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A Comprehensive Metric to Assess the Security of Future Energy Systems Through Energy System Optimization Models

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ABSTRACT

Ensuring energy security is one of the main objectives of energy policies of many countries worldwide. In this regard, this paper proposes a metric to evaluate energy security under medium-to-long term energy scenarios generated by the TEMOA-Italy model. Such a metric consists of an energy security index covering several dimensions of energy security. Among them, the inclusion of the supply risk of critical raw materials represents a novelty, compared to the existing literature. Moreover, critical raw materials are crucial for the decarbonization of urban energy systems, for instance through smart cities and vehicles to grid strategies. The analysis here shows how the penetration of low-carbon technologies can provide significant benefits to energy security, while their dependence on critical raw materials could represent a bottleneck for the evolution of the energy system. Accordingly, the metric presented in this paper can provide relevant policy insights on the effects of the transition from fossil fuels to low carbon sources on energy security.

Keywords: Energy Security, Energy System Modeling, Energy Supply Risk, Material Supply Risk, Critical Raw Materials, Decarbonization.

NOMENCLATURE

BAU	Business As Usual
BEV	Battery Electric Vehicle
CRM	Critical Raw Material
DEC	Decarbonization
ESI	Energy Security Index
ESOM	Energy System Optimization Model
HHI	Herfindahl-Hirschman Index
LIB	Lithium-Ion Battery
MSR	Material Supply Risk
REE	Rare Earth Element
RES	Reference Energy System
RESI	Renewable Energy Security Index
TPES	Total Primary Energy Supply

1. INTRODUCTION

The recent energy crisis emphasized the urgent needs for a more resilient energy infrastructure, pointing to energy security (ES) as one of the priorities for policy makers. Accordingly, the current European Union (EU) ES policies aim at reducing the risk of energy supply disruption [1], defining the ES as a multidimensional target [2], with a close linkage to related energy-policy problems, such as equitable access to energy supply and the mitigation of climate change [3]. The adoption of policies aiming at enhancing the ES can be considered as a win-win condition in the long-term, being the issues related to ES, economic development and climate change mitigation strongly interconnected [4].

Energy System Optimization Models (ESOMs) are suitable tools in supporting policy makers in the identification of energy policies, also regarding the improvement of ES [5]. An ESOM framework typically relies on the definition of different interconnected sectors of a specific Reference Energy System (RES) through a technology-rich database. The models are based on a minimum-cost paradigm, subject to a set of constraints depending on the analyzed scenario, matching the commodities produced in the supply-side and the end-use demands over a medium-to-long-term time scale and a (possibly) multiregional spatial scale. The demand-side sectors, including transport, buildings, and industry, consume commodities to satisfy the final energy service demands, while the supply side (upstream and power sector) produces intermediate commodities, such as fossil fuels and electricity, meeting the requirements of the demand side.

The application of ESOMs to the analysis of ES, based on quantitative approaches through the definition of a suitable metric, introduces the possibility of investigating the evolution of ES in a long-term time scale for specific scenarios and under different conditions [6]. Looking at existing literature, the ES is endogenously integrated in the model only in [7], where a Renewable Energy Security Index (RESI) is proposed, whereas in all the other

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analyzed studies the model results are exogenously connected to an Energy Security Index (ESI). The latter can include a broad collection of indicators [8], [9] or may simply be defined based on crucial aspects for the ES [10], depending on the data provided by the model itself.

The future evolution of energy systems is generally expected to be more material intensive, due to dependence on so-called Critical Raw Materials (CRMs) of many energy transition technologies [11], but the effects of possible supply chain disruptions of CRMs is still not explicitly investigated in the analysis on ES. Facing this lack, this work aims at providing a comprehensive metric to evaluate the ES, accounting also for the supply risk associated with critical raw materials. This can lead to crucial considerations for the future of urban systems, the economic development of which is particularly sensible to the risk of energy shortages. Moreover, their sustainable evolution may depend on initiatives such as smart cities and vehicles to grid, which strongly rely on transition technologies and CRMs. The proposed case study focuses on future energy scenarios generated using the TEMOA-Italy model [12], [13].

2. METHODOLOGY

The proposed metric consists of seven indicators, connected to the results (installed capacity and activity of technologies, as defined in [14]) produced by an ESOM, as shown in Table 1.

