Energy Strategy Reviews 6 (2015) 48–56

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.ees.elsevier.com/esr

ANALYSIS

Energy security matters in the EU Energy Roadmap

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ARTICLE INFO

Article history:
Received 10 October 2014
Received in revised form
29 January 2015
Accepted 11 March 2015
Available online 1 April 2015

Keywords:
Energy security
Security of supply
Climate change mitigation
EU Energy Roadmap
Low-carbon scenarios

ABSTRACT

Energy security has gained increasing prominence on the EU political agenda, but is often framed narrowly, in terms of import dependency or security of supply. In this paper we screen and scope out a more comprehensive suite of energy security aspects to be considered when assessing low-carbon energy scenarios and apply it using the EU Energy Roadmap as an example. Availability and affordability issues as well as security of demand matters and geopolitical security aspects are identified and discussed. External factors, e.g., future international climate treaties and international relations, are important for some energy security outcomes. A broader framing of energy security together with structured assessments on the security implications of energy transitions would benefit future EU energy policy.

1. Introduction

The climate change challenge requires a transformation of the energy system from conventional fossil fuels to low-carbon alternatives and high energy end-use efficiency. The EU Energy Roadmap for 2050 and its impact assessment [1,2] illustrates, in the form of scenarios, alternative development paths, for the European energy system that are consistent with the EU ambition to reduce greenhouse gas emissions by 80% by 2050. The scenarios vary in terms of energy sources and technologies, level of demand reductions, and costs. The impact assessment [2] addresses the three overarching energy policy objectives, i.e., sustainability, competitiveness, and energy security, but with different levels of ambition and stringency.

Since the early 2000s, energy security has gained increasing prominence on the EU political agenda [3], and even more strengthened due to the recent developments in the Ukraine and the strained EU-Russia relations. Energy security is a multidimensional concept including aspects such as security of supply, security of demand, affordability issues and revenues from energy, geopolitical considerations associated with security and defense policy, other political risk factors, economic risk factors and energy poverty, as well as technological and environmental risk factors. However, in most EU policy documents the main energy security aspect discussed is security of supply. This is true also for the EU Energy Roadmap [2] where a limited set of issues of security of supply are raised, only two of which, i.e., import dependency and more variable electricity production, are described in any detail.

The past decade, import dependency for EU-27 increased from 75.7% (2000) to 84.3% (2010) for oil, and from 48.9% (2000) to 62.4% (2010) for gas [4]. But the extent to which import dependency, as highlighted in the Energy Roadmap impact assessment, is important for energy security can be debated. Furthermore, the results and approach concerning import dependency used in the impact assessment are not entirely consistent with the main report that argues for increased interchange with the Southern Mediterranean, Russia and Ukraine [1, p. 11]. Nor is it consistent with other documents where the international cooperation and partnership dimensions of energy security are underlined (e.g. Ref. [5]).

Framing the energy security concept narrowly when examining the effects of alternative low-carbon scenarios increases the risk of incoherent policy when the broader EU policy arena is considered (e.g. security and defence policy, foreign and neighbourhood policy, critical infrastructure protection,

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http://dx.doi.org/10.1016/j.esr.2015.03.002
2211-467X/

economic and social policies, environmental policy, etc.). Conversely, the integration of a broad energy security frame into key policy documents and impact assessments could facilitate increased policy coherence.

2. Methods

In this paper we elaborate and apply a broad approach to energy security in order to identify plausible synergies and conflicts between low-carbon transition strategies and energy security. We use the scenarios of the EU Energy Roadmap as an example and for illustration. The purpose is here to screen and scope what are relevant aspects to study based on assumed policy relevance. Our approach is qualitative and does not provide a conclusive assessment of energy security impacts from low-carbon energy road maps. Our aim is to broaden the perspectives on the relations between climate policy and energy security and identify salient issues and further research needs.

In section 3.1 we describe various energy security perspectives and aspects and assemble them in a framework. In section 3.2, we apply this framework to the EU Energy Roadmap scenarios. In the discussion section 4 we reflect on the framework, the roadmap scenarios and external uncertainties, before concluding in section 5.

3. Results

3.1. Energy security aspects

Energy security is a concept with many meanings. There is no established, all-encompassing definition of energy security partly because the notion of energy security is highly context dependent [6]. Moreover, since security generally is a question of subjective perceptions [7] such definitions would not be universally applicable. In order to facilitate an understanding on the meta-level however, we promote the view that energy security can be regarded from two separate perspectives; 1) when the energy system is *exposed to insecurity*, and 2) when the energy system *generates insecurity*. This view was presented by Johansson [8], distinguishing between security aspects related to either;

1. the *energy system as object* which could be exposed to insecurity and the threats which would disturb the functioning of the energy system (these aspects can be described under the concepts of security of supply and demand), or
2. the *energy system as subject* generating or enhancing insecurity (or security) or functioning as a threat multiplier, which for example include conflicts generated as a side-effect of the economic value of energy, geopolitical considerations, as well as social, political, technological and environmental risk factors.

