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Prospective analysis of energy security: A practical life-cycle approach focused on renewable power generation and oriented towards policy-makers

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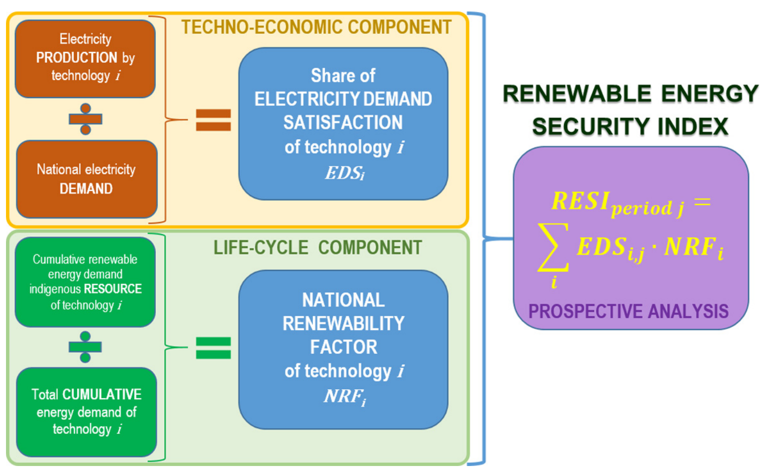
HIGHLIGHTS

- Formulation and application of the Renewable Energy Security Index (RESI).
- Prospective analysis combining Energy Systems Modelling and Life Cycle Assessment.
- Feasibility proven through two case studies of power generation in Spain and Norway.
- Good coverage of key energy security aspects (availability, affordability, etc.).
- Novel and easy-to-report index suitable for energy policy-making.

GRAPHICAL ABSTRACT



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ABSTRACT

Energy security is a wide-ranging term to encompass issues such as security of supply, reliability of infrastructures, affordability and environmental friendliness. This article develops a robust indicator – the Renewable Energy Security Index, RESI – to enrich the body of knowledge associated with the presence of renewable energy technologies within national electricity production mixes. RESI is built by combining environmental life cycle assessment and techno-economic energy systems modelling. Spain and Norway are used as illustrative case studies for the prospective analysis of power generation from an energy security standpoint. In the Spanish case, with a diversified electricity production mix and a growing presence of renewable technologies, RESI favourably "evolves" from 0.36 at present to 0.65 in 2050 in a business-as-usual scenario, reaching higher values in a highly-restricted CO_2 scenario. The Norwegian case study attains RESI values similar to 1 due to the leading role of renewable electricity (mainly hydropower) regarding both satisfaction of national demand and exportation of electricity surplus. A widespread use of RESI as a quantifiable energy security index of national power generation

Abbreviations: BaU, Business as Usual; CED, cumulative energy demand; CHP, Combined Heat and Power; EDS, Electricity Demand Satisfaction; EDS_r, electricity demand satisfaction by renewable power generation technologies; ESM, Energy Systems Modelling; ESRI, Energy Security Risk Index; EU, European Union; IEA, International Energy Agency; LCA, Life Cycle Assessment; LCEA, life cycle energy analysis; MSW, Municipal Solid Waste; NRF, National Renewability Factor; PV, Photovoltaics; RESI, Renewable Energy Security Index; RoR, Run of River; SOS, security of supply.

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sectors is found to be feasible and practical for both analysts and energy policy-makers, covering a significant number of energy security aspects.

1. Introduction and background

The International Energy Agency (IEA) defines energy security as "the uninterrupted availability of energy sources at an affordable price" [1]. Even though the idea of long-term security of supply (SOS) is generally used, the actual definition of energy security has not yet reached consensus due to the involvement of different types of risks. Geopolitical aspects are relevant to energy security since energy resources are limited and often come from specific countries, which is linked to the notion of 'energy dependence' [2]. This concept is affected by e.g. imports/exports of energy carriers/fuels, interconnectivity of the region in terms of dispatchability and/or reliability, proven reserves of energy sources, and fuel prices. Nevertheless, other economic, technical and environmental aspects should be considered since energy security is a cross-cutting concept requiring holistic approaches and qualitative-quantitative judgements. Kruyt et al. [3] identified the main SOS-related elements (the four A's) based on a report from the Asia Pacific Energy Research Centre [4]: availability, accessibility, affordability and acceptability, considering geological existence as well as geopolitical and sustainability aspects. The survey performed by Ang et al. [5] showed a similar approach, considering that the notion of energy security is context-dependent, and added other dimensions such as infrastructure, governance and energy efficiency.

