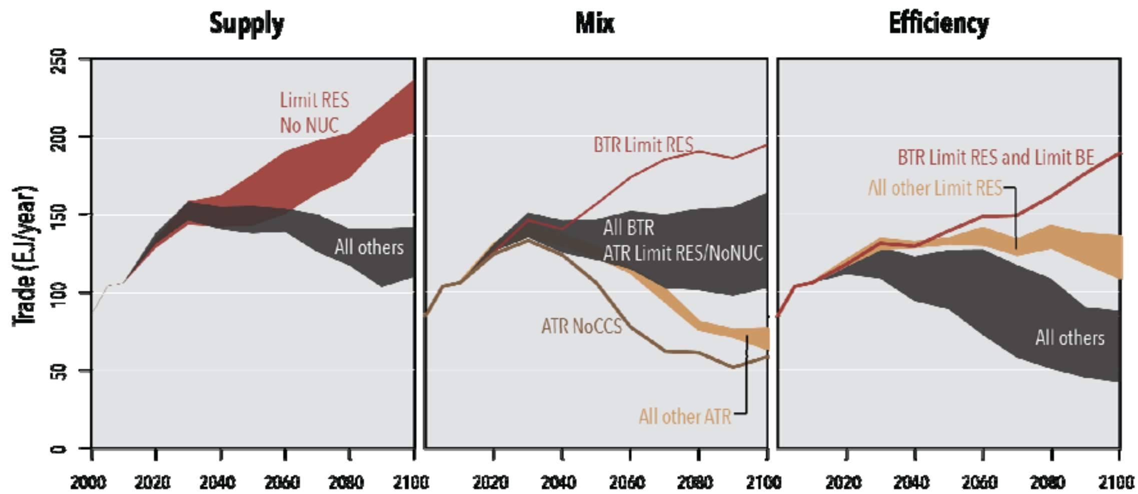
Figure 4 Global energy trade in the Baseline and GEA scenarios



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

In all Supply scenarios, the trade increases to about 150% of the present level by 2030. In Supply scenarios with no nuclear or with limited renewables the 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, it levels off at ~100-140 EJ/y by 2100.

Figure 5 Global energy trade and choices within GEA scenarios



In all Mix scenarios, global energy trade rises to ~120-130 EJ/y by 2030. Subsequently the highest trade is in scenarios when the conventional transport (CTR) is combined with limitations on renewables, because 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 (ATR) 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.

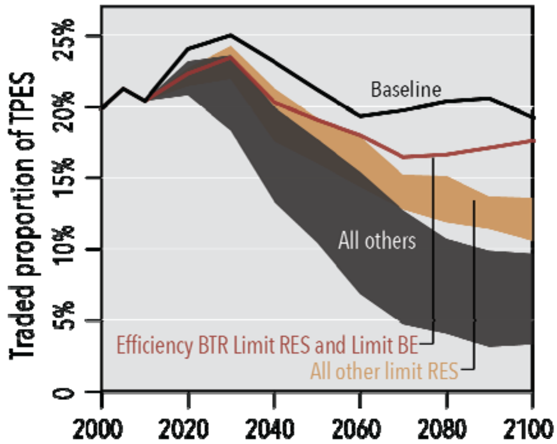
In the majority of **Efficiency** scenarios, the initial moderate rise in energy trade is followed by a decline below the current levels by the end of the century. In scenarios with limited renewables the trade does not decline and when limited renewables are combined with conventional transport and limited bioenergy the trade actually rises by the end of the century to about 2.5 times the current level because of the continued dependence on traded energy.

In summary, the higher the demand, the more easily the rise of energy trade 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.

The trade intensity (shown in Figure 6) rises in the Baseline scenario from the current 20% to 25% by 2030 before returning to ~20% and leveling off. 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.

