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A systemic approach to assessing energy security in a low-carbon EU energy system

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HIGHLIGHTS

- Develops a framework for a comprehensive and systemic assessment of energy security.
- Develops a scenario analysis to identify the structural changes of a Low-Carbon energy system.
- Assesses the implications of a Low-Carbon EU energy system on energy security.
- Provides foundations for more detailed analysis of climate change/energy security nexus.

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ABSTRACT

Until now, the complex relationship between energy security and climate change has been addressed using a partial understanding of security, one that is based on simplified indicators such as import dependence or fuel mix diversity. As a consequence, the synergies and trade-offs between climate change and energy security policies have not been systematically explored according to a wider understanding of the latter concept. The purpose of this article is to resolve the resulting knowledge gap by proposing a theoretical approach to energy security that is consistent with its multi-dimensional nature, taking into account the whole energy supply chain. Five key 'systemic' properties of energy security will be identified – namely, stability, flexibility, adequacy, resilience and robustness. The paper proposes a novel framework to assess energy security and uses this framework to develop a comprehensive approach to the interactions between climate change policies and energy security. The impact of a low-carbon scenario on one of these five properties (long-term robustness) will be assessed using a complex multi-regional energy system model. The results demonstrate how this scenario induces structural changes along the whole energy supply chain, revealing dynamic vulnerabilities and trade-offs that are not adequately accounted for by existing indicator-based assessments. Finally, the paper provides solid foundations for further analysis of these trade-offs using more detailed sectoral models.

1. Introduction

In recent years a wide range of policies has been introduced in Europe to pave the way towards a low carbon energy system, with the dual objectives of combating climate change and breaking "the cycle of increasing energy consumption, increasing imports and increasing outflow of wealth created in the EU to pay energy producers" [1].

Security of supply, sustainability and competitiveness are the three complementary pillars/goals of the European energy policy [2]. As stated in [3] "these goals are part of the same strategy. Work to achieve one should help deliver the others." The current EU climate and energy targets were designed to be mutually supporting and there are indeed synergies between them. But, as recently recognized by the European Commission there is also a risk that climate-focussed energy policies, if not properly designed, can affect energy security and bring about extra costs, as they support technological and market solutions designed to achieve a different policy objective [4]. Therefore, "the 2030 framework must identify how best to maximise synergies and deal with trade-offs between the objectives of competitiveness, security of energy supply and sustainability" [4].

A key challenge in meeting this objective lies in the different 'natures' of energy security and climate change mitigation. Because GHG mitigation is measurable in a relatively straightforward way, it is clear whether policies are heading in the right direction. On the other hand, even without being set in the context of sustainability, security of energy supply is an inherently complex topic: as underlined by most of the recent literature, much of the discussion

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is "conducted without a clear idea of the dimensions of energy security and their relative significance" [5–8]. In contrast to other energy policy objectives, there is no obvious or universally accepted measure of supply security [9], for two key reasons: (a) energy security is a product of many diverse attributes, from the diversity of gas imports to the capacity margins in the power sector; therefore, it needs to be assessed from a systemic perspective that takes all of these attributes into account [10]; (b) energy security is a product of the interactions and interdependencies of a complex system, one "whose properties are not fully explained by an understanding of its component parts" [11].

The purpose of this article is three-fold: first, to identify methodological deficiencies in existing indicator-based assessments of the links between climate change and energy security and, secondly, to develop a novel theoretical approach to energy security that is consistent with its polysemic and multi-dimensional nature. This requires a 'systemic' understanding of energy security that takes into account the whole energy supply chain and categorises the multitude of threats that may affect the capacity of this supply chain to deliver energy services to end-users. In so doing, the properties of a "secure" energy system will be identified – namely, stability, flexibility, adequacy, resilience and robustness. Thirdly, the methodological requirements deemed crucial for adequately assessing the interactions between a low-carbon and secure energy supply chain will be applied in practice by assessing the implication of a low carbon energy system in Europe by using a complex multi-regional energy system model (TIAM).

2. Assessing the interactions between energy security and climate change policies; a review

The debate on the interaction between energy security and climate change policies is typically framed in terms of the trade-offs and synergies between the two policies. Many studies argue that optimal policies, which can mitigate climate change and enhance security at the same time, are possible (e.g. [12–14]). Others contend that the two goals are often fundamentally at odds [15]. Evidence can be presented for both sides, as considerations of energy security have sometimes trumped climate change commitments and sometimes not [10].

Framing the energy security/climate change policy nexus in terms of synergies and trade-offs creates a compelling case for quantification. Most studies combine a model-based scenario analysis with a set of indicators, which can help to operationalise and hence assess a system as complex as the energy supply chain. Designed to reduce complex phenomena to simple terms and functions, indicators are widely used to abstract from the energy system a few key parameters to give an overall indication of its level of security (for an overview see [13,16,17]). Yet despite their ability to simplify complex phenomena, indicators suffer from some key weaknesses that challenge their actual usefulness as policy instruments. Indeed, the debate about the effect of climate change policies on energy security strategies may defy resolution precisely due to the methodologies that are typically applied in both sides of the argument. Often a handful of parameters to represent 'energy security' and 'climate change' are selected for comparison and analysis under a set of different long-term energy scenarios. But whereas the essence of climate change mitigation policies can indeed be reduced to a desire to control the amount of carbon emitted by humans into the atmosphere, energy security – given its conceptually elusive and multi-dimensional nature – is not so easily reducible to a single property. The consequence is that the existing literature presents at least one of the following shortcomings:

First, energy security indicators are signals useful in conveying condensed information about the state of an energy system, particularly about its potential vulnerabilities. As such, their essence is to simplify what would otherwise be a complex phenomenon defying quantification, because the complexity of energy systems hides multiple dynamic vulnerabilities [18]. The consequence is that a number of studies purporting to explore the interactions between climate and energy security policies end up evaluating the impact of climate policies on only a sub-set of factors that may or indeed may not capture the essence of energy security (e.g. [19]).

Secondly, energy security is a "property of the energy system" [20], therefore an adequate assessment must include all the significant elements of the system and emphasize the relations and interactions between them [21]. It is this interaction of different components that determines the capacity of the energy system "to tolerate disturbance and to continue to deliver affordable energy services to consumers" [22], acting as a cushion to dampen the impacts of a threat [13]. By their very nature, indicators are unable to assess the energy system's *response* to adverse events, i.e. the vulnerability of the system in terms of the actual consequences of energy insecurity, despite claims to the contrary in [13,23,24]. This is because indicators cannot capture the chain of substitutions triggered by an adverse event along the whole supply chain, and hence processes such as primary energy substitutions or demand elasticities go unaccounted for. Indeed, even the most sophisticated analyses of the interactions between energy security and mitigation policies are ultimately based on variables which are *proxies* of the vulnerability of the system [13,25].

A direct consequence of these weaknesses is that many indicator-based assessments often focus on diversity as a desired state for energy systems, making the degree of diversification the *de facto* measure of energy security [26]. For instance, energy security is represented by an index combining import dependency, commodity dependency and energy intensity in [27], by an indicator of diversity of primary energy sources and import dependency in [28], and by the diversity of fuel source mix in electricity in [29]. However, there exist many other dimensions of supply security that extend beyond the issue of diversity alone [30]. Indeed, according to [31] energy security is related to different types of incomplete knowledge: risk, uncertainty, ambiguity, ignorance; each type requiring a different analytical armoury (see Table 1). But the rationale for focusing on diversity is only under the condition of ignorance, i.e. when sources or modalities of the threats are unknown.

Moreover, options to increase diversity means investing in alternatives whose lack of penetration in the energy system may be due to poor performance; thus, enlarging their contributions often incurs some penalty [33]. A key limit of indicators is that they cannot provide insights on this key issue of the costs and benefits of alternative levels of energy security [9,34], which can then be benchmarked against climate targets. Two interesting exceptions on this respect are [35,36], who assess the economic cost of two specific threats, oil price hikes and oil scarcity, with and without a climate policy, as well as the economic costs of not exploiting fossil fuels versus suffering through climate change.