Table 1 Overview of the ESI adopted in the present paper

Indicator	Dimension	Data Sources
Material Supply Risk (MSR) $^{+}$	Supply Risk	[15],[16], [17],[18]
Renewable Energy Supply (RES) $^{++}$		[4],[19],[20]
Diversification (DIV) $^{++}$		[10],[20], [21],[22]
Self Sufficiency (SS) $^{++}$		[8],[9], [23],[22]
Energy Intensity (EI) $^{++}$	Reliability	[9],[23], [24],[25]
Capacity Factor (CF) $^{+}$		[26],[27]
Capacity Credit (CC) $^{+}$		[25],[28],[29]

$^{+}$ Related to technology capacity.
$^{++}$ Related to technology activity.

Referring to the analysis conducted in literature to provide a multidimensional definition of ES [2], [30], [31] and considering the purpose of the proposed work to quantitatively represent the ES of the RES, two dimensions are considered (see Table 1):

- Supply Risk (SR), including the Material SR (MSR) and the Energy SR components.
- Reliability, focused on the internal resilience and robustness of the system.

The SR of raw materials is defined following the methodology proposed by [16], [17], [18], that refers to the MSR composite indicator defined by the EU Commission [15] and involves the material intensity of the energy technologies [16], [32], [33]. Fig. 1 reports the specific material consumption for three key energy transition technologies, expressed in kg/MW.

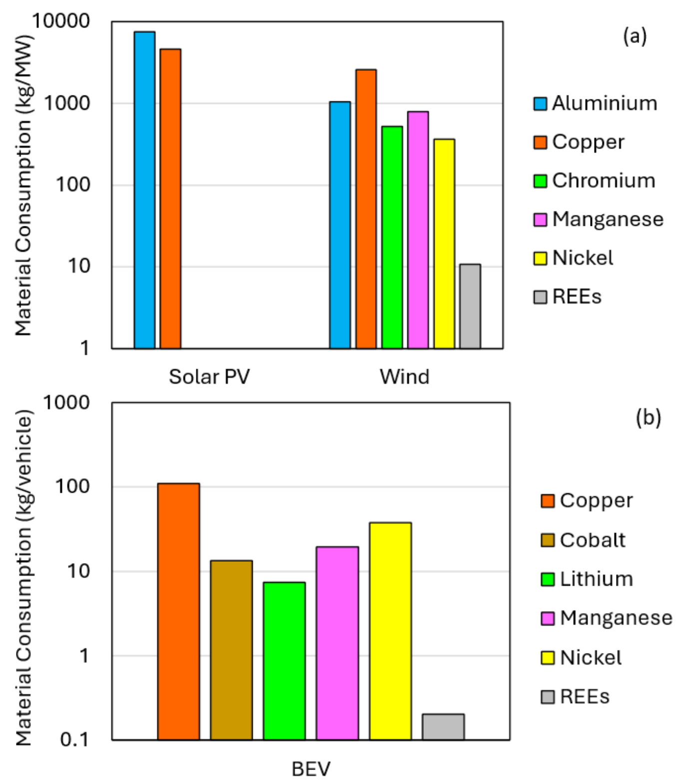

Fig. 1 Material consumption, reported on a logarithmic scale, for Solar PV and Wind (a) and Battery electric vehicles (BEVs) (b)

Renewable energy contributes to a more distributed power generations increasing the spatial distribution of energy supply and reducing the dependency from fossil fuels, generally imported by many countries worldwide, and the GHGs emissions, contributing to long-term energy security, as discussed in [4], [19]. The Renewable Energy Supply (RES) in Table 1 is then evaluated as the percentage of renewable energy with respect to the total primary energy supply (TPES).

Increasing the available portfolio of energy sources reduces the risk of energy supply disruption and the price volatility referred to the supply of energy [23]. These aspects are accounted for by the diversification index DIV, evaluated as in [21], where the Herfindahl-Hirschman Index (HHI) is adopted as shown in Equation (1), being b_i the fraction of a certain energy source with respect to the TPES.

$$1-\mathrm{HHI}=1-\sum_{i}^{n}(b_i)^2 \tag{1}$$

Similarly to DIV the self-sufficiency of a region, represented as the internal energy production over the total final energy consumption, is considered as an indicator of ES [23], [34].

Focusing on the consumption side, [24] discusses the linkage between the efficiency in the use of energy (considered as energy consumption to produce a certain amount of good) and the ES. To account for this aspect, considering the results in [35], the energy intensity (EI) is included as an indicator for the metric and corresponds to the final energy consumption of the system over the projected gross domestic product (GDP).

The last components included in the ESI are the capacity factor CF and the capacity credit CC, which provide a quantification of the resilience and reliability of the power sector [36], [37], and will gain particular interest in future due to an expected increase in the electrification of the energy system [26].