Figure 6 Global trade intensity



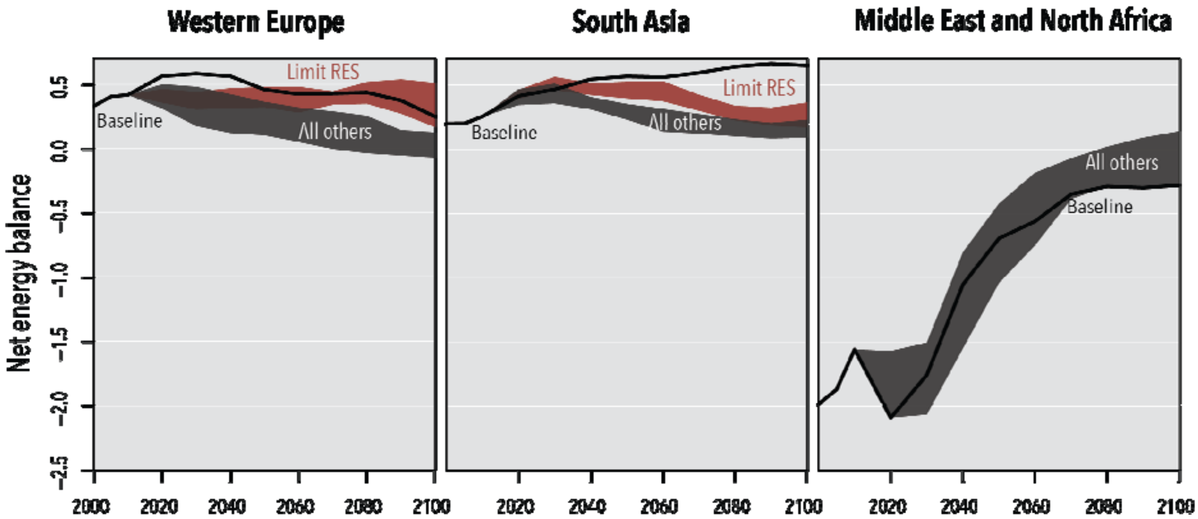
At the same time, trade intensity is affected by supply-side constraints. In scenarios with no limitations on RES, trade intensity declines to 1-10% by the end of the century. When RES are limited, this decline is less pronounced (11-15% by the end of the century) since the world is pushed to using more tradable fuels. If limited RES are combined with conventional transport and limited bioenergy the trade intensity of the GEA 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 paper. 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 the region's resource availability and pace of economic development. Figure 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 the current levels in the latter half of the century.

Figure 7 Net energy balance of selected regions

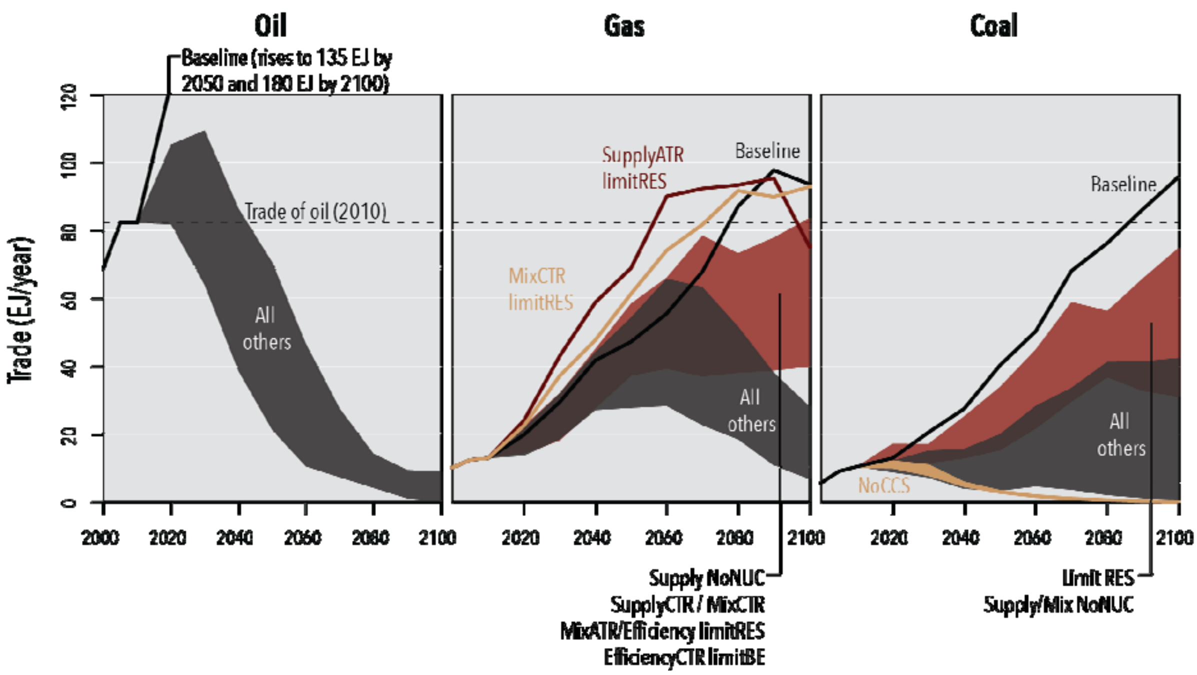


Note: Net energy balance is a proportion of imported or exported energy to the total energy supply in the region. It is positive for importers and negative for importers.

4.1.3 Trade in individual fuels

Figure 8 illustrates the trade in fossil fuels, which currently make 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 subsequently rapidly declines because oil is phased out of the energy system in order to de-carbonize.