Finally, the indicator-based approach is particularly prone to view energy security as a distinctly supply-side phenomenon. This is the case in several studies where the energy security implication of mitigation scenarios are assessed by looking at aspects such as the market concentration in competitive fossil fuel markets and pipeline-based gas import for regulated markets [37,38]; the structure of global oil and gas production and trade [14]; or a wide set of indicators related to oil and gas resources and production, market concentration and energy trade [13,16,24]. Studies that narrowly focus on supply side-aspects of energy security tend to see positive outcomes of climate change policies since they usually result in the receding dominance of fossil fuels in the supply mix [37,39].

Our view is that in order to meaningfully assess how climate change policies may impact on energy security and vice versa, there must be a disciplinary pivot away from indicator-based assessments, given their partial and simplified view of energy security. Instead, a conceptual and methodological framework must be developed which accounts for the multi-dimensional nature of energy security and its 'systemic' quality encompassing the entire energy supply chain. Only in this way can the catalogue of various threats and opportunities emanating from climate change policies be ordered, interpreted and assessed according to their impact on various properties of a 'secure' energy system.

3. Methodology. A systemic approach to the interactions between mitigation policies and energy security

Having questioned the conceptual and methodological utility of indicator-based methodologies, an alternative paradigm must be proposed, one which addresses the weaknesses discussed above whilst simultaneously reflecting the 'polysemic' and multi-dimensional nature of energy security. Following [40], the alternative paradigm should be a systemic framework that is used "to analyse the impact of specific security events, the level of risk attached to such events, and the cost of measures which would provide insurance against them". Despite the confusion about the concept of energy security, there seems to be an agreement that security is concerned with risk [41]; therefore, a formal Risk Assessment framework can be useful in addressing the flaws discussed above. Indeed, the recognition that energy security is related to different types of incomplete knowledge [32], among which even the conditions of *ignorance*, does not diminish the usefulness of such a systematic methodology. The combination of scenario analysis with probabilistic techniques will cover a wider range of 'incertitudes' rather than restricting oneself to one type (e.g. uncertainty).

3.1. A categorization of threats to energy security

Given the multidimensionality of energy security, a necessary starting point for any assessment is to clarify the key threats to the security of a given energy system [10]. This is indeed the same starting point in the risk assessment, whereby the researcher is prompted to the question, 'what can go wrong and why?'

There is a wide range of events which have the capacity to negatively affect energy systems, and several studies have identified and discussed them (e.g. [37,42–44]). Adapting a framework proposed in [31], we categorise potential threats to energy security on the basis of three *primary* dimensions:

- *Location* in the energy supply chain, whereby threats may arise in the extraction of energy, through its production, transport and conversion, all the way down to its final use.
- *Temporality*, whereby transient disruptions (shocks) can be differentiated from more enduring pressures (stresses). The primary ordering principle proposed here is the period from when the risk materialises to its observed (negative) effect on the energy system. As such, the very short-term timeframe is related to the need for real time balance between supply and demand along a whole interconnected system. The short to medium-term timeframe represents an interval during which a fundamental change of the system is not feasible, therefore it is only possible to consider whether the system "as it is" is able to cope with an adverse event. The long-term timeframe is one which covers the investment cycle and beyond, which means that the system can take a different trajectory to adapt to a stress.
- *Provenance*, whereby shocks and stresses may originate either inside or outside the energy system under study, which will affects the degree of control over their origin: internal events can be "controlled" in the sense that there is a freedom to choose strategies that affect the likelihood of the threats; in case of external events, on the other hand, the main strategy available is to "respond" in ways that maintain the level and quality of energy services or improve the capacity of the system to adapt to events (e.g. the increase of short-term flexibility through storage).

Taken together, these dimensions are designed to enable comprehensive categories with which to identify risks. Fig. 1 presents a graphical representation of this wide range of energy security threats in a two dimension space. There are other categorisations in the literature that frame the risk identification process differently but nonetheless can be absorbed in the current framework (e.g. all six 'severity filters' in Winzer's study of energy security [41] can be integrated into the broader categories of temporality, provenance and location). The combination of the three dimensions of different risk sources in Fig. 1 give an indication of the *nature* of risks that need to be addressed. For example, whereas climate policies may create short-term grid intermittency risks that arise in the transmission and distribution portion of the supply chain, the longer-term threat posed by climate change itself can affect the entire supply chain, from resource extraction to end use.

3.2. The properties of a 'secure' energy supply chain

The second fundamental component of the condition of risk is the actual impact produced by a threat, once it materialises. Whereas the probability of threats may vary independently of the constitution of the system, their actual impact is contingent on the structural characteristics of the system present during the timeframe in which the threat is manifest, i.e. on its ability to withstand the effects. A systemic approach is built around the capacity of the energy system to tolerate disturbance rather than focusing on single measures, since the security of an energy system "shall be judged by its ability to withstand shocks and to adapt", which implies that "the resilience (flexibility, elasticity) of the system thus becomes key" [34,45,46].[1]

But how can this systemic security of an energy supply chain be conceptualized and practically assessed? To provide energy security requires consideration of issues as diverse as efficient investments, operational maintenance, and adequate regulation for the whole value-chain, from resource extraction and/or import to end use. Moreover, from the risk identification phase it quickly becomes clear that the supply chains making up the energy system are subject to a wide range of different threats; accordingly, a 'secure' energy system must have a number of different types of properties. Drawing from [30] we identify five properties of a secure energy system (Fig. 2), by associating each of them to the categories of threats identified in Table 1. This leads to a categorization of the energy security problem which is in fact close to the one

[1] Whereas the energy systems include all the extremely complex, interrelated chains of commodities and processes linking the extraction of primary energy to the satisfaction of the demands for energy services [21]. More properly, the system under analysis can be as wide as to "the whole set of technologies, physical infrastructure, institutions, policies and practices, located in and associated with a geographical area, which enable energy services to be delivered to consumers" [22]. Or, given that the energy system constitutes a part of the macroeconomy, the system can be even include also the rest of the economy and factors of production that drive it.