All the indicators are percentages between 0 and 1, except for MSR and EI: hence, for consistency reasons, the latter are normalized following the approach reported in Equation (2):

$$\bar{\chi}_{s,t}=\frac{\chi_{s,t}-\chi_{min}}{\chi_{max}(s,t)-\chi_{min}} \tag{2}$$

where: $\chi_{s,t}$ is the value referring to a certain scenario *s* and specific period *t*; $\chi_{max}(s,t)$ represents the maximum value obtained across all the scenarios and over the entire time scale; χ_{min} is an ideal minim, for both the MSR and EI, assumed equal to 0.

The ESI are then aggregated following two different approaches concerning the weighting. The first one (Equation (*3*)) aggregates the ESI under the two dimensions of SR (MSR, RES, DIV, SS) and reliability (EI, CF, CC). In the second one, the material supply risk (MSR) and the ESR (RES, DIV, SS) are considered separately within the SR dimension: this increases the importance of the MSR contribution to the ES, as represented in Equation (4). Considering equal weights for the indicators composing the different dimensions, the value of the weights for the ESI belonging to the SR dimension is $w_{SR}=0.125$ for those belonging to the reliability dimension are $w_R=0.167$. In the second approach, the weight for MSR is $w_{MSR}=0.333$ and those for the indicators associated with the ESR and reliability dimensions are $w_{ESR}=w_R=0.111$.

$$\mathrm{ESI}'=w_{SR}\cdot\big((1-\mathrm{MSR})+\mathrm{RES}+\mathrm{DIV}+\mathrm{SS}\big)+w_R\cdot\big((1-\mathrm{EI})+\mathrm{CF}+\mathrm{CC}\big) \tag{3}$$

$$\mathrm{ESI}=w_{MSR}\cdot(1-\mathrm{MSR})+w_{ESR}\cdot(\mathrm{RES}+\mathrm{DIV}+\mathrm{SS})+w_R\cdot\big((1-\mathrm{EI})+\mathrm{CF}+\mathrm{CC}\big) \tag{4}$$

Note that for the MSR and the EI respectively, the complement to one is taken, due to their decreasing effect on the ES level.

The methodology developed in the previous steps is then applied to the case study of TEMOA-Italy model [12], [13] used to analyze the Italian RES. In this work the scenarios analyzed are two: the Business As Usual (BAU) scenario, representing the reference scenario, in which the model is free to evolve according to the stated policies; a decarbonized scenario (DEC), whose evolution is influenced by a 2050 Net0 emissions reduction trajectory, derived from [38], [39].

3. RESULTS AND DISCUSSION

This section compares the evolution of the seven indicators analyzed for the proposed scenarios (BAU, DEC) and the resulting ES level obtained applying the two aggregation methods explained in Section 2. The TPES of the two scenarios is reported in Fig. 2, showing a higher penetration of wind, solar and biofuels in the DEC scenarios to the detriment of crude oil and natural gas, mainly.

The evolution of the selected indicators over the entire period is represented in Fig. 3, from 2007 to 2050, in which the MSR is particularly increasing in the de-carbonized scenario. The latter is characterized by a significant penetration of renewable energy technologies such as wind turbines, resulting in almost 70 GW of installed capacity reached in 2050. Moreover, a high penetration of lithium-ion batteries (LIBs) is present, too, with more than 90 GWh of installed capacity in 2050.

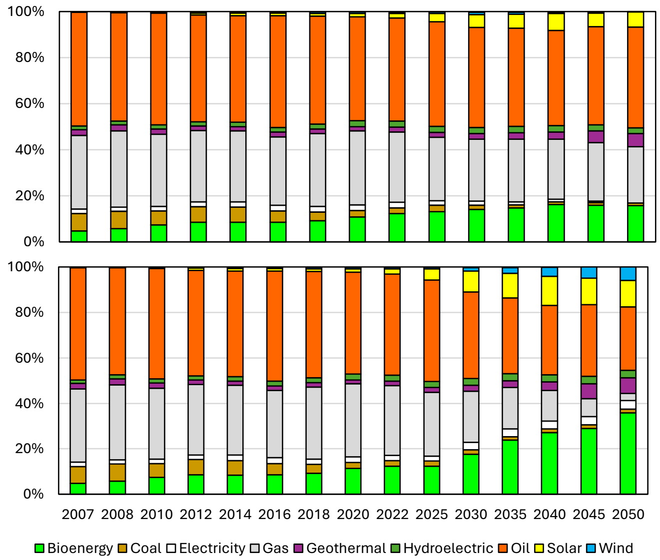

Fig. 2 Comparison of the TPES for the BAU (top) and DEC (bottom) scenarios, respectively