3.1.1. Security of supply aspects

Security of supply can be interpreted as reliable access for consumers to energy resources (primary energy or energy carriers) at reasonable costs (see e.g. Ref. [9]). Security of supply requires that there are available energy resources, a capacity to exploit and convert these resources to suitable energy carriers, and that there is a secure system for energy distribution. Security of supply includes both physical aspects (e.g. availability of energy to the consumer at the time of demand) as well as economic aspects (e.g. affordable and stable prices) [10]. Generally, much of the discussion regarding security of supply deals with external dependencies [11]. A broader meaning of supply security, however, also includes the character and functionality of the domestic energy system in terms of energy mix, primary resources as well as conversion, infrastructure facilities and end users (see e.g. Refs. [12,13]).

Resource Availability is an important and well described aspect in the energy security field (e.g. Ref. [14]). When it comes to fossil fuels this is often associated with geological existence (e.g. Ref. [6]) whereas a renewable source such as biomass is determined by biological factors. Moreover the availability of non-energy resources (e.g. rare earth minerals) may in some cases be a limiting factor for specific energy technologies [15–17].

Accessibility (e.g. Ref. [14]) can be understood as the aspects necessary to transform and transport the resources to supply energy services to the users. Poor accessibility could result from a number of things ranging from infrastructural disturbances (e.g. broken links) to supply and demand imbalances, perhaps due to lack in investments in energy extraction, non-functioning markets or systemic flaws in terms of bottlenecks [18]. It could also be the result of intentional disturbances of energy flows in order to gain political advantages or unstable political situations in regions of origin and transit (see section below).

When the technical and infrastructural dimensions of accessibility is considered, risks and security aspects related to transport routes, transmission networks and other distribution systems can be relevant to include. It can be a question of systemic vulnerabilities to antagonistic threats (e.g. terrorism) and extreme weather events, or a question of technical system characteristics such as grid stability and power quality (see e.g. Ref. [19]).

From the consumer perspective, diversity is an important security of supply aspect (e.g. Ref. [6]), in terms of *diversity of resources* and *diversity of suppliers*. Stirling in turn identifies three aspects of diversity namely variety, balance and disparity [20]. Diversity reduces the sensitivity to disturbances in the supply of a specific resource from a specific supplier. A related and well described aspect – focussing on the state-level – is *import dependency* which is further elaborated and discussed below.

Affordability aspects in terms of *high costs* and *high volatility* may be considered a threat against a well-functioning energy system. Longer periods of high prices affect industry and the purchasing power of households, thus affecting the overall economy. It can also give direct negative social effects for households subject to energy poverty, i.e., when poorer groups in society have difficulties to afford levels of energy necessary to maintain a minimum living standard (e.g. Refs. [21–23]). Short term volatility in energy prices can also create uncertainty affecting investments decision [24].

3.1.2. Security of demand and revenue aspects

The functionality of the global energy system is also crucial for producers and exporters. From the producer perspective, the most important negative effect of a disturbance in the energy system may be that security of demand cannot be maintained. Security of demand is fundamental for energy exporters in order to be able to sell their product and generate revenue. Security of demand can be seen as the mirror image of security of supply. The basic requirements are thus the same; availability of energy resources and distributional security, associated with the same problems as described previously. In addition, security of demand also needs availability of customers and preferably diversity of customers as well. The profound difference between the consumer and the producer in this context is that energy services are essential to the consuming part, while the revenue from energy is essential to the producing part. Despite different perspectives, it is obvious that there are many mutual consumer and producer interests (see e.g. Refs. [25,26]).

When it comes to security of demand and revenue aspects, it should be recognized that there are different conditions for different actors, e.g. exporting countries, upstream companies (e.g. exploration and extraction of crude oil), producers of energy carriers (e.g. power companies), energy traders and infrastructure owners and operators.

3.1.3. Import dependency and its relation to geopolitical aspects

Import dependency is often considered a risk factor and is probably the main aspect that many intuitively associate with energy security.

Import dependency is, however, not a problem *per se*, and the security implications depend on the diversity and liquidity of the upstream market as well as of existing governance mechanisms. Import dependency may cause insecurity, e.g. when markets fail. Import dependency can be considered a risk factor due to geographical distances as well as control and disposition issues, i.e. for some reason the desired energy services cannot be delivered.

Another case when import dependency can be a security problem is the potential exposure to intentional actions or strategies of an exporting country aiming to put political pressure on an importing country in order to gain political or economic benefits, or security concessions. This geopolitical dimension of dependency is usually denoted *the energy weapon*, which could be understood as the possibility to exercise power through energy dependencies (e.g. Refs. [27–29]). The energy weapon has seldom been used and the effectiveness has been questioned (e.g. Ref. [30]). For example, as oil is traded on a global liquid and flexible market via shipping, the energy weapon, for bilateral situations, is rather ineffective. Pipeline-distributed gas, exclusively from producer to consumer is more suited for an actor aiming to use the energy weapon. The 'demand and revenue weapon' in terms of trade blockades directed towards energy suppliers (e.g. Iran and Iraq), has however, been used from time to time in order to achieve political goals [8]. The risks associated with international energy relations are more dependent on the context in terms of other frictions in the international system and specific power relations than on the actual energy dependencies (see e.g. Refs. [30,31]).

An import dependent energy system will be dependent on external factors that cannot easily be controlled by national governments. But when paying attention also to security of demand, it becomes clear that dependencies are to various degrees mutual. It could therefore be argued that a symmetric dependency, in terms of a well-balanced relation between importers and exporters, leads to absolute gains in terms of security. It is however crucial to emphasize the 'well-balanced' part in order to avoid an energy security dilemma, where for example too much focus on diversification by the importer could result in more insecurity for an exporter in a zero-sum calculation (see e.g. Ref. [32]).