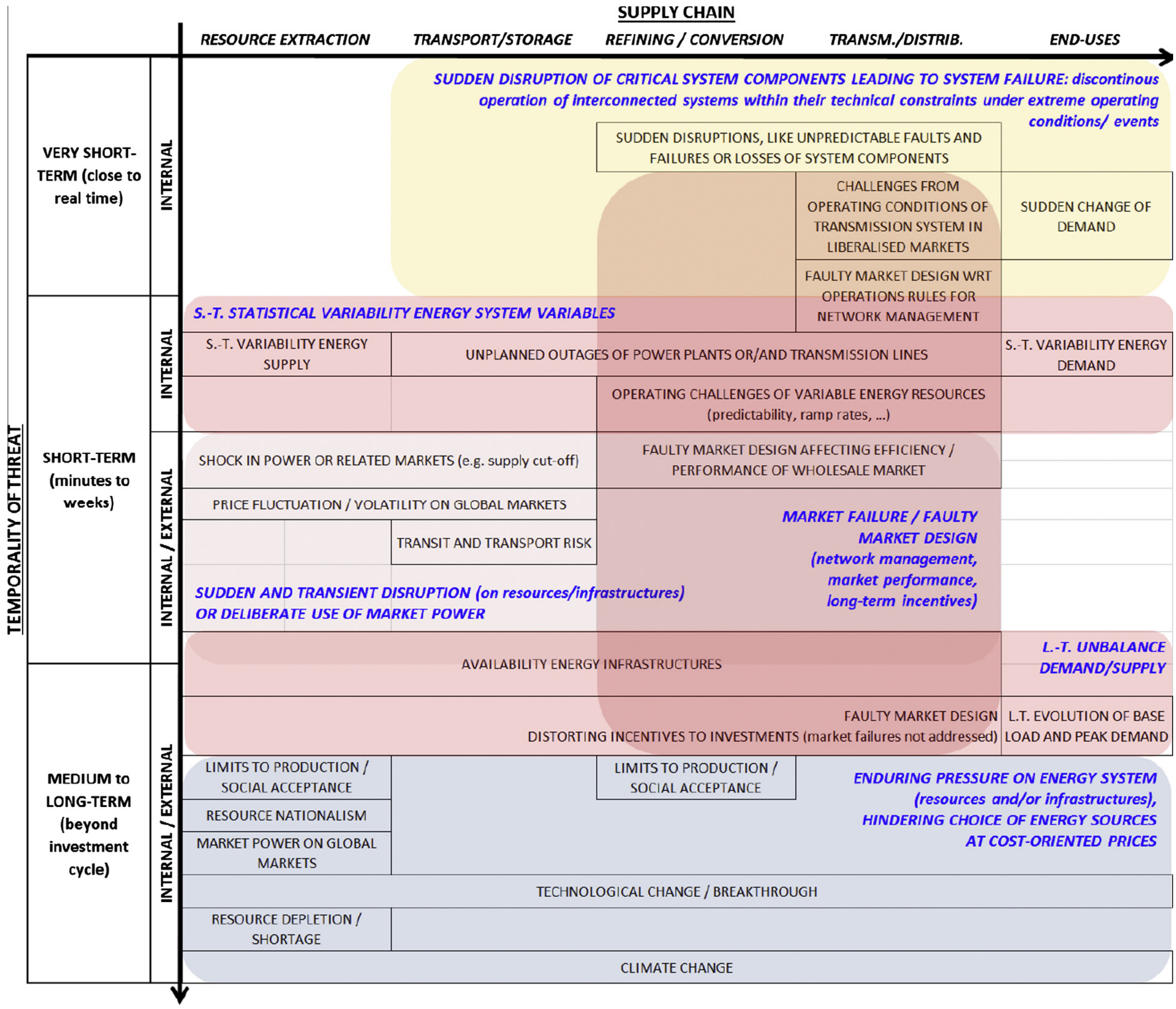

Fig. 1. Threats to the security of the energy system – a map.

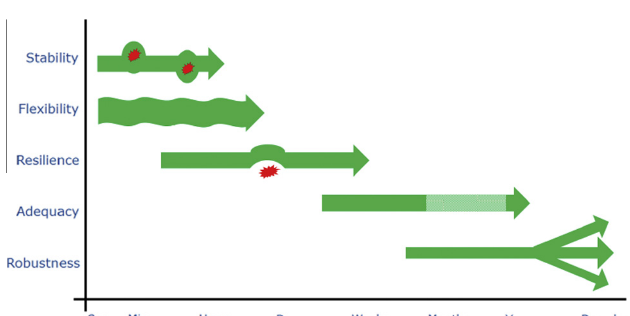

Fig. 2. The five properties of a secure energy system.

Table 1
Uncertainties resulting from knowledge of likelihoods and outcomes. *Source:* [32]

Knowledge about likelihoods	Knowledge about outcomes	
	Well-defined outcomes	Poorly-defined outcomes
	Degree/type of uncertainty	
Some basis for probabilities	Risk *(Apply: probabilistic techniques)*	Ambiguity *(Apply: sensitivity analysis/ fuzzy logic)*
No basis for probabilities	Uncertainty *(Apply: scenario analysis)*	Ignorance *(Apply: precaution/diversity/ redundancy)*

often used in literature, particularly with regard to the electricity sector (e.g. [47–49], where the concept is "unbundled" according to the value chain of electricity markets).

Stability, or operational security, is the capacity of highly interconnected energy systems to withstand sudden disturbances, such as unanticipated losses of critical system components, by maintaining their operation within defined technical constraints. This property is mostly related to the power network, where it is necessary to meet defined voltage and frequency requirements at all times, as electrical imbalances at any point of the interconnected transmission network can have immediate and severe repercussions throughout the whole system. As a result, supply and demand must be balanced in real time across the whole network. In gas networks too, any physical imbalances between supply and demand result in a variation of the pressure in the network, however high pressure pipelines are generally designed to accommodate considerable pressure fluctuations, which can be absorbed through the inherent storage capability of the network. The effective real-time management of the electricity and gas systems implies centralised operation and the use of standards (like the

$N-1$), together with safety regulations which set out sufficient maintenance and monitoring of critical infrastructure (e.g. [49] provides an overview of the operational security criteria used by some EU TSOs).

Flexibility is the ability of a system to cope with the short-term uncertainty of energy system variables (whatever the cause), by balancing any deviations between the planned or forecast supply and demand, on one side, and the actual outturn in real time, on the other side. Although timeframes, physical needs and resources for balancing may vary across different energy markets, flexibility is nonetheless a typical system property applicable to the whole supply chain. For instance, in the power system it can be provided by "dispatchable" power plants, storage, trade with neighbouring markets via interconnectors, and demand-side response (the problem of the appropriate flexibility in a system with high renewables is now widely recognized, however so far it has not been addressed properly [4]; see more discussion in Section 4.3).

Resilience means that the energy system can source alternative modes of production or consumption in response to sudden and transient shocks, such as the interruption of a major supply source (e.g. the gas supply cut-off to Europe due to the Russia-Ukraine crisis in 2009). The impact of a shock and the ability of the system to tolerate and absorb change are crucially determined by structural characteristics of the energy system, both physical (such as redundancy, spare capacity and fuel-switching capabilities) and abstract (e.g. the market structure, the regulatory environment, etc.). The interplay of these factors determines the capacity of the energy system to continue to deliver *affordable* energy services to consumers (an example is the response of the Japan energy system to the shutdown of most of its nuclear power plants in the aftermath of the Fukushima accident).

Adequacy is the reasonable expectation that the system is able to meet demand at all times under all anticipated conditions, typically in reference to peak demand. This implies that investments in supply capacity and infrastructure are made at sufficient volumes, both in terms of overall level and of technology mix, in a timely fashion. Adequacy is related to the way the energy market is designed and its performance: on one hand, its capacity to set prices under undistorted competition and to smooth price fluctuations due to imbalances between supply and demand or resulting from market power abuse; on the other hand, the capacity of a decentralized market environment to provide incentives for timely and efficient investments in infrastructure, in production/import, generation, transmission, storage, including investments in overcapacity [4] (e.g. some EU countries have introduced capacity markets as a way to address this issue in power markets; as regards gas markets, an interesting case study is the way liberalization changed investment decisions in UK [40]).

Finally, the *robustness* of an energy system is related to its capacity to adapt its long-term evolution to economic and/or (geo)political constraints. It implies that actors in the energy market are allowed to choose from primary energy sources at cost-oriented prices, without being hindered in their choice by economic or (geo)political constraints on energy resources and infrastructures (e.g. the vulnerability of the long-term cost of energy to the traditional issue of resource concentration [38], as well as to recent issues like nuclear phase-outs and shale gas bans).

While stability can largely be assessed with technical and operational criteria, establishing the resilience, adequacy and robustness of an energy system requires an additional analysis of the 'efficient' allocation of resources based on supply, demand and price dynamics.

It is useful to differentiate these properties with other accounts in the literature of the primary dimensions of energy security. For example, the oft-cited 4 'A's of energy security – availability, accessibility, affordability and acceptability – have been used as an analytical framework [50]. All of these concepts are implicitly included in our characterization, as they cut across the analytical boundaries set by the five properties we have proposed. This renders them as generic terms of reference rather than criteria upon which to assess system behaviours for coping with specific adverse events. For example, affordability assumes different meanings depending on the property in question; for market adequacy, it refers to the capacity of the specific energy market to set prices at equilibrium and provide investment signals, while for resilience affordability may relate to the capacity of the system to smooth price hikes induced by supply shocks. Finally, affordability as it relates to long-term robustness indicates the capacity of the system to select the cost-effective energy portfolio subject to constraints (e.g. climate policies).