Figure 8. Global trade in fossil fuels



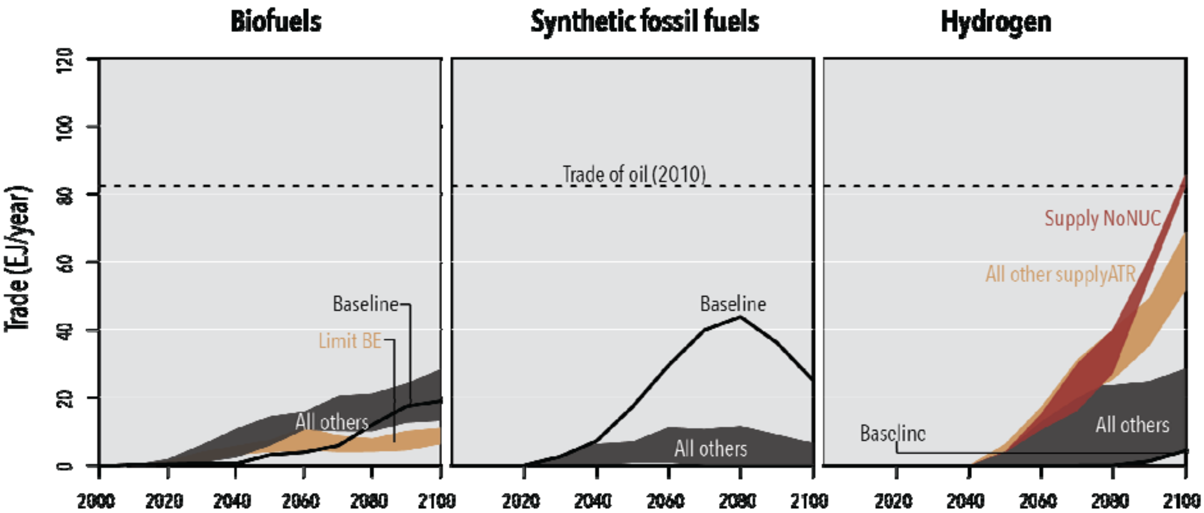
Natural gas trade rises in both the Baseline and low-carbon scenarios in the first half of the century. In the second half of the century, the trade in the Baseline continues to rise reaching over 100 EJ/year (more than oil trade at present). At the same time GEA scenarios diverge falling roughly into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

a) In one Supply and one Mix scenario with limitations on RES, gas trade increases to levels comparable to the Baseline and exceeding present-day oil trade volumes. In these scenarios, with limited RES, natural gas continues to be a critical part of the energy system until the end of the century. (Marked with dark gray lines in Figure 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 no nuclear development (leading to gas being used in electricity); Supply or Mix combined with conventional transport (leading to the use of gas-liquids in transportation); Mix or Efficiency combined with limited RES (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 isn't 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 the 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 (Figure 9).

Figure 9 Global trade in "new" fuels and carriers



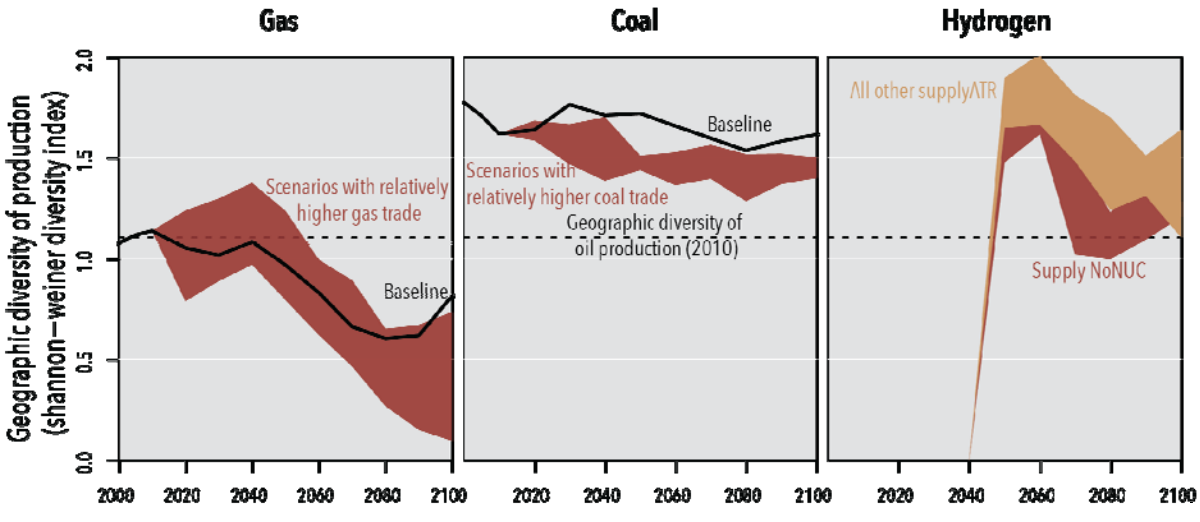
In the Baseline scenario the trade in biofuels after 2040 rises to ca 20 EJ/year by the end of the century. In low-carbon scenarios, the trade in biofuels increases to comparable levels (quicker), but less so in scenarios where the production of bioenergy is limited since this in turn limits the extent of biofuel use. In all scenarios the levels of trade in biofuels are 2-10 times lower than the volumes of oil trade at present.