A possible bottleneck for the penetration of these technologies could be considered the dependency on CRMs like rare earth elements (REEs), for wind turbines, and lithium and cobalt, for LIBs. The increment in the MSR is strongly related also to the substitution of traditional vehicles with battery electric vehicles (BEVs). Considering the vehicle installation from 2020 up to 2050, the BEVs fraction in the BAU scenario is zero as expected, contrarily to the DEC scenario in which the electric cars cover almost entirely the car's transport demand in 2050 (99.7%), which represents the 65% of road vehicle's demand. The material consumption by power and transport sector is represented in Table 2: the majority of material demand growth comes from the transport sector, and this is in accordance with other analyses in literature such as [33].

Table 2 Material consumption from 2020 to 2050

Scenario	Power Sector [kt]	Transport Sector [kt]
BAU	2 783	2 638
DEC	4 490	16 284

Analyzing the other indicators, the most remarkable variations are attributed to RES and SS, which their increment is caused by the high penetration of renewable technologies. It is observed that, also for the BAU scenario, a significant fraction of renewable sources is integrated into the energy system, representing 30% of the TPES in 2050. In the DEC scenario it reaches the 61%, mainly concerning the photovoltaic technologies and due to the expected technology learning [40] and EU Emission Trading System [41], which makes PV competitive with respect to natural gas even in the BAU scenario. This is reflected by a very low variation in DIV of energy supply between the two scenarios and the overlap of CF and CC indicators, which are representative of the power sector reliability. The last remarkable result is the reduction in the EI of the system. Being the GDP an input for the TEMOA-Italy model [42], [43], it is resulting in a reduction of the TPES and an energy saving over the