Without prejudice to other methods of ordering the energy security debate, it can be claimed that a secure energy system is

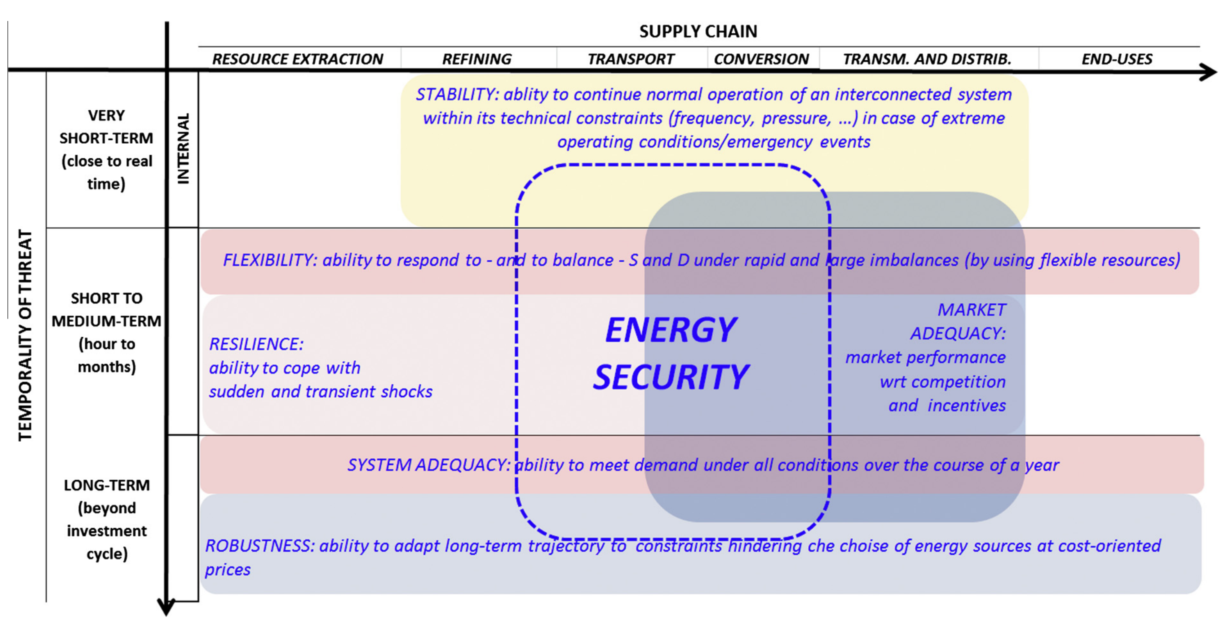

Fig. 3. Energy security as the sum of five secure system properties.

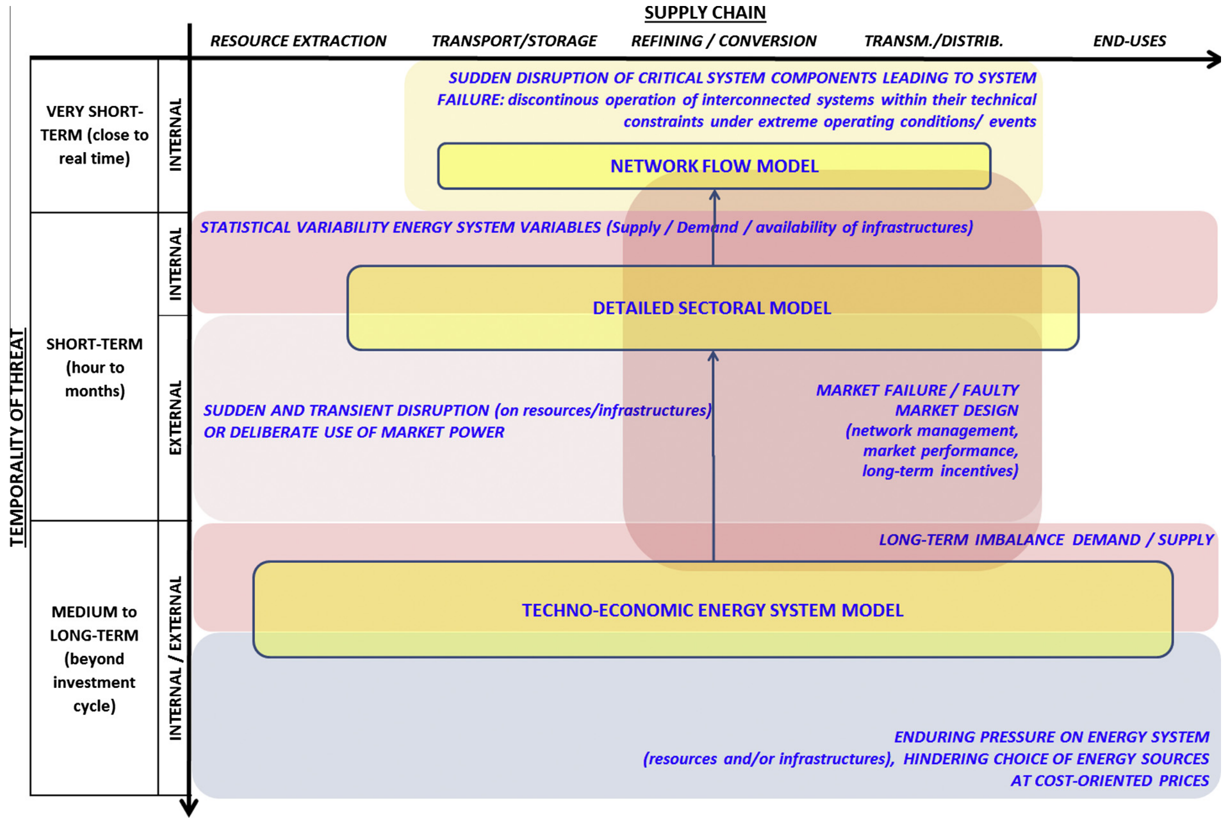

Fig. 4. The place of models in the energy security assessment framework.

one with an 'appropriate' level of stability, flexibility, adequacy, resilience and robustness in the face of short-, medium- and long-term threats (as depicted in Fig. 3). The term 'appropriate' is related to the intrinsically relative nature of energy security, which as such can only be assessed in relative terms, as far as possible by considering the costs and benefits of alternative level of security [9,34].

3.3. Modelling the links between energy security and climate change

Assessing the potential consequences of the different types of potential threats on the performance of the energy supply chain requires a simulation of the response of the energy system to different contingencies. Quantitative models describing the energy system with the appropriate level of detail, including the wide range of factors that can exercise a stabilizing influence on the energy services delivery system, together with their relations and synergies [51], are powerful tools with respect to this goal. However, the five properties of energy security cannot be assessed with the use of a single model. Rather, a range of models must be employed, each addressing a different set of temporal and physical parameters demanded by the property in question. For example, the stability of the energy system is most adequately assessed if the specific characteristics of electricity, including its physical laws, are taken into account. This, in turn, requires the use of a power network model which can evaluate the real-time stability of the power system. Quantitatively assessing the resilience of an energy system to a cut of natural gas supply, on the other hand, requires a tool that can account for the market conditions in terms of flows, capacities, storages, contractual bounds and demand-side responses that can be used to absorb the shock over a short- to medium-term horizon. Assessing the system's adequacy over a period of months and years requires a different emphasis, one that is more strongly linked to market design and optimisation as well as the regulatory conditions and energy policies impacting on operational considerations as well as investments. In all cases, different model types are required to adequately consider the trade-offs and feedbacks inherent to assessing various types of risks.

Despite the different models required for analysing different properties of energy security, there does exist one particular type of model – technology-rich energy system models – which provides a useful analytical canopy from which to conduct more in-depth analyses related to single sectors, technologies or supply chains. Indeed, detailed assessments of the energy security properties of stability, flexibility, adequacy, resilience and robustness are not possible without first formulating internally consistent images of the future system. While energy system models cannot fully capture the whole spectrum of energy security threats, they arguably constitute the appropriate starting tool before evaluating other properties using more detailed sectoral models (as in Fig. 4).