Regarding the development of energy security indicators, there have been many efforts to comprehend the most adequate and efficient variables covering the different security aspects. Kruyt et al. [3] made a broad literature review and distinguished between simple indicators, such as reserves-to-production ratios, import dependence, energy prices, political stability and demand-side requirements, and aggregated indices. Löschel et al. [6] compiled contributions showing the plethora and disparity of concepts and indicators on energy security. The in-depth state-of-the-art presented by Ang et al. [5] found that the number of indicators varies significantly among the identified studies (ranging from 1 to more than 60).

Some authors propose the use of composite indicators. Costescu Badea et al. [7] developed a method for building composite indicators based on the ranks of a set of individual indicators (energy and carbon intensity, import dependence rate, primary production, electricity generation capacity, and energy demand in transport) taking into account different weights associated with diverse risk-averse levels. Augutis et al. [8] presented a method to integrate the values of several individual indicators into a single integral concept based on an algorithm for SOS. Moreover, Martchamadol and Kumar [9] developed a zero-to-ten scaled index by considering a set of individual indicators representing the three pillars of sustainability, in order to evaluate national energy security.

There is no international standard to guide the establishment of energy security indices. Most of the available studies on developing energy security indicators and indices are performed at the national level. For instance, the well-known Energy Security Risk Index (ESRI) covers the most relevant aspects with potential effect on the national security of the U.S. energy system [10]. Among the metrics included in ESRI, there are 37 indicators representing features such as global/national resources reserves, energy intensity, fuel prices, imports, gross domestic product per capita, carbon dioxide emissions, etc. Furthermore, there is an aggregation process resulting in a set of 9 categories which are then further aggregated into four main sub-indices (geopolitical, economic, reliability, and environmental risks). The final ESRI value is obtained by weighting the sub-indices (30%, 30%, 20% and 20%, respectively).

Concerning the role that renewable energies play in energy security, IEA stated that renewable technologies have the potential to contribute to energy security intensely while meeting environmental objectives at the regional, national and/or global level [11]. In this respect, the International Renewable Energy Agency declared in 2015 that almost 150 countries had (increasingly ambitious) renewable energy targets [12]. Furthermore, there are many examples of techno-economic studies concerning renewable energy technologies in different applications [13,14] and sectors [15–17]. Nevertheless, renewable energy alone cannot deal with all energy security aspects. Johansson [18] highlighted several risks that should be considered through different economic-political, technological and environmental approaches, e.g. competition for scarce and valuable resources, accidents or attacks, and climate change or health threats from air and water pollution. In order to assess and quantify the impact of renewable energy systems on global energy security, Augutis et al. [19] presented a methodology in terms of system's resistance to disturbances through the calculation of an energy security coefficient applied to the Lithuanian energy sector. Armstrong et al. [20] discussed the frontiers of the energy systems for the upcoming future, stressing the importance of – in addition to the massive penetration of renewable energy technologies – upgrading the current energy grids according to new decentralised schemes, which means a challenge from an energy security perspective. The IEA developed the Model of Short-term Energy Security (MOSES), which focuses on evaluating a set of sub-indicators based on two concepts: risks of energy supply disruptions, and system's resilience (i.e., the ability of a national energy system to manage disruptions) [21]. This global indicator model looks at the nature of each primary energy source besides their origin, domestic or external, and establishes a specific sub-indicator, e.g. net import dependence, diversity of suppliers, average age of nuclear power plants, etc.

While there are many studies concerning energy security-related topics such as energy dependence and resilience of energy systems and infrastructures, there is a lack of comprehensive works facing energy security holistically according to the spatial and temporal dimensions of the energy systems. In this regard, Jewell et al. [22] compared energy dependence and climate policies in the long term using five global energy system models, and Lima et al. [23] developed a modelling framework introducing sustainability indicators in MESSAGE, a recognised energy system model, concluding the positive effects of deploying sustainable technologies on the security. Energy planners must guarantee that energy supply systems are capable of providing enough, stable, affordable, environmentally sustainable, and inclusive services to meet the economic needs of a country [24].

At the policy level, energy security is assessed in several studies [18,25–27] and systemic approaches have recently been proposed [28,29]. Gracceva and Zeniewski [30] proposed a framework to tackle issues regarding energy security using Energy Systems