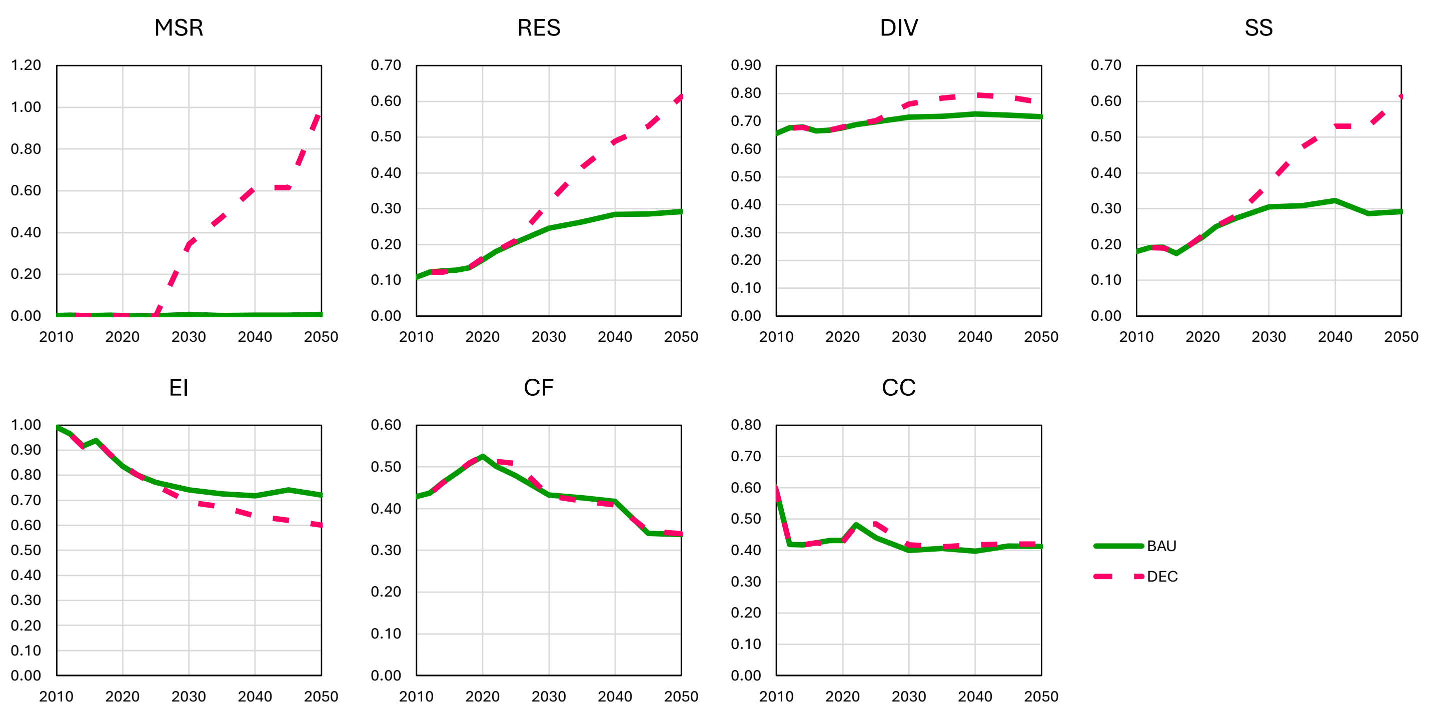

Fig. 3 Representation over the whole time horizon of the seven energy security indicators.

entire period, mainly due to an increase in the electrification of the end use sectors.

Considering now the ESI obtained following the two aggregation methods explained in the Equations (3) and Equation (4), the resulting ES level of the investigated scenarios over two time intervals is analyzed. The first one considers the 2020 (excluded) up to the 2030 (included), representing the first de-carbonization target imposed by the FitFor55 European program [38], while the second one covers the remaining years, from 2030 (excluded) to the 2050 (included), associated with long term targets stated in [44] and [45]. As demonstrated by Fig. 4, considering the second aggregation method (ESI), results in the increment in the material supply risk causes a significant reduction in the level of ES for the decarbonized scenario in the second period (2030-2050) in which the penetration of low-carbon technologies in the power and transport sectors is higher for the stringent emission-limit.

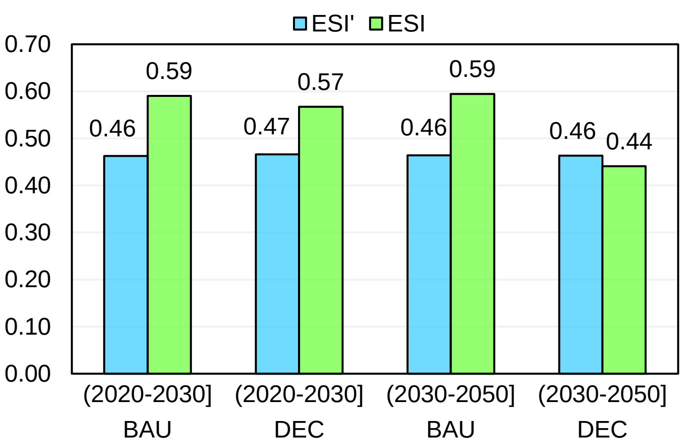

Fig. 4 Resulting energy security level obtained applying the two aggregation methods (ESI' and ESI)

These results could be particularly useful in the analysis of different energy strategies, comparing and identifying the relative highest level of ES. Looking, instead, at the ESI' methodology, being the weight of each indicator in the supply risk dimension smaller than the others which compose the reliability dimension, the variation of one of the indicators will produce a lower variation on the final value of ES. This result is shown to underline which indicators may be considered more important in the evaluation of ES, going to analyze the weight assigning.

Comparing the outcomes shown Fig. 4 it is possible to observe how the information related to the increment in material supply risk are completely lost in ESI', in which the level of ES appears almost unchanged in the different scenarios and periods.

4. CONCLUSIONS AND PERSPECTIVES

This work presents a methodology to quantitatively evaluate the level of energy security through the construction of a comprehensive metric and its application to the future energy scenarios generated by the implementation of the energy model TEMOA-Italy. The main novelty of the work is the integration in the metric of an indicator to account for the supply risk of critical raw materials, which represents a crucial aspect in future energy security evaluation and that will gain always more relevance for the definition of energy policies.

With the higher penetration of energy transition technologies like renewable energy sources, LIBs, and BEVs, passing from the BAU scenario to the decarbonized one, the level of ES is found to be particularly sensitive to the weighting methodology: indeed, by providing a high weight to the MSR indicator, the ESI of the decarbonized scenario results much lower than in the BAU scenario, due to the higher critical raw material consumption of the low-carbon technologies.

However, the methodology adopted to evaluate the MSR is considering only aspects related to the extraction and refining of materials, without including critical aspects concerning the components building and assembly, which could significantly impact on the energy security. Another possible future perspective to improve the analysis consists of the adoption of a multi criteria decision analysis (MCDA) to assess the results dependency on the weighting methodology (see [46]), and the possibility to endogenously evaluate the level of ES in a multi-objective optimization framework.

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