The wide definition of energy security adopted in this paper and the multi-dimensional effects occasioned by a low-carbon transition naturally call for a system-level analysis. By virtue of their technological detail and empirical breadth, such system models are often used as the focal point for assessing the interaction between climate change and energy security under radically different future energy system scenarios [14,27,52]. The attraction of employing systemic models rests in the ability to account for a large number of feedbacks and interdependencies between different technologies, flows and commodities characterising the energy system. It also permits an evaluation of different energy policy objectives, making it particularly useful as a policy support tool. Indeed, the European Commission has recently noted that its 2030 energy policy framework "must identify how best to maximise

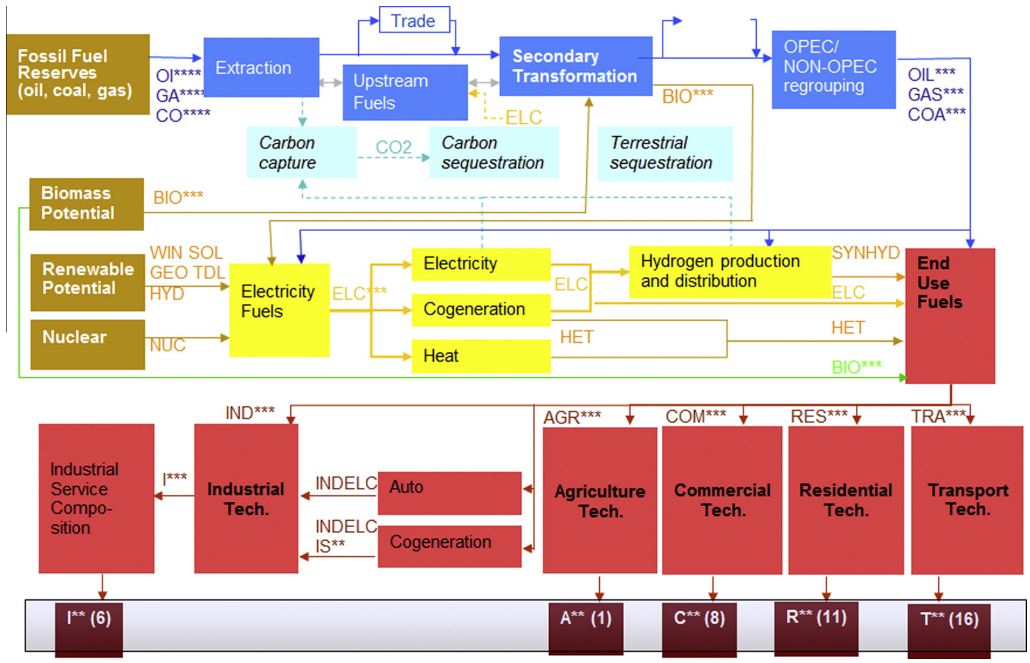

Fig. 5. Structure of the energy supply chain within TIAM.

synergies and deal with trade-offs between the objectives of competitiveness, security of energy supply and sustainability" [4]. An energy system model is well-equipped to consider the long-term contraints and opportunities arising from different policy options addressing any number of these goals. Thanks to their technological detail, energy system models can also provide several insights into system properties related to medium and long-term threats, i.e. system resilience and robustness. Moreover, the alternative projections of the future energy system produced by energy system models can provide qualitative insights into the capacity of the system to cope with short-term shocks, and can be used to provide inputs to other models more suited to assessments of the short-term behaviour of the system.

For present purposes, we analysed the impact of different European climate change policy scenarios on the robustness of the European energy system using a complex multi-regional energy system model, ETSAP-TIAM (Energy Technology Systems Analysis Program-TIMES Integrated Assessment Model). ETSAP-TIAM is a partial equilibrium model of the energy systems of the entire world divided in 15 regions.[2] It belongs to the TIMES family of models, i.e. a group of bottom-up, cost-optimization models that identify least-cost solutions for the energy system under given sets of assumptions and constraints and for a given time horizon. ETSAP-TIAM covers the entire energy system (Fig. 5) from the extraction of resources, to conversion of primary energy carriers, to the trade of all the main energy commodities and to the use of final energy carriers in end-use technologies across different demand sectors (as for the latter, TIAM distinguishes 42 demand sectors). A detailed documentation can be found in [59].

4. Results

The transition to a low-carbon energy system will generate significant changes in virtually every major link and interdependency of the energy supply chain. How will such changes impact on energy security? In coherence with the conceptualization of energy security discussed thus far, we will attempt to answer this question by observing how the structural changes determined by a low-carbon system can affect the threats described in Table 1. Indeed, any increase in the impact or likelihood of threats that occurs as a result of structural changes will serve as an indication of the need to improve the corresponding system property that is necessary to respond to the threat (i.e. stability, flexibility, resilience, adequacy or robustness). As said above, the energy system model used here is particularly suitable to evaluate the long-term robustness of this system, while at the same time indicating areas of investigation for more detailed, sectoral models. Thus, the following constitutes a useful exercise in demonstrating the value added of combining energy system scenario analysis with a theoretical systemic approach to energy security. It provides a comprehensive overview of the different aspects of energy security affected under different system conditions, at the same time providing a solid foundation for further analysis.

4.1. Key changes in the energy supply chain

We explored a Low Carbon (LC) scenario consistent with the objective of halving global CO_2 emissions by 2050 to limit the global temperature increase to 2 °C, while the reduction is 85% in Europe (by contrast, in the Business-as-Usual scenario global CO_2 emissions almost doubles in 2050 with respect to 2010). The Low Carbon state of the world developed through the global energy system model TIAM shows how the success in achieving a low-carbon energy system requires deep structural changes affecting the

[2] Currently, TIMES models (and its predecessors MARKAL models) are used in about 100 institutions in nearly 70 countries for the compilation of long term energy scenarios and in-depth national, multi-country, and global energy and environmental analyses. Global energy system models based on MARKAL/TIMES are used quite extensively for long-term energy system analysis (e.g. the periodic IEA study Energy Technology Perspective is based on a TIMES model), as well as for systematic analysis of global energy issues, such as climate mitigation options [53], a fully renewable energy system [54] and long-term decarbonisation scenarios [55,56], and the deployment of alternative fuels and technologies for transportation [57,58].

Table 2
Energy balance for Europe, 2010. *Source:* IEA.

(mtoe)	Coal	Crude oil	Oil products	natural gas	Nuclear	Hydro	Renewables	Biofuels and waste	Elc	Heat	Total
Production	169	194	0	241	239	48	29	124	0	1	1.047
Trade	121	460	38	218	0	0	0	6	1	0	*844*
Total primary energy supply	**296**	**654**	**−52**	**467**	**239**	**48**	**29**	**131**	**1**	**1**	**1.817**
Electricity Plants	−145		−14	−89	−236	−48	−22	−23	252	0	*−326*
CHP plants	−65	0	−11	−63	−3	0	−1	−23	58	44	*−63*
Heat plants	−5	0	−1	−8	0	0	0	−6	0	16	***−4***
Refineries	0	−674	668	0	0	0	0	0	0	**0**	***−5***
Other Transformation		16	−17	0	0	0	0	0	0	**0**	
Energy industry own use and losses	−6	0	−37	−19	0	0	0	0	−24	−5	−91
Total final consumption	**54**	**5**	**532**	**284**	**0**	**0**	**5**	**79**	**266**	**51**	**1.275**
Industry	32	2	34	87	0	0	0	24	99	16	*293*
Transportation	0	0	312	3	0	0	0	13	6	0	*334*
Residential	17	0	47	124	0	0	4	38	79	21	*329*
Commercial	2	0	21	50	0	0	1	2	77	10	*162*
Agricultural	1	0	18	4	0	0	0	2	5	0	*30*
Non-energy use	1	2	98	13	0	0	0	0	0	0	*114*

Table 3
Energy balance for Europe, low carbon system 2050.

(mtoe)	Coal	Crude oil	Oil products	Natural gas	Nuclear	Hydro	Renewables	Biofuels and waste	Electricity	Heat	Hydrogen	Total
Production	11	2	0	294	358	57	178	484	0	0		1.383
- Conventional		*2*		*53*								*55*
- Unconventional				*241*								*241*
Trade	15	310	−20	282	0	0	0	0	0	0		587
Total primary energy supply	**26**	**312**	**−20**	**576**	**358**	**57**	**178**	**484**	**0**	**0**	**0**	**1.970**
Electricity plants	0	0	0	−201	358	−57	−169	−18	454	0		
CHP Plants	−8	0	0	−27			0	0	18	17		
Heat Plants	0	0	0	−23			0	−25	0	41		
Refineries	0	−329	292	−7			0	0				
Other transformation	−9	10	−11	−1			0	−6				
Hydrogen production	0	0	0	−53			0	0	−1	0		
Energy industry own use and losses	5		26	12			0	12	44	1		
Total final consumption	**3**		**235**	**252**			**9**	**422**	**426**	**57**	**39**	**1.443**
Industry	1		24	138			0	103	116	29	0	411
Transportation	0		66	0			0	279	0	0	39	384
Residential	0		6	71			1	35	189	10	0	313
Commercial	0		1	12			4	2	97	18	0	134
Agricultural	2		5	9			2	3	25	0	0	46
Non-energy use	1		134	21			0	0	0	0	0	155

whole energy supply chain. In particular, changes are needed in the relationships between the demand for energy services and energy consumption and between energy consumption and CO_2 emissions will be explored. This can occur through a reduction of the energy use per unit of activity within each end-use sector, through a change in the fuel shares among end-uses and through the decarbonisation of energy carriers.