The realist school of international relations studies, views transactions and negotiations as 'zero-sum games' (see e.g. Refs. [33,34]), while the liberal school of thought in turn sees it as 'win–win games'. In the latter, international *interdependency* can be seen as an important security building aspect (e.g. Refs. [35,36]). Mutually dependent countries with interconnected economies are, according to this school of thought, less willing to engage in political or armed conflicts with each other. The cost of harming the bilateral interdependency relations is higher than the possible gains from a potential conflict. International flow security enables the intricate system of inter-woven international interdependencies which may be conducive to overall energy security.

The optimistic interdependency theory has been debated, nuanced and criticized (e.g. Refs. [37,38]). One argument is that interdependency does not eliminate struggle and conflict but rather alters the forcible means [33,39]. Moreover, in reality there are no symmetric interdependencies, only asymmetric ones associated with various political risk factors. In addition, interdependency is not confined to energy and it can be maintained with other exchanges and flows e.g. information, ideas, manpower, capital, products, and raw materials.

A related aspect is that indirect effects of measures aiming to increase distribution or flow security might entail increased securitisation [40] and military involvement in the energy supply chain. In short, the concept of *securitisation* is how a certain issue is transformed by an actor into a matter of security, and enables the use of extraordinary means in the name of security [40,41] Increased tensions due to increased military presence – as a reaction to a perceived security threat – can thus be considered as an example of the energy system possibly generating or enhancing insecurity.

3.1.4. Other political, economic, social, technical and environmental risk factors

From the previous discussion it is clear that energy, or the energy system, can be a generator or enhancer of insecurity. An aspect, at least in part measurable, is the occurrence of international or domestic conflicts where energy resources play some kind of a role [42–44]. The global asymmetry in concentration of resources is one part of the explanation. Internationally, global scarcity can motivate states to use force to secure their access to resources [42,45]. In regions with resource abundance the economic value of the resource and the revenue stream from extracting it, can provide a source of funding for belligerents and thereby impact the onset, duration and intensity of armed conflicts [43].

When it comes to social risk factors the energy/fuel poverty has been mentioned above. Even when energy security is high on average, large differences may exist within as well as between communities. Another socio-economic aspect is the 'resource curse', whereby resource rich countries suffer from poor governance and corruption as a consequence of the resource. One specific aspect of the resource curse is the 'Dutch disease' – currency appreciations that lead to competitiveness losses for the rest of the economy (e.g. Refs. [46–48]). Despite possessing an abundance of non-renewable resources, countries associated with the resource curse are overrepresented in terms of local and regional conflicts, less economic growth and worse development outcomes than other countries as a result of resource mismanagement, decline in the competitiveness of other sectors, or ineffectual and corrupt institutions. An underlying problem, in addition to low economic diversity, is the regime's lack of accountability to the population as government services are financed through resource revenues rather than paid for by its inhabitants through taxation [49]. This hampers the development of democratic institutions. Slightly more than 30 countries have a least 30% of their export revenues from oil and gas [50,51].

Political aspects concerning exporting countries may also relate to political (or regime) stability, or the reversed view that imports might be an indirect support of authoritarian and repressing regimes. An estimate (from 2000) claims that by 2020, approximately half of total global oil demand will be supplied by countries associated with high risk of internal instability, of which 10 of the 14 top oil-exporting countries [51,52]. Such aspects also have social dimensions in terms of human security, livelihood and poverty in the concerned countries, sometimes mirrored by the United Nations' Human Development Index (HDI) (e.g. Ref. [6]), or the Geopolitical Instability Index (GPI) (e.g. Ref. [53]). Another indirect energy security aspect is the livelihood conditions in 'third countries', i.e. people in countries which neither export nor consume large energy volumes but still are indirectly affected by changed supply and demand patterns globally and its impact on energy prices.

Technological and environmental aspects may also be relevant. Energy security aspects associated with technological risk factors involve for example technical safety aspects (e.g. electrical safety) and the occurrence of accidents, hydro power dam safety, security associated with nuclear materials, as well as explosive risks from fuels, toxicity issues, etc. Environmental aspects can involve e.g. climate impact and other pollutants [8]. A related aspect is threats to food security, when agricultural land is used for, or degraded by, energy production [54]. On the local level, also drinking-water security might be affected.

3.1.5. Framework to identify potential energy security issues in low-carbon scenarios

Based on the scoping of security aspects we propose an analytical framework, a policy assessment matrix, to identify potential energy security issues associated with the realization different energy scenarios. A set of alternative scenarios can be assessed and compared, regarding energy security effects, to a reference scenario. The principles of the framework and the energy security aspects we propose to include are shown in Table 1.

3.2. Potential energy security issues in the EU Energy Roadmap

We use the framework (Table 1) to identify and discuss potential energy security issues related to the EU Energy Roadmap scenarios. The EU Energy Roadmap's low-carbon scenarios for 2050 mirror transformative changes compared with today's situation and compared with the reference scenario for 2050, which is a projection of a development assuming no new policies after 2010.