The trade in synthetic fuels (liquids produced from coal or gas) in the Baseline 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 GEA 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 with no nuclear energy. For the advanced transport scenarios this is because these scenarios assume a higher potential for fuel cell technologies; thus combined with high demand, the hydrogen trade in these scenarios is particularly high. For the no Nuclear scenarios, this is because the limitations on nuclear limit the number of regions where it is economically feasible to produce hydrogen but at the same time there is high demand for hydrogen around the world.

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

Figure 10 Geographic diversity of production of fuels with highest global trade (high trade scenarios)



In the case of limited renewables and other scenarios associated with higher gas trade (groups (a) and (b) in the explanation to Figure 8) natural gas is indeed produced in an increasingly smaller number of regions. This is because natural gas resources are not evenly distributed and large volumes of extraction inevitably lead to increasing geographic concentration of production. In fact, in these scenarios (as well as in the Baseline) the production of gas may become far more geographically concentrated than the production of oil today.

Figure 10 also illustrates that geographic diversity of coal remains high even in higher trade scenarios. 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 planet than natural gas or oil resources. The geographic diversity of hydrogen production remains high under most scenarios but not all. Under supply scenarios with no nuclear development, the geographic diversity of production 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

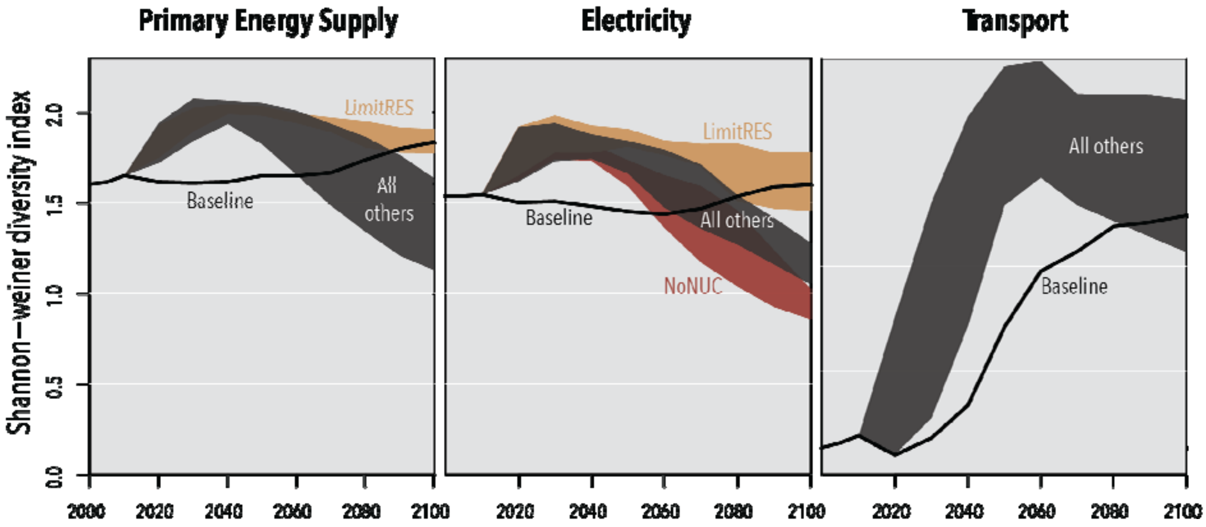
4.2.1 Energy intensity

Figure 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

Figure 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 it rapidly rises by 2030-2040 and then either declines (to the levels below the Baseline and the present) 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.