Comparing the BaU and Low Carbon 'states of the world' (summarized by the respective energy balances, see Tables 2-4), it appears that, notwithstanding significant economic growth (EU GDP is assumed to increase by 1.5% per year), total primary energy supply (TPES) remains more or less constant in both cases between 2010 and 2050. In the LC case the demand for fossil fuels is about 40% lower compared to 2010 levels and about 35% lower compared to the BaU scenario: there is a noticeable shift away from coal, which by 2050 falls to about a tenth of 2010 levels. Liquid fuel demand stabilises at around today's levels, but with a very strong increase of liquid biofuels (making up two-thirds of fuel use for transportation) and hydrogen ($\sim$10% of transport). As a consequence, in the Low Carbon system by 2050 final consumption of oil reaches only half of the current level, while natural gas becomes the dominant fuel in TPES, making up 30% of the total (assuming its emissions are managed by CCS), and in fact is the least penalised fossil fuel when transitioning to a low-carbon system. A significant part of this gas is unconventional, which continues to increase throughout the whole time horizon, such that internal production can be sustained above current levels.[3]

Electricity is at the core of the future clean energy system in Europe and becomes the dominant energy carrier in final consumption, as a result of increased electrification of end-use sectors, decarbonisation of electricity generation, and energy efficiency improvements. In the LC scenario electricity demand almost doubles with respect to the current level (a greater increase than in the BaU scenario), as efficiency improvements in electricity use are offset by increased electricity demand, mainly from the rising use of heat pumps for heating and cooling. By 2050, heat pumps deliver almost 50% of useful energy demand for space heating (see Fig. 5).

[3] Bearing in mind that this result depends on optimistic assumptions about the production cost and resource size of shale gas (see [60]); a specific sensitivity is carried out later in this paper.

Table 4
Energy balance for Europe, Business as Usual 2050.

(mtoe)	2050											
	Coal	Crude oil	Oil products	Natural gas	Nuclear	Hydro	Renewables	Biofuels and waste	Electricity	Heat	Hydrogen	Total
Production	90	33	0	363	116	48	94	250	0	0		994
- Conventional		*32*		*47*								*79*
- Unconventional		*1*		*316*								*317*
Trade	234	414	79	294	0	0	0	0	0	0		1.020
Total primary energy supply	**324**	**446**	**79**	**657**	**116**	**48**	**94**	**250**	**0**	**0**	**0**	**2.014**
Electricity plants	−176	0	0	−41	116	−48	−85	−100	310	0,5		
CHP plants	−33	0	−1	−36		0	0	−7	31	29		
Heat plants	−18	0	0	−1		0	0	−2	0	17		
Refineries	−1	−472	418	−10		0	0	0				
Other Transformation	−8	14	−6	−14		0	0	0				
Hydrogen production	0	0	0	−33		0	0	0	0	0		
Energy industry own use and losses	11		33	18				12	29	1		
Total final consumption	**76**	**0**	**457**	**504**			**9**	**128**	**312**	**46**	**25**	**1.558**
Industry	74		23	155			0	25	113	18	0	408
Transportation	0		258	71			0	64	0	0	25	417
Residential	0		37	172			1	35	85	10	0	341
Commercial	0		1	75			4	2	90	18	0	189
Agricultural	2		5	9			2	3	25	0	0	46
Non-energy use	1		134	21			0	0	0	0	0	155

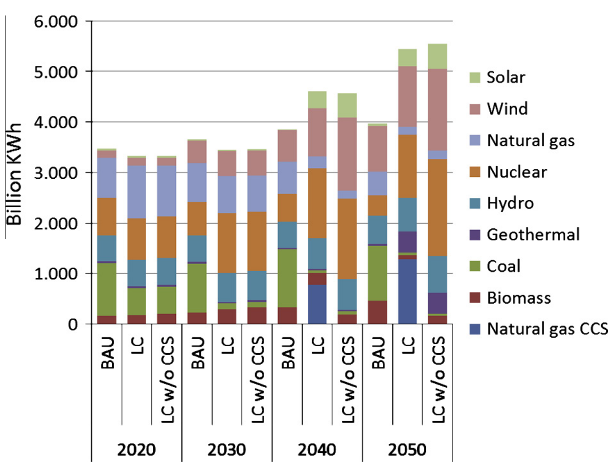

Fig. 6. Electricity generation mix in the base case, low carbon, and low carbon CCS systems.

In the LC scenario, power generation is also the largest contributor to the reduction of CO_2 emissions. Assuming the relatively widespread availability of CCS, in the long-term electricity generation is almost decarbonised in the LC scenario: natural gas is the only remaining fossil fuel used in electricity generation by 2050, with a share of 27% (roughly the same as today). Renewables produce half (with wind and solar together comprising almost 30% of the mix at European level). Nuclear power takes a quarter of the total electricity generation share while biomass assumes the remainder (see Fig. 6). Interestingly, while gas-fired generation gains an even stronger role in the LC system than in the BaU case, coal is completely phased-out. This is due to the fact that natural gas plants are best placed to provide peak-load and back-up capacity to balance the variability of renewable energy sources. Moreover, the competitiveness of unconventional gas resources along with its softer carbon emissions profile relative to coal leads to larger-scale deployment of gas plants with CCS at the expense of coal CCS. However, if CCS is unavailable, the change in results is dramatic: gas-fired power generation drops by 87%, with nuclear, wind and solar power picking up the slack (see Fig. 6).

Final energy consumption is 5% lower in the LC scenario than in the BaU, thanks to energy efficiency in buildings and transportation. Fuel use in the demand sectors is also more diversified, as new fuels such as biofuels and hydrogen significantly impinge on oil's dominance in the transport sector.

4.2. New challenges for system robustness

Any given energy policy tends to place a stress on the energy system, as it constrains the options available to it while narrowing the range of permissible outcomes of its behaviour. Carbon policies are no exception, as they are designed to limit the resources and technological investment options available to the system. According to the categorization proposed above, the actual impact of this stress will depend on the system's robustness, i.e. on its capacity to adapt its long-term trajectory to the constraint.

The TIAM model is well-placed to consider the robustness of the European energy system. In line with our systemic framework, we assess the robustness of the low carbon system by measuring the impact of long-term stresses on cumulative total system cost over the period 2030-2050 (broken down into investment, operating and maintenance, and import expenditure, see Table 5). The cost increase produced by a constraint is indeed the consequence of the new trajectory found by the system to adapt to the constraint; as such, it is also the measure of the actual impact of the constraint. At the outset it is notable that from 2030 to 2050 a low-carbon system will impose a total additional cost of 12% (113.9 tn$ vs 91.5) relative to the business-as-usual system. Indeed, the carbon constraint leads to an increase in the price of all fossil fuels, with a direct impact on the cost of electricity generation. Secondly, the reduction of fossil fuel imports is achieved thanks to significantly higher expenditure on low-carbon technologies, which are typically characterised by high initial investment costs. The offsetting of these increased costs by the reduced need for fossil fuels (and, in particular, imports) is not enough to confer a positive value on the transition to a low carbon system.

Table 5
Total energy system costs in BaU and LC scenarios and additional system costs under different long-term stresses (cumulative costs 2030–2050, Europe).