The scenarios were generated with the cost optimization model PRIMES, based on various boundary conditions and assumptions concerning policies, technology development and not the least costs (see e.g. Ref. [55]). There are identifiable main drivers for each scenario (see Table 2), in terms of efficiency, renewables, nuclear, CCS, and electrification and diversification.

There are a number of additional factors that are important, when evaluating the energy security of the studied system, and for which relevant data is presented in the roadmap, see Table 3. However, sometimes the information in the roadmap lack in detail in a way that prevents some security implications to be adequately evaluated [56].

The approach to identify potential energy security matters was to answer the following questions for each energy security aspect:

- Is the security aspect worsened, when comparing the low-carbon scenarios with the reference scenario?
- Is the potential negative outcome difficult or impossible to mitigate?
- Is the outcome of this aspect mainly dependent on external factors? What are the main uncertainties?

We analysed mainly aspects that arise due to differences between the reference scenario and the low-carbon scenarios, but also due to differences between the low-carbon scenarios. An important step was also to identify the importance of external factors and their potential influence. External factors are all factors that are not directly shaped by the EU energy system or policy interventions that address it. For example, global market prices, the energy and climate policies of other countries, geopolitical preconditions, etc.

Our approach should be seen as a learning tool and not one that can provide conclusive answers. We identify and discuss potential energy security matters but do not provide any complete or exhaustive assessment. Doing this thoroughly and consistently would require involvement of stakeholders and experts in various fields, and probably a number of iterations as well in order to guarantee consistency (see e.g. methods for scenario planning [57,58]). The analysis here is based on qualitative expert judgment among the group of authors providing a bird's eye view and broad perspective where potential energy security matters can be identified.

3.2.1. Availability issues as potential security problems?

3.2.1.1. Global climate action or not is important for availabilities. EU accounts for a minor fraction of global demand of energy and this fraction is expected to diminish in the future. For example for 2035 in its new policy initiatives scenario, the IEA expects the EU to account for 9% of global primary energy demand compared to 13% in 2011 [59]. Therefore, the availability of various energy resources is dependent on what happens in the rest of the world. If it stays on the fossil based business as usual path, there is a risk of availability problems of fossil energy resources for the EU, due to resource competition. Although the rest of the world may have even greater problems, EU will also see some problems as scenarios with high shares of CCS fuels rely on the availability of especially natural gas.

If, on the other hand, there is 'Global climate action', the EU may face availability problems in the High Renewable scenario, especially when it comes to imports of bioenergy. If EU is a climate forerunner however, the competition over imported energy carriers in the renewable scenario will probably be lower. In this context, differences between the various renewable sources should be noted. Biomass, in contrast to flowing renewable energy (sun, wind, waves), share some availability characteristics with fossil fuels and it is reasonable to expect some negative impact due to the resource constraint on biomass production both in Europe and globally [60].

All scenarios involve great reductions of primary energy outtake, in particular the High Energy Efficiency scenario. Energy efficiency as a unilateral EU strategy can entail improved energy security in reducing vulnerability, but will probably only bring marginal positive effects on total global resource availability since EU accounts for a limited share of demand. Efficiency probably does not affect accessibility — the risk for supply disturbances remains. Seen from a multilateral perspective, absolute energy demand reductions imply less pressure on limited resources, i.e. improving the long-term availability, resulting in a positive effect on collective security. 'Global climate action' with reduced demand will probably render positive security of supply effects when the resource availability aspect is considered involving less stress on both energy resources

Table 1
Principles of framework with suggested energy security aspects to include.

Energy security aspects		
Energy system as object	Security of supply aspects	Resource availability and accessibility; Import dependency; Diversity of supply and suppliers; Transport route, distribution and transmission security; Affordability (high costs and stable prices/volatility)
	Security of demand and revenue aspects	For exporting countries, energy producers, energy trade companies and infrastructure owners
Energy system as subject	Political aspects	Geopolitical dependency risks (the energy weapon); Security through interdependency weakened; Military involvement due to securitization of energy supply chain; Political effects of sabotage or terrorism on energy facilities; Bad governance due to resource curse/the Dutch disease; Political stability in exporting countries; Indirect support of authoritarian regimes; International or domestic resource conflicts
	Economic aspects	Economic dependency risks (the energy weapon); Unbalanced economy due to resource curse/the Dutch disease; Economic effects of sabotage or terrorism on energy facilities; Economic security through interdependency weakened; Economic effects of resource conflicts
	Social aspects	Energy/fuel poverty; Poverty, livelihood and human security in exporting countries and 'third countries'; Threats to food or drinking-water security; Human security effects of resource conflicts
	Technological aspects	Risk for accidents affecting environment or health; Nuclear and radiological risks; Explosivity; Toxicity
	Environmental aspects	Air pollutants; Land use and degradation; Water degradation; Climate impact

Table 2
Some characteristics of EU Energy Roadmap low-carbon scenarios and reference scenario for 2050 [2, p. 38] with main driver highlighted in bold style.

