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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,

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