Figure 11 Diversity of PES, Electricity and Transport sector



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

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

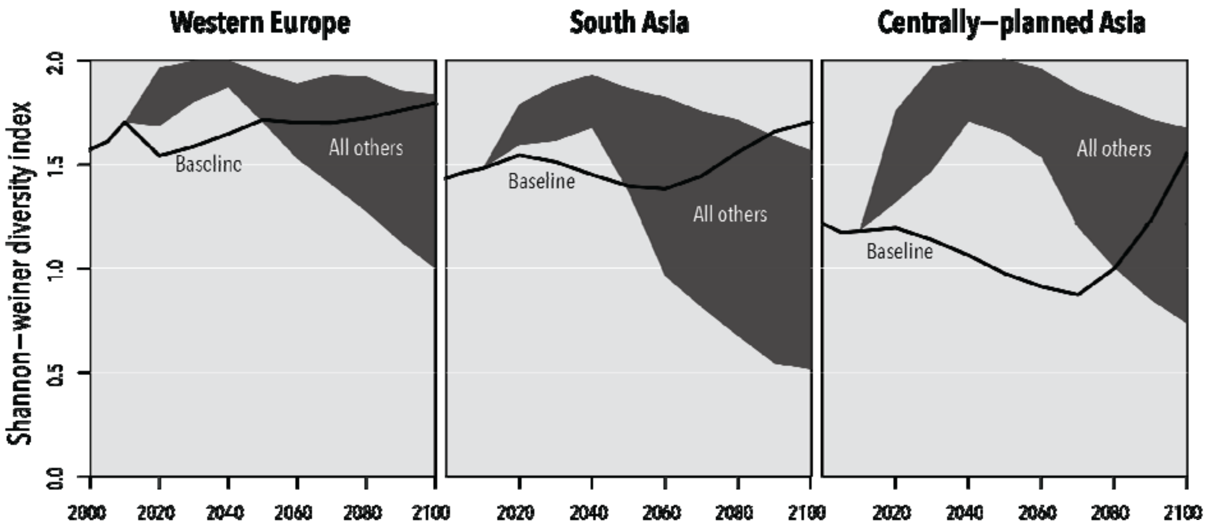
to significantly lower levels than baseline and the current value.

The low diversity of energy sources used in Transport is one of the main energy security concerns at present (Cherp et al. 2012). This diversity 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 commercial and residential) the diversity of energy sources does not change significantly in either the Baseline or low-carbon scenarios.

4.2.3 Diversity of energy supply at the regional level

Figure 12 shows PES diversity in Western Europe, South Asia and “Centrally-planned Asia”. It illustrates that whereas the three representatives regions generally repeat the global pattern (compare with Figure 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 comes to lower levels in very populous South Asia with limited energy options.

Figure 12 Regional diversity of PES



In summary, the diversity of energy options in 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 Baseline because of the dominance of renewables, particularly in scenarios where renewables are not limited or where nuclear energy is.

5 Discussion

This section summarizes the overall effect of energy transitions on energy security and discusses how this effect depends on policy and technology choices modeled in the low-carbon scenarios in this paper.

5.1 Energy security in low-carbon scenarios.

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

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

Indicator:	2010	2050 *low-carbon*	2050 *Baseline*	2100 *low-carbon*	2100 *Baseline*
PES trade	106 EJ	89 – 175 EJ	243 EJ	42 – 227 EJ	420 EJ
PES 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
Geographic div. of Gas prod.	1.1	0.8 – 1.1*	1.0	0.1 – 0.7*	0.8
Coal trade	10 EJ	3 – 34 EJ	40 EJ	0 – 75 EJ	96 EJ
Geographic div. of Coal prod.	1.6	1.4 – 1.5*	1.7	1.4 – 1.5*	1.6
Hydrogen trade	-	0 – 6 EJ	-	5 – 86 EJ	4
Geographic div. of Hydrogen prod.	-	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
PES 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

Note: * Only reports geographic diversity of production for scenarios with high trade in that fuel or carrier (see Figure 10).

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 of diversity of energy for transport and electricity production: with respect to these indicators low-carbon scenarios are stronger than both the Baseline and the 2010 situation.

By 2100, the picture becomes more nuanced. On the positive side, the overall energy trade as well as oil and gas trade are lower in low-carbon scenarios. On the negative side, in some GEA scenarios the levels of gas trade reach the levels of oil trade today while its production becomes even more geographically concentrated than today's oil trade production. Thus, while oil clearly ceases to be a major energy security issue, the trade of natural gas may acquire insecure patterns resembling the oil system and associated energy security concerns 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 will be a smaller energy security risk compared to the risks associated with the present oil trade.

The diversity of energy sources in electricity generation and the overall PES is also lower in some GEA 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 GEA scenarios as further explored in the next sub-section.