Scenarios/Characteristics	Reference scenario	High energy efficiency	High renewables	Delayed CCS	Low nuclear	Diversified supply technologies
Primary energy (% compared to 2005)	−3.5	**−40.6**	−37.9	−32.2	−37.7	−33.3
Renewables in gross final consumption (%)	25.5	57.3	**75.2**	55.7	57.5	54.6
Nuclear energy in primary energy (%)	16.7	13.5	3.8	**17.5**	2.6	15.3
CCS in power generation (%)	17.8	20.5	6.9	19	**31.9**	24.2
Electrification (% of total energy)	29.1	37.3	36.1	38.7	38.5	**38.7**

as well as extraction and conversion facilities. In a long-term perspective the outtake of, e.g., oil and gas will most likely be adjusted to match demand, which may entail similar risks for short-term imbalances as today and as in the reference scenario, in spite of the fact that there will be more available volumes (i.e., reserves) in the ground. However, since decreased volumes are involved in the scenarios, short-term imbalances resulting in increasing prices will render less negative impact on the users, compared with the reference scenario. A potential negative effect of energy efficiency on availability would be that lower price make unconventional oil and gas extraction less profitable, thereby reducing both reserve availability and diversity.

3.2.1.2. Can energy efficiency threaten domestic supply sources?. When we apply a broader interpretation of *supply*, which does not only include imports but also domestic supply, additional observations can be made. From the EU perspective, reduced demand can reduce import dependency, which has been the classic measure of security of supply. On the other hand, lowered demand and related price decreases could make (more expensive) domestic energy production less profitable which in turn could lead to lower investments in domestic production capacities. Although the lack of domestic production may not be a problem under normal conditions, it could increase supply risks in case of disturbances on international markets or distribution breaks due to e.g. natural disasters or wars. It is difficult to draw any general conclusion on this issue as conditions vary depending on specific future energy system, market and governance structure. In some cases diversification through domestic supply is more secure than imports, in other cases it may be the other way around. Therefore, one important analysis to perform is to identify the fundamental limiting factor for the availability, and assess the vulnerability, of each specific energy resource and flow [61]. Moreover, depending on the specific energy aspect in focus, *flexibility* may be more important than *diversity* in order to achieve *security*, e.g., when domestic systems of energy carrier production (e.g. district heating) are flexible to use many energy resource inputs (e.g. gas, waste, and biofuels).

3.2.1.3. Availability of other energy related resources uncertain. The future availability, and necessity, of energy related resources, such as special materials and minerals required in energy technologies (e.g. in batteries, fuel cells, wind turbines, solar cells, etc.), is associated with great uncertainty. We cannot predict the specific technological developments. Moreover, the predictions of today over future availability of such resources (needed or desirable in today's technology) are associated with major uncertainties.

This aspect might come into play as an insecurity factor in some scenarios but is highly dependent on the specific technologies used in future energy applications as well as the technological possibility and economic rationality for implementing recycling systems for specific materials. Furthermore, scarcity will drive technological innovation that will continue to enable substitution of materials for the energy sector as it has always done.

3.2.2. Affordability; the risks of high costs and high volatility respectively, spread unevenly over the low-carbon scenario space

According to the roadmap, total energy system costs (subject to assumptions about the cost of capital, fuel and electricity, and direct energy efficiency investments) are quite similar in the long term perspective (2050) in all the low-carbon scenarios. The low-carbon scenarios with the lowest costs are

Table 3
Import dependency, oil and natural gas consumption, share of total electricity production for a number of energy sources, total energy system costs, fixed costs as fraction of total energy costs and total grid investments in the EU Energy Roadmap scenarios [2].

Scenarios/Characteristics	Reference scenario	High energy efficiency	High renewables	Delayed CCS	Low nuclear	Diversified supply technologies
Import dependency 2050 (%)	57.6	39.7	35.1	38.8	45.1	39.7
Oil consumption 2050 (Mtoe)	560	168	176	174	173	175
Natural gas consumption 2050 (Mtoe)	359	257	210	288	294	282
Electricity production (% of total electricity production 2050)						
Fossil fuel	33.3	21.6	9.6	20.1	32.7	24.8
Nuclear	26.4	14.2	3.5	19.2	2.5	16.1
Renewable energy	40.3	64.2	83.1	60.7	64.8	59.1
Other fuels (hydrogen, methanol)	0	0	3.9	0	0	0
Variable electricity production[a]	25.2	43.8	65.1	42.3	46.4	41.5
Cost aspects						
Average annual total energy system cost 2011–2050 (Bln Euro'08)	2582	2615	2590	2525	2552	2535
Fixed costs (% of total energy costs, average 2011–2050)	49	65	63	62	62	62
Grind investment costs 2011–2050 (Bln Euro'05)	1269	1518	2195	1717	1793	1712

[a] Wind, solar, tidal etc. which is also included in the fraction for renewable energy.

the Delayed CCS scenario and the Diversified supply technologies scenario. The cumulative total energy system costs[1] 2011–2050 as a fraction of GDP varies between 14.1 and 14.6% among scenarios. The estimates are subject to great uncertainties regarding, e.g., future prices of oil, gas and coal, technology development and costs of new technology, policy and effects of implemented means of control, acceptance and behavioural patterns, etc. Other assessments highlight the possibility of actions at no net cost (e.g. Ref. [62]). The scenarios definitely imply a shift from variable costs to up-front costs associated with investments in efficient end-use technologies, infrastructure and energy conversion facilities, including CCS.

The efficiency scenario requires great investments in end-use technologies. The renewable scenario requires investments on all levels. The scenarios relying on nuclear and CCS require great investments on the production level. Capital expenditures is an important issue when it comes to *affordability*, depending on external factors such as business models, financing, economic growth, future EU energy and economic policy, distribution of wealth, etc.