	Total cost	Stress (a): High demand Energy service demands increased b/w 5–20%		Stress (b): Low nuclear Nuclear pwr in Europe constrained to max. 1/3 of 2010 capacity		Stress (c): No shale gas No Shale gas available in Europe (RoW = conservative est.)		Stress (d): Low OPEC Oil production capacity in OPEC limited to 1/3 of global oil prod	
	bn$	Δbn$	Δ (%)	Δbn$	Δ (%)	Δbn$	Δ (%)	Δbn$	Δ (%)
Business-as-usual	**91.526**	**10.221**	**11.2**	**117**	**0.1**	**955**	**1.0**	**1.583**	**1.7**
- O&M costs	19.476	1.664	8.5	12	0.1	−163	−0.8	718	3.7
- Investment costs	61.796	6.153	10.0	59	0.1	498	0.8	608	1.0
- Implied costs of endogenous trade	10.254	2.404	23.4	46	0.4	620	6.0	257	2.4
Low carbon	**103.893**	**14.517**	**13.9**	**808**	**0.8**	**720**	**0.7**	**1.274**	**1.2**
- O&M costs	21.440	2.064	9.7	−91	−0.4	−725	−3	1.188	6
- Investment costs	71.055	7.978	11.2	39	0.1	314	0	1.207	2
- Implied costs of endogenous trade	11.398	4.475	37.7	860	7.5	1.131	10	−1.121	−9
Low Carbon_NoCCS	**107.414**	**16.097**	**15.0**	**2.147**	**2.0**	**462**	**0.4**	**1.208**	**1.1**
- O&M costs	21.256	1.828	8.6	−346	−2.0	−578	0	1.210	6
- Investment costs	74.230	7.729	10.4	−437	−1.0	108	0	360	1
- Implied costs of endogenous trade	11.929	6.540	54.8	2.930	25.0	932	0	−362	−3

Additional insights are derived from comparing the different costs associated with four contrasted scenarios, each one imposing a further stress to the system. The Low Carbon state of the world is less robust than the BaU case under assumptions of high demand, lower availability of nuclear energy, or a lack of deployment of carbon capture and storage technologies (as in the LC scenarios the additional cost necessary to adapt to these stresses is higher than in BaU). For the latter two cases, it is worthwhile to note that the effects of a low nuclear scenario are relatively minor compared to the denial of CCS technologies. Intuitively, this is due to the applicability of CCS to the two incumbent fossil fuels – coal and gas – which together currently provide roughly 50% of electricity generation in Europe. This point is made starker by observing the impact of the four long-term stresses on a low carbon system that is also deprived of the opportunity to deploy CCS technologies.

For the BaU case, a lack of significant recoverable shale gas resources or constrained production potential in oil-exporting countries impose higher costs than for an LC system. But the cost differences between the BaU and LC systems are not as stark in such gas- and oil-constrained scenarios, despite the BaU system's greater reliance on these fuels. This implies that the BaU system possesses greater room for manoeuvre to invest in alternative technologies and can thereby accommodate pressures emanating from reduced fossil fuel production capabilities.

One clear message emanating from the present analysis is that the successful transition to a LC system is dependent on the availability of technologies such as nuclear power and CCS, which require a great deal of investment and long-term policy commitment. Unfortunately, robust policies related to these technologies are inhibited by a lack of public acceptance of the former and a high degree of techno-economic uncertainty in the latter. Indeed, while nuclear power is one of the most important energy resources identified in the LC scenario, the current projections of its deployment by 2025 will be significantly below levels required to achieve carbon emissions targets. This is partly

Table 6
Summary of impacts of a low-carbon transition on the five properties of energy security.

Impact of low-carbon transition	Further analysis needed
Stability	
× De-centralised generation imposes control risks	Assessment of power flows in an electrified energy system (e.g. power network model)
× Electrification, including inter-regional electricity transfers, amplify probability/impact of disruption	
Flexibility	
× Intermittent RES increase variability of system variables	Optimisation of flexible resources such as back-up, interconnections, storage (e.g. short-term sector model)
Resilience	
✔ More RES increase fuel mix diversity	Need for greater interconnections, storage, contracts, demand-side response (e.g. sectoral flow model)
× Lower fossil fuel use decreases import diversity	
× Decreased demand diversity as a result of electrification	
Adequacy	
× More investment uncertainty	Market valuation of externalities
× Tighter energy market and heightened sensitivity to demand	Costs and benefits of capacity mechanisms (e.g. sectoral market model)
Robustness	
✔ Minimised impact of climate change on energy system	Further analysis of potential long-term stresses, such as impacts on economic growth or biodiversity (e.g. energy system model linked with macro-economic and/or environmental models)
✔ Less resource depletion	
✔ Less resource nationalism	
✔ Greater adaptability to fossil fuel availability	
× Less freedom to choose PES at cost-oriented prices (including technology constraints)	
× Greater sensitivity to technological constraints (e.g. on Nuclear/CCS)	

due to the aftermath of the Fukushima accident in Japan in late 2011.

As a low-carbon EU energy system orients itself away from fossil fuels, its robustness with respect to other traditional long-term stresses, such as resource depletion, production limits or resource nationalism, can be expected to increase. However, the scenario analysis shows an increase in the regional concentration of imported sources, as the number of producers decrease. The probability of market power abuse may therefore increase, even if its impact may be moderated by the lowered reliance on fossil fuels.

In conclusion, the denial of key technologies enabling a low-carbon transition along with a reduction in the diversity of fossil fuel imports would constitute a clear case of a trade-off between climate policies and long-term energy security. However, synergies exist that lie outside the scope of this analysis; whilst difficult to quantify, the reduced risk and/or consequences of climate change events (such as sea level changes or extreme weather events) in the LC scenario may very well offset any of the above-named challenges to energy security.

4.3. New challenges for system and market adequacy

The LC scenario depicts a future where fossil fuel consumption is dramatically different from the BaU case. The huge uncertainty on the actual implementation of stringent climate policies, and the consequent impact on future energy demand, particularly for fossil fuels, may affect investment decisions in supply capacity and infrastructure worldwide (and first in producing countries), leading to heightened risk of insufficiently matching forecasted supply with demand. The strong impact of a high demand scenario on the cost of a low-carbon system reveals its sensitivity to an efficient allocation of resources to meet planned energy demand. It may also transpire that global energy markets become tighter as carbon policies are implemented. An extension of the current analysis with a myopic version of the energy system model could provide more insights on this point.

At European scale, in the aftermath of the economic crisis, there is currently over-capacity in many national markets. However, given the massive deployment of low- or zero-carbon technologies implied by the LC scenario, a critical issue is the availability and cost of capital to finance the transformation of the energy system in deregulated markets. A key challenge is the substantial network upgrades, both for electricity and gas, needed to enable the use of flexible resources in the LC system [61]. The investments in flexibility required by the LC scenario can be difficult to achieve in liberalised markets, as the market does not properly value the benefits of flexible resources. For instance, the LC power system is characterised by a new market rationale, where the merit order is replaced by net demand. As gas plants increasingly provide peak load, the lowering of the capacity factor threatens the viability of existing plants and detracts from investment in new plants. Moreover, prices in the day ahead electricity market are often very low and the profile of the price curve is now different from the demand curve [62–64]. A more detailed analysis of this wide low-carbon energy system scenario in terms of the short-term power market equilibrium can provide additional insights.

The energy system must adapt to market-related challenges of low-carbon policies by devising new regulatory mechanisms to manage the interaction between incumbent fuels and infrastructures and the less carbon-intensive technologies that are meant to replace them. For example, capacity mechanisms, which aim at keeping sufficient dispatchable generation capacity online even though it may not necessarily be used, can address the viability of generators with low reserve margins. The costs and benefits of this scheme, however, require detailed analysis.

Finally, in the longer-term, the investments needed for the revolution of the infrastructure system in the transport sector, required by the introduction of biofuels and hydrogen, can be a further challenge.

4.4. New challenges for system resilience

The Low Carbon EU energy system is characterised by a slightly higher diversification for energy portfolios (as measured by the Herfindahl–Hirschman Index, which yields values of .32 and .28 for the BaU and LC systems, respectively), as the share of the dominant fossil fuels in TPES decreases and is compensated for by nuclear power and different forms of renewable energy. Following Stirling's framework, this increase in diversity can potentially provide protection against 'unknown' risks and therefore this outcome can be seen as beneficial for enhancing the resilience of the system to short-term disruptions of energy supply. However, a closer look reveals a more complex picture: for instance, the lower total gas consumption relative to the BaU case is accompanied by a lower diversification of the sources of import. This is because the sources of supply which are marginal under BaU demand conditions are effectively cut out in the LC scenario, due to lower gas demand. Looking beyond primary energy, the increased importance of electricity in final energy consumption in the low-carbon system lowers the diversity of demand, which may also have an impact on system resilience.

Having to select the 'right' diversity measures to capture the relationship between carbon policies and energy security is problematic to say the least. Eschewing their use, a more precise assessment of the impact of the LC scenario on the resilience of the EU system requires an integration of a wide energy system analysis provided by TIAM with an analysis accounting for the peculiarities of an individual sector (e.g. a gas network model).