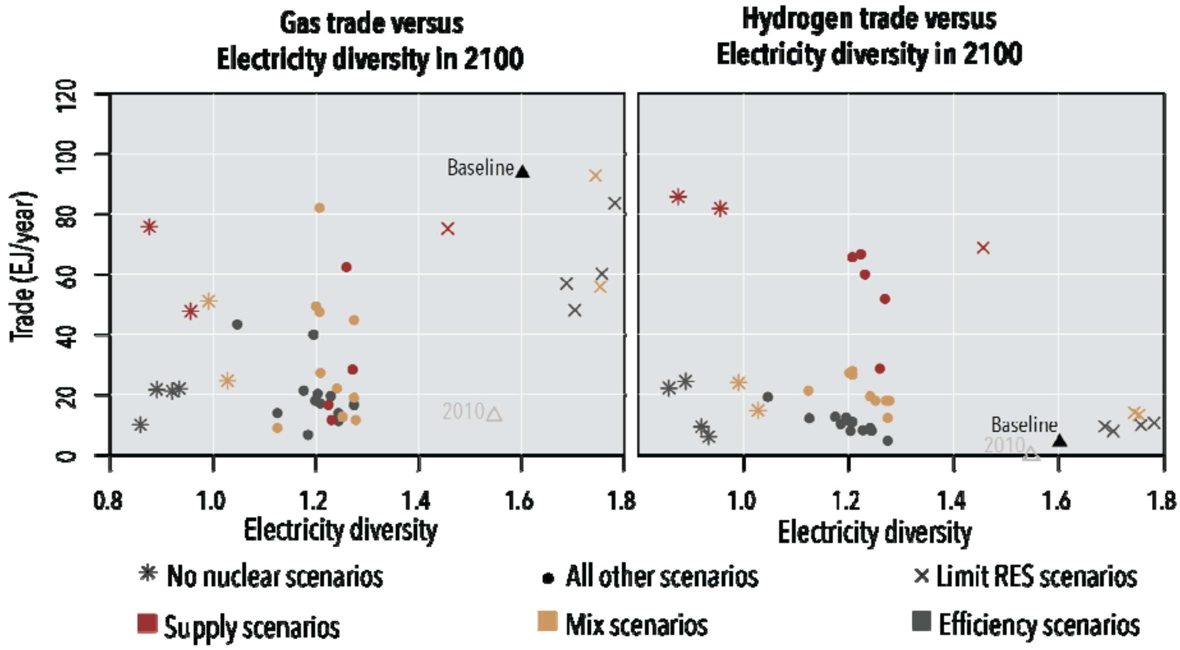
5.2 Impact of policy and technology choices on energy security in GEA scenarios

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

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

Thus limitations on renewables lead to higher energy trade, particularly in Supply and Mix scenarios whereas unlimited renewables are associated with lower diversity of energy options. While the energy security improves in most aspects there are three global energy security concerns which emerge under some scenarios: high gas trade, high hydrogen trade, and low electricity diversity. Both effects are more pronounced in Supply and Mix scenarios, particularly when nuclear energy is phased out. Figure 13 shows that only a limited number of scenarios are not located in “dangerous” corners where either trade is too high or diversity is too low. The relatively “secure” scenarios are Efficiency with limitations on renewables where both high diversity and lower energy trade can be assured simultaneously.

Figure 13. Diversity of electricity production, trade in gas and hydrogen in GEA scenarios



Note: 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.

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 Figure

13). In many cases, however, such a direct presentation of multiple indicators may not be sufficient 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. E. Gupta, 2008; Scheepers, Seebregts, de Jong, & Maters, 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 indicator 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 by McCollum et al. (under review). It was based on a more complex index originally proposed by Jansen, van Arkel, and Boots (2004) (who also suggested to penalize sources coming from unstable countries or scarce resources).

While this index shows 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 (in press) 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 but this does not exclude the possibility that appropriate aggregated indices will be developed for further studies of future energy security.

6 Conclusions

Ensuring stability of the global climate will require transformative changes in energy systems. The main difficulty in assessing energy security implications of such changes is finding metrics of energy security that are sufficiently specific to allow policy-relevant quantification and yet sufficiently generic to be applicable to energy systems radically different from the present ones.

Two main perspectives on energy security which existed for most of the history of modern energy systems are 'sovereignty' associated with the degree of domestic control over energy systems and 'resilience' - the ability of energy systems to respond to disruptions. To evaluate future energy security, this paper uses indicators reflecting global energy trade and regional energy balances as indicators of

[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 doesn't distinguish them.

sovereignty concerns. The diversity of energy options and energy intensity are used as indicators of resilience.

Although the use of diversity and import dependency indicators is common in energy security analysis, this paper proposes a novel method in which they can be applied to energy decarbonization scenarios. It starts with the recognition that energy security concerns have always been expressed with respect to distinct 'vital energy systems' defined in terms of their geographic or sectoral boundaries. Thus, energy security indicators should be applied to vital energy systems of the 21st century. Under different energy scenarios some of today's vital energy systems would persist and evolve (e.g. the global gas market, production and generation of electricity, transport energy use), some could disappear (e.g. oil and its products) and some might emerge or radically expand (e.g. global markets for biofuels and hydrogen). By applying commonly used indicators to both old and new energy systems this paper portrays energy futures in the familiar light of today's energy security concerns.