In the impact assessment of the EU Energy Roadmap, especially the High Energy Efficiency and High Renewables scenarios are highlighted as costly scenarios for households, as these scenarios are particularly investment intensive [2]. The former scenario implies direct household costs in terms of energy efficient end-use technology. The latter renders indirect costs mirrored in increased consumer prices due to upstream investments.

However, there are uncertainties related to the implementation of CCS technology (see e.g. Ref. [63]), as well as nuclear power expansion (see e.g. Ref. [64]) that could result in significant cost increases also for the CCS and Nuclear scenarios. Future legislation and regulations and low public acceptance can lead to long and costly lead times and extra cost for systems guaranteeing safety/security when CCS and nuclear are considered.

The most efficient and diversified scenarios, i.e. High Energy Efficiency, and Diversified Supply Technologies, should intuitively be the ones associated with lowest vulnerability to price shocks. Short-term price shocks can be negative for the economy as rapidly increasing price levels can be difficult for business and households to adapt to. Businesses risk losing competiveness and households will use a larger fraction of their economic resources on energy and thus less on other consumption. Increasing prices on fuel imports will furthermore impair the trade balance. The consequences in the form of price shocks will most likely be lowest in the High Energy Efficiency scenario, which has lower energy use. The Low Nuclear scenario, relying on CCS, involves a greater gas dependency compared with the reference (relying more on coal), causing increased vulnerability to higher gas prices. Moreover, the large-scale nature of energy conversion in the Delayed CCS scenario, associated with much nuclear power, imply a potential price risk when, for example, major nuclear plants stop operation or if certain reactor types have to stop production due to new security problems being discovered.

The High Renewable scenario has a relatively diversified supply base and is less exposed to fossil fuel prices. On the other hand, as much of the renewable energy production is dependent on varying wind and solar conditions, short-term volatility could be relatively high, even though production differences between years are rather low. Biofuels will probably follow oil prices [65], at least initially, and substituting oil with biofuels can compensate for some of the depletion of oil reserves. Depending on how this would affect major oil producers' investment decisions, it could increase the spare capacity in oil extraction and dampen volatility on oil markets. The mechanisms of today, for dampening oil price volatility and avoiding oil market turmoil, are based on overcapacity in production.

An electricity production system based on non-fossil production with high investment costs and low variable costs will be less sensitive to changes in fossil fuel prices. Electricity prices may, however, still be sensitive to fossil fuel prices if fossil fuel based electricity constitutes marginal production and thus determines the prices.

3.2.3. Security of demand will be threatened but perhaps not revenue?

Lower quantities of fossil fuels are expected to be sold at lower prices (before CO_2 pricing) in a low-carbon future. Probable losers are countries and companies stuck with territorially bounded (fossil) energy. Some suppliers will also be exposed to the risk of stranded assets, for example capital-intensive coal extraction technologies, especially in scenarios with low CCS penetration. The most obvious hotspot in our framework, when discussing security of demand, would then be in the scenarios with least aggregate demand, i.e., the High Energy Efficiency and High Renewables scenarios.

Winners from 'global climate action' with regard to security of demand will probably be exporters of renewable energy. Some energy exporters will probably have greater possibilities than others to transform industries and value-chains to adapt to the demand for low-carbon energy. One example could be Russia's great potential bioenergy resources. Energy traders of 'carbon neutral' energy carriers, e.g. electricity, will probably also see possibilities for new revenues.

However, the conclusion that climate policy will reduce security of demand for fossil fuel exporters, does not necessarily hold in all circumstances and the consequences for various countries will differ depending on the type of resource considered, the availability of this resource and the actual policy framework. For example, Persson et al. [66] in a modelling exercise that suppliers of conventional oil (in this case OPEC is the study object) could even gain from a low-carbon future, under certain conditions (including a cost-effective global climate regime). This is partly because all conventional oil reserves are used up also in the low-carbon scenario, and partly because the prices on conventional oil are higher in the low-carbon scenario than in the baseline scenario. This perhaps counterintuitive result comes from the price setting role of high carbon unconventional oil that is punished by high CO_2 prices increasing the willingness to pay for conventional oil with lower carbon emissions.

When it comes to energy brokers and energy trade companies the outcome depends on the business models they rely on and the conditions – in terms of legal, economic, consumer attractiveness, etc. – to implement and use new business models. All the low-carbon scenarios imply great cuts in aggregate demand. A business model based on revenue from sold volumes would be more vulnerable compared with an energy service rather than volume oriented model.

3.2.4. External factors, rather than the EU Energy Roadmap, determine if and how the energy system generate or enhance insecurity (the 'energy as subject' perspective)

External factors determine many of the different energy security outcomes. The most prominent external factor when considering risks and threats to the energy system is 'Global climate action or not?'. This factor may also play a part when analysing if the energy system might generate or enhance insecurity, but in that case, specific local, national, regional and contextual factors with indirect implications are more important.