4.5. New challenges for system flexibility

A critical implication of the increased electrification resulting from the LC scenario is a substantial need for additional power system flexibility. On the supply side, variable energy resources (VER) (wind and solar) reach 28% by 2050 and rise to 46% if CCS is unavailable, compared with less than 5% today. Their increased role creates a new set of operating challenges for the power system, impacting on issues such as peak load adequacy, minimum load balancing and capacity margins, ramp-up rates of residual demand and the predictability of VER [63,65]. Interestingly, the ratio of peak to average demand is in fact 10% lower in the LC scenario than in the BaU case. This is due to the increased electrification of final energy consumption, which smoothens the load curve for demand as electricity finds a greater number of applications. At the same time, however, the increased call on heat pumps significantly increases the spread between summer and winter days, since these pumps are most likely to be employed during the latter period, which also coincides with peak demands for electricity for other uses. Moreover, if heat pumps are operated on a time-of-day cycle, similar to many central-heating timers, this could lead to substantial additional peak electricity demand (an estimated addition of 22% in the OECD, according to [66]).

In light of these challenges, the electricity system must be highly flexible – able to rapidly ramp its output up or down in response to fluctuations in either supply or demand. However, currently, not even ENTSO-E assessments focus on the flexibility of the EU power system [67], meaning that its flexibility remains uncertain [68]. Moreover, as gas plants are generally expected to provide a key source of flexibility for the power system, a substantial impact can be expected on the gas market too, as it will face growing diurnal swing [69]. Clearly, the appropriate level of flexibility in a LC scenario is an issue deserving more in-depth analysis, for instance by passing the results of the energy system analysis to a model with a more detailed representation of the operational requirements of power and gas systems [70].[4]

4.6. New challenges for system stability

For the large-scale and highly complex interconnected power system, the challenge to maintain the system frequency within very strict limits at all times across the whole network is magnified by the dynamic nature of flows and the operational complexity in liberalised markets [72]. The strong role of distributed generation in the LC Scenario can impose additional burdens in terms of managing generation, given the lack of centralised (or co-ordinated) monitoring and control systems for medium and low-voltage networks. An additional risk emanating from the LC scenario is the possibility of more common and widespread electricity disruptions due to the increase in bilateral electricity transfers (which may be amplified in cases where this trade is based upon large-scale solar and wind power plants). In light of these challenges, the future stability of the power system rests on a smarter, more unified and integrated system. Deployment of 'smart grids' can result in an increase in available system capacity, a reduction of congestions and the possibility to implement a range of operating paradigms previously not feasible, key among which is the full participation of residential customers in generation and demand-side flexibility services. Whereas the TIAM model is well placed to draw attention to the increased transfer of electricity across borders, a rigorous assessment of the stability of the system requires a detailed network simulation using a power system model. These models can show security margins, changes in load profiles and responses to $N-1$ situations. The next step to assess the implications of this low carbon scenario on network stability, therefore, would be to combine the energy system analysis with a more detailed network simulation.

5. Conclusions

The purpose of this paper was to introduce a novel systemic approach to the dual problem of defining and assessing energy security while considering its complex interaction with climate change policies. Unlike most existing approaches which limit their discussion of security to a handful of indicators, this approach considers security dynamically in terms of the entire energy supply chain – from extraction to end-use – with all of its various feedbacks and interdependencies that evolve over various timeframes.

On a practical level, it is apparent that a low carbon system will bring about fundamental changes to the energy system. Change means risk, but it can also bring about new opportunities; the current emphasis in the literature on both the trade-offs as well as the synergies between energy security and climate change policies is an appropriate starting point. The challenge is to develop a sound methodology for assessing these trade-offs and synergies while accounting for the multiple technologies, processes, fuels, policies and actors that make up the global energy system. The systemic approach adopted in this paper used a scenario analyses to analyse how structural changes to the EU energy supply chain creates threats that require mitigation and/or management through the strengthening of the five properties of a "secure" energy system – stability, flexibility, resilience, adequacy and robustness.

[4] The authors are currently linking the output from the energy system model (TIMES–TIAM) with a detailed power system model (PLEXOS), see [71] The methodological framework introduced in this paper will serve as a guide to practically assess the interactions between energy security properties through linked models.

Table A1
TIAM – investment cost assumptions for new build power plants (€/KW).

	2010	2030	2050
Biomass			
Biomass gasification	3282	2626	2626
Biomass gasification decentralized	3610	2708	2708
Biomass gasification w CCS	–	3357	3133
Coal			
Coal IGCC	2462	2216	2216
Coal IGCC w CCS	–	3119	2954
Conventional pulverized coal w CCS	–	2954	2872
Geoth.			
Geothermal shallow	2359	2257	2051
Geothermal very deep	13,970	8910	3850
Natural gas			
Natural gas comb cycle	821	821	821
Natural gas comb cycle w CCS	–	1044	970
Auto CHP with NGA new	880	792	792
Hydro			
Generic impoundment hydro	914	893	872
Nuclear			
Advanced nuclear	–	4400	4400
Advanced nuclear LWR	5500	5500	5500
Solar			
Solar centralised	3482	1151	930
Solar decentralized	4029	1827	1108
Wind			
Wind offshore	2,543	2,297	2,052
Wind onshore	1,640	1,453	1,265

Table A2
TIAM – assumptions on extraction costs for the three main primary energy resources ($/GJ).

$/GJ		2010	2050
Panel (a)			
Oil – non-energy extraction cost			
Reserves	Min	3	3
	Max	5	7
Enhanced recovery/reserves growth	Min	6	6
	Max	9	14
Undisc. resources/new discovery	Min	4	4
	Max	13	19
Oil sands	Min	5	5
	Max	7	9
Extra-heavy oil	Min	5	5
	Max	9	11
Oil shale	Min	11	11
	Max	17	17
Natural gas – non-energy extraction cost			
Reserves	Min	2.3	2.3
	Max	3.4	5.0
Enhanced recovery/reserves growth	Min	6.1	6.1
	Max	7.9	11.8
Undisc. resources/new discovery	Min	3.2	3.2
	Max	5.2	7.7
Coal-bed methane	Min	3.0	3.0
	Max	7.6	7.6
Tight gas	Min	3.6	3.6
	Max	7.6	7.6
Shale gas	Min		3.4
	Max		16.7
Panel (b)			
	Min		Max
Hard coal			
Reserves	0.9		4.0
Resources	1.2		4.3

Panel (a). N.B.: including exploration and development, if needed, and production.
Panel (b). N.B.: Min and max values refer to lowest and highest cost across regions.

The analysis provides several insights about the complex interactions between energy security and climate change policies, revealing how no simple answer to the question is possible. A low-carbon scenario has a wide range of implications for the security of the energy system (as conveyed by Table 6). Multiple options can help to minimize the potential trade-offs. It is only by thinking in terms of complete systems that optimum solutions can be found.

The analysis has provided a more nuanced alternative to the prevailing assumption in the existing literature that a low-carbon system – by virtue of increasing primary energy diversity while obviating the need for imported fossil fuels – can increase the robustness of the system. It is apparent that different stresses can impact differently depending on the 'state of the world'; since a low-carbon scenario must evolve within a narrow band of possibilities, constraining technological options that enable this trajectory is bound to impose higher costs than a scenario in which energy use is less restricted by carbon policies. The point may seem trivial, but it is often under-examined when analysing the long-term impact of a low-carbon system on energy security.

The present analysis constitutes a first step in devising a comprehensive framework to explore in greater depth the wide range of impacts of a low-carbon scenario on energy security. Indeed, there are different possible pathways towards a low carbon system, each of them implying radical structural changes. This paper has demonstrated the key role played by energy system models in identifying areas of change in a consistent way, The next step in this endeavour is to combine such models with more detailed sector models of the different energy markets, which can provide a more accurate assessment of the differentiated properties of a secure energy system.

Appendix A

The following two tables illustrate the assumptions used in the modelling analysis for two key areas – namely, investment costs in electricity plants and extraction costs of fossil fuels. These are largely indicative, as the technology-rich energy system model (TIAM) contains a great deal of assumptions on technologies and commodities. Thus, we refer interested readers to the documentation in [59] (see Table A1 and A2).

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