The energy transformation scenarios developed with the Global Energy Assessment provide quantitative representations of future energy systems which illustrates the use of this method of energy security assessment. The first results reported in this paper indicate that key energy systems in low-carbon scenarios have lower trade and higher diversity than in the Baseline scenario. These gains are more profound in the mid-term perspective (by 2050) although most of them persist or expand until 2100. In particular, the present-day energy security risks associated with global oil trade rapidly subside and eventually disappear under low-carbon scenarios while nothing of a similar scale emerges in their stead.

At the same time the present analysis identifies several concerns associated with certain energy systems in some scenarios, particularly at 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 it is low diversity of electricity generation options evolving by the end of the century. We show that the scenarios where both the global energy demand and the use of renewables are constrained make it possible to avoid both of these concerns simultaneously.

The analysis presented in this paper is an illustration of a method to quantify long-term energy security. It opens an extensive research agenda for further studies. In particular, we primarily discussed global-level results, whereas energy security futures of individual regions (and potentially individual nations) should be further explored. One specific concern is the future of energy-exporting regions which may experience a dramatic decline of energy export revenues, potentially a security concern. These results come from one modeling framework. Comparing the results to scenarios from other models will be necessary in the future.

Another interesting area to explore is the third 'robustness' perspective on energy security by overcoming the difficulties of developing meaningful indicators for IAMs. Future research related to the "robustness" aspect of energy security may focus on adding new indicators as well as the use of alternative scenario designs to explore the relationship between the robustness characteristics and other of energy security concerns, including the costs of low-carbon energy transitions. For example, resource scarcity is exogenous for most energy models and thus can be analyzed for the effect it has

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

on trade flows and the geographic diversity of production. Finding proxies for the reliability of an electricity system (such as spare capacity constraints) or the presence of "buffers" to mitigate resource shocks also offers an interesting future research area.[12]

There may also be energy security concerns associated with the very scale and speed of radical transformations of energy systems (e.g. the flows of capital and technologies). Analyzing these types of concerns would require more sophisticated conceptualization of energy security but may eventually be a productive method to identify political bottlenecks of low-carbon scenarios. Finally, detailed understanding of energy security concerns may allow introducing relevant constraints in energy models and thus producing more realistic images of possible futures.

Acknowledgements

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[12] Turton and Baretto (2006a) offer one useful approach to measuring the presence of buffers.

7 Appendix. Formulas for Indicators

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

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

Indicator	Energy security Concern(s)	Unit	Definition (formula)*	Applies to	
				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	PES, 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 PES used in this paper)	Global
Geographic diversity of production	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 PES used in this paper)	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	PES 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	PES	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					

Indicator	Energy security Concern(s)	Unit	Definition (formula)*	Applies to	
				Sector	Geography
Energy intensity	Overall vulnerability to energy supply and price shocks	MJ/$ GDP	TPES divided by GDP	PES	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	PES	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

Indicator	Energy security Concern(s)	Unit	Definition (formula)*	Applies to	
				Sector	Geography
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		
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*	PES	Regional

Bold text represents the indicators used (or energy systems addressed) in this paper

Normal text represents other indicators potentially suitable for assessment of energy security in future energy scenarios

* see the formulas and the explanation in the main text

7.1 Energy trade

Global fuel trade is the sum of all net exports for each globally-traded fuels or carriers. 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 each of these global fuel trade sums. This value only accounts for interregional trade which is likely to be a large part of country-to-country trade.[13]

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 traded energy/fuel/carrier in its overall regional supply; (c) as costs of 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 Figure 14 below) and sum the net-imports for each globally-traded fuel or carrier. This indicator could capture concerns which today are the high import dependence of the transportation sector in most countries (Cherp et al 2012).

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

7.2 Diversity

For diversity, we use the Shannon-Weiner 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[14] (HHI) has also been used in the literature as a measure of diversity (Chester 2009; 2009; Grubb, Butler, and Twomey 2006b; Jansen and Seebregts 2009; Jewell 2011; Neff 2010). Stirling argues that the SWDI is better than the HHI because the ordering of results are not influenced by the base of the logarithm which is used (Stirling 1998).