For example, the occurrence of conflicts may involve energy issues, but often just as a subset of other causes [43], which will

[1] Total costs for the entire energy system include capital costs (for energy installations such as power plants and energy infrastructure, energy using equipment, appliances and vehicles), fuel and electricity costs and direct efficiency investment costs (house insulation, control systems, energy management, etc).

probably not be a direct effect of EU energy policy. The geopolitical risk factor, i.e. the potential risk associated with a certain dependency, is always a product of political intentions, on the one hand, and subjective perceptions of security, on the other hand. In the geopolitical context it should be noted that more prominent importers have greater possibilities to affect supplier behaviour than small consumers [30]. Thus, a coherent European energy policy based on unity and solidarity among member states, regardless if EU is following the EU Energy Roadmap or not, will be a robust strategy to handle geopolitical risks.

Increased securitisation of energy, bringing more military involvement and thus more bilateral or international tension can function as a unilateral strategy, but in that case only to protect specific flows. Anyhow, it will not be a direct effect of the realization of low-carbon scenarios. When it comes to increased securitisation in order to maintain international flow security, with the higher aim to promote continued globalization, the EU can hardly act unilaterally but is dependent on the political intensions of, and cooperation with, other countries. As of today, both the EU and the US are dependent on functioning global markets, which to various degrees are protected with military power [67].

Bad governance in terms of, for example, 'resource curse' or human security issues in exporting countries are also products of a number of local circumstances, rather than a simple cause-effect chain determined by what the energy system looks like. More decisive characteristics associated with the exporting country seem to be the presence of a democratic system (e.g. Canada) or the absence of such (e.g. Turkmenistan), if revenue is distributed among the population (e.g. Norway), if the general corruption level is high (e.g. Venezuela), or if there is a lack of diversity in the economic base (e.g. Saudi Arabia).

As a general conclusion, external factors often play decisive roles for the energy security outcomes in the 'energy as subject' category. Some potential hotspots will however be exemplified below.

3.2.4.1. Should interdependency be recognized or not?. Interdependency can be regarded as a security enhancing aspect due to the incentives created when economies become mutually dependent and interconnected. Following from this perspective, measures resulting in decreased demand and possibly decreased volumes of trade and broken trade links entail at least a small contribution to increased *insecurity* due to decreased interdependencies. This would apply to the High Energy Efficiency and High Renewables scenarios (involving the smallest traded volumes).

The interdependency theory has however been questioned, and our tentative conclusion is that if the EU goes in an opposite direction to the rest of the world, problems will occur, irrespective of scenario. If other great countries and regions recognize and benefit from globalization in an interdependent, liberal and market-oriented world, energy self-sufficiency would probably be an unfavourable strategy for the EU. If the globalization trend is broken and rest of the world returns to geopolitics and zero-sum games, dependencies are bad and interdependency would be an aspect to ignore. This points to the critical importance of this external factor (international relations shaped by geopolitical securitisation vs. liberalization and open markets) as a scenario variable.

3.2.4.2. Nuclear and other technological risks. When it comes to energy security aspects associated with technological risk factors, one part of this category can be associated with risks and safety issues during normal operation. For example, on the lower system levels reliability of electricity will not be affected by lowered demand due to the realization of a low-carbon scenario. Risks of interruptions are associated with voltage and frequency rather than volume. The other part can rather be associated with certain events or accidents, e.g. oil tanker accidents causing oil spillage. Technological risk factors can never be eliminated regardless of energy volumes, as long as the systems and associated facilities exist, but the flow volume can affect the overall probability of an accident to occur, e.g. the more oil tankers the greater risk. Also when certain systems are stressed near maximum capacity, risks are generally enhanced, especially in inherently complex systems [68].

The scenarios with high nuclear shares differ somewhat from the other scenarios since they are associated with specific nuclear related risk factors such as radiation, the spent fuel management, the relation to nuclear and radiological weapons including nuclear proliferation issues, as well as potential catastrophic effects from major accidents. Thus the nuclear related risks embrace a wider area than just technological risk factors. For example, when it comes to potential effects of terrorist or other antagonistic attacks, the low-carbon scenarios with low nuclear shares do not imply more risk than the reference scenario. Moreover, the effect of attacking a nuclear plant is probably not only a question of harming vital societal infrastructure and destroying economic values but also eventual human health and environmental effects. Nuclear goes hand in hand with public acceptance and fear and has a symbolic value which also makes such a potential event a direct security policy issue.

In summary, the low-carbon scenarios would have at least some possible positive energy security effects, regarding this category, with reservation for the nuclear factor. Furthermore, significant demand decreases would probably give the opportunity to entirely eliminate certain more risk associated elements in the energy system.

3.2.4.3. Potential new or increased risks from renewables. Increased use of renewable energy will impact on several of the security aspects presented above. In the long-term, reduced dependency of fossil fuels will improve resource availability. Although the potentials of renewable energy sources such as solar and wind are in theory significantly greater than any future energy demand, and may increase beyond present expectations (see e.g. Ref. [69, Appendix A]), the availability of biomass, is heavily restricted by the conflicting demand for land and water to produce food, feed, fibres and bio-chemicals. This could generate conflicts around land ownership and water supply, increasing prices on arable land, and increasing food prices, which also could increase the risk for local and regional political conflict.

Variable electricity production grows in importance in all low-carbon scenarios but especially in the High Renewables scenario. This could be a problem for a functioning electricity system unless investments are made in transmission and distribution infrastructure and/or smart grids. This is, however, a well-studied area (e.g. Ref. [70]) and it is hard to imagine that the regulators would allow an expansion of variable production unless system reliability can be maintained. This will, however, lead to extra investments which have to be included in system cost comparisons. In the EU roadmap it results in significantly higher grid investment costs in the High Renewables scenario than in the other scenarios. Hydrogen could also increase its role in a system based on renewable energy although it is not explicitly stated in the EU roadmap. Hydrogen would require resolving new safety aspects due to explosion risks.