Much more important than the question of *which* diversity index is the issue of the diversity of *what*. The

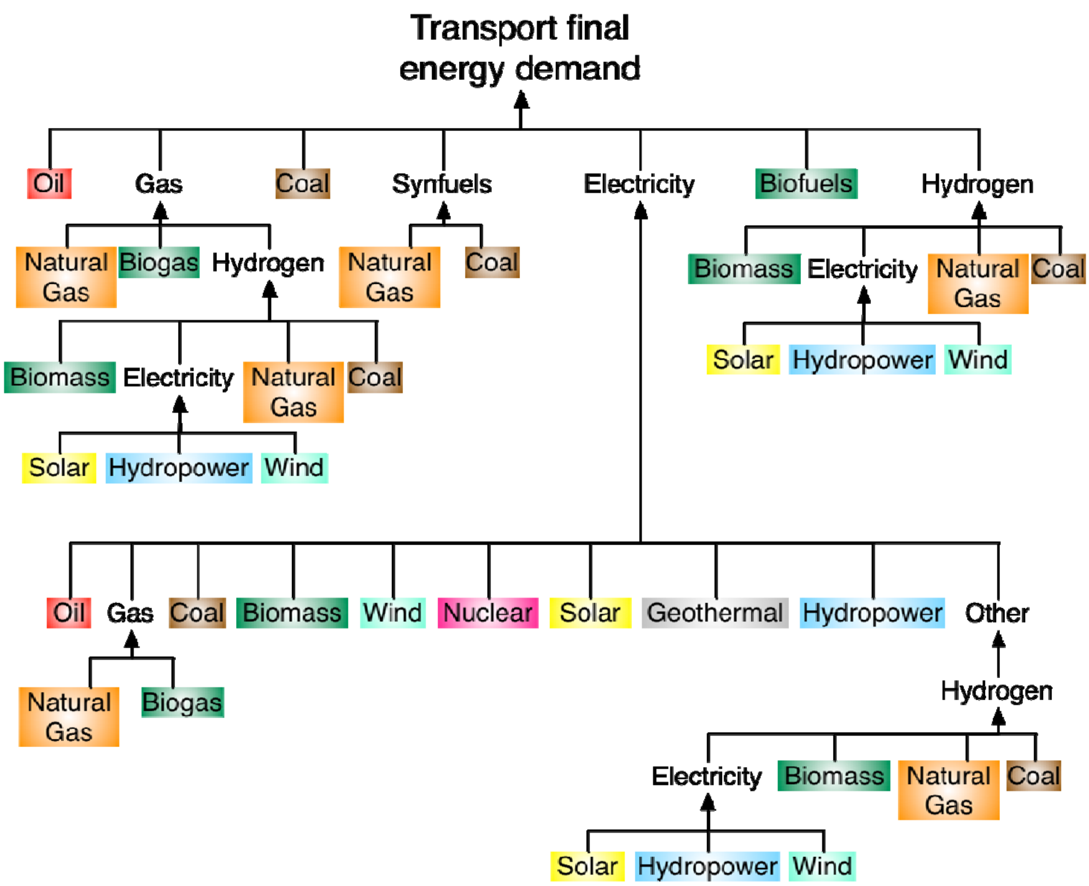
[13] Country-to-country oil trade in 2005 was about 110EJ (British Petroleum 2009) compared to 83EJ of the interregional trade in the MESSAGE model for this year. Thus, interregional trade currently accounts for about 75% of all oil trade.

[14] Herfindahl Hirschmann index = $\Sigma_i\, p_i$

most useful 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, materials, infrastructure, technologies, markets and other elements connected to each other stronger than they are connected to the outside world. From the energy security angle, the meaning of such connections is that in case disruption the elements within a system can replace each other, but the elements from outside the system - can't (Cherp and Jewell in press). Indeed diversity indices were first proposed to measure the diversity of sources in an electricity system (Stirling 1994). Electricity systems are both vital to modern economies and the various sources of electricity production are substitutable.

In the paper, we present the diversity of PES as well as the diversity of energy sources used for electricity generation and transport. The PES diversity was calculated based on the proportion each primary energy source contributed to the TPES (using the substitution equivalent PES 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 Figure 13). This proportional allocation 'map' needs to be tailored for the specific configuration of energy system, actual or modeled. Thus the way we apply the end-use diversity index accounts for disruptions which would occur at the primary energy level. One can also measure the diversity of carriers (e.g. electricity vs. liquid fuels) used in an end-use sector.

Figure 14 Proportional allocation of primary energy sources for transportation



As discussed in section 5.3, some studies have used a compound diversity indicator on the regional level, to combine the import dependency and diversity on the regional level according to the following formula:

$$\text{Compound diversity indicator} = \Sigma_i \left[\left[1-m_i \left(1-S_i^m/S,^{\max}\right)\right] p_i \ln(p_i)\right]$$

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 $S,^{\max}$ is the maximum possible value of the Shannon index if all regions exported an equal amount.

7.3 Energy intensity

Energy intensity is the amount of energy used per dollar of GDP or value-added (in this study it is 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.

7.4 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 included at the moment, 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 by Turton and Barretto (2006a).

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