New dependencies with potential security implications can be the result of an expansion of renewable energy, for example through new interconnections from northern Africa, in order to provide electricity to Europe, or through long-distance transport of biofuels. The security impact of this will depend on several external factors such as systems for global governance and the stability of exporting countries, but also factors that could be seen as internal, for example, which strategy EU chooses for sharing the economic benefits with exporting countries.

4. Discussion

Using roadmaps or strategic plans for long-term policy making, assessed against the various societal objectives of today, is an important but challenging task. The complexity inherent in energy security, in political as well as analytical terms, accentuates this problem and makes it extremely difficult to rank alternative low-carbon strategies against each other. Instead the energy security analysis, including all its qualitative aspects, can be used as a deliberative and learning tool, enhancing the transparency of policy making, and exposing how trade-offs are made and reasoned about in the process.

4.1. External uncertainties require external scenarios

Since so many of the energy security impacts depend on external factors, an impact assessment concerned with energy security could preferably be done in the framework of a scenario exercise, so impacts can be examined under different external conditions. Using explorative scenario approaches is often considered best practice in such impact assessments (see e.g. Refs. [71,72]).

Perhaps two of the most important external factors are the development of key energy markets such as for oil and gas, and the degree of international coordination in climate change mitigation (see also Refs. [73,74]). Another related external factor relevant for some energy security aspects is the future character of international relations. For example, whether interdependence generated by low-carbon strategies is positive or not depends critically on whether international relations are shaped by geopolitics and zero-sum games, or by liberalization and open markets, or by new future global power structures.

4.2. There may be a need for more diverse energy scenarios

Reaching EU's climate targets involves major sociotechnical changes. However, the different low-carbon scenarios of the EU Energy Roadmap are rather similar in many aspects and they share three characteristics: (i) the share of renewables of gross final energy is quite large; (ii) primary energy use has been substantially reduced; and (iii) the degree of electrification has increased (see Table 2). The stated purpose of the Roadmap to provide more certainty (rather than exploring uncertainty) to investors and other stakeholders when it comes to possible future policy orientations [75] may explain the similarities.

Stretching the main drivers (bolded text in Table 2) and thus exaggerate system characteristics of the scenarios could enable a more informative discussion about potential energy security differences of various scenarios and their dominant technologies and systems attributes. For example, the Delayed CCS scenario, which actually could be considered a nuclear scenario (see Table 2), could involve even less CCS and thus even more nuclear power, but also less renewable energy. The use of an outspoken nuclear scenario (instead of the indirect "Delayed CCS") would direct attention to nuclear security and safety issues in a more direct manner, analogous with a distinct CCS scenario and its characteristics.

More diverse scenarios would, for example, render greater differences between the low-carbon scenarios when it comes to risks associated with variable electricity production. Also infrastructural differences would be highlighted, e.g. in terms of land use and economic risks for infrastructure owners, especially in the Diversified Supply Technology scenario.

4.3. Reflections on the analytical framework

We have focused mainly on negative energy security effects in this paper. A comprehensive assessment of a certain development (e.g., a scenario) should of course also take positive aspects into account. A focus on only negative effects does not support comprehensive comparisons between alternative scenarios but is nevertheless useful for anticipating and analysing future risks.

The framework was used here to identify some key issue areas for energy security assessment of long-term climate mitigation strategies. In order to develop a better understanding of these areas, methods development is needed. The obvious route is to develop methods and indicators for quantitative measurements [76]. But a deeper qualitative analysis is also highly relevant. Using a sociotechnical systems perspective, such an analysis could, for example, study in depth the actor configurations and institutional arrangements associated with different strategies, and how these may impact on energy security aspects.

Moreover, additional assessment criteria could be added to support the process of choosing which energy security aspects to analyse. We have focused on negative effects and increased risks (and to some extent if they can be mitigated) but have intentionally left out the judgment 'important or not important', which in the end is a political question.

5. Conclusions and policy implications

Our analysis shows that there is a wide range of security aspects that are important to consider in the context of low-carbon energy transitions. Some potential availability and affordability issues, as well as security of demand matters and geopolitical security aspects have been identified. External factors, e.g., the contents of a future global climate treaty and the character of future international relations, are in many cases important for specific energy security outcomes.

We purport that a broad framing of energy security is desirable, including several qualitative aspects. This stands in contrast to many quantitative energy security analyses that mainly focus on what can be counted rather than what may count. The EU Energy Roadmap is no exception. Although there is an ambition to deal with energy security aspects, the analysis is restricted to a few quantifiable factors and several important aspects are omitted. An approach as the one used in this article can be a useful tool for learning and deliberation, and it can help increase policy coherence. Thus, EU could benefit from a more holistic approach to energy policy and energy security. For this purpose, new institutional arrangements for policy coordination and integration may be needed, ones that can handle and adapt to continuously changing conditions in the transition towards a low-carbon society.

Acknowledgements

The authors gratefully acknowledge the economic support provided by the Swedish Energy Agency.

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