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May the availability of critical raw materials affect the security of energy systems? An analysis for risk-aware energy planning with TEMOA-Italy

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ABSTRACT

The energy transition requires the deployment of clean energy technologies, which typically requires critical raw materials. Their supply chains are characterized by high geographical concentration and political instability, thus leading to potential supply chain bottlenecks and negative impacts on the security of energy systems. However, these aspects are not considered in traditional energy security metrics. To address this lack, this paper proposes a novel energy security metric to study the impact of potential materials supply chain bottlenecks on future energy systems. First, a comprehensive metric is developed by including the supply risks associated with clean energy technologies. Second, the metric is applied to materials supply disruption scenarios. The case study is the Italian energy system, though the TEMOA-Italy open model. The results show that transport is the sector most contributing to the material consumption and mostly affected by the considered materials disruption causes, especially concerning the battery electric vehicles penetration. On the contrary, the power sector is minorly influenced by the introduction of supply disruptions except for storage technologies. Lastly, the material supply risk dimension strongly influences the overall energy security of the system, which increases in disruption scenarios when a lower consumption of critical raw materials is forced.

Abbreviations

Acronym	Meaning
ALKEC	Alkaline Electrolyzer
BAU	Business As Usual
BEV	Battery Electric Vehicle
CC	Capacity Credit
CF	Capacity Factor
CRM	Critical Raw Material
CSD	Chinese Supply Disruption
DES	Diversification of Energy Supply
DSG	Demand Supply Gap
EI	Energy Intensity
ES	Energy Security
ESI	Energy Security Index
ESOM	Energy System Optimization Model
ESR	Energy Supply Risk
EU	European Union
FCV	Fuel Cell Vehicle
FHEV	Full Hybrid Electric Vehicle
GDP	Gross Domestic Product
GSI	Gini-Simpson Index
HHI	Herfindahl-Hirschman Index
IR	Internal Reliability
LGR	Low Governance Region
LIB	Lithium Ion Battery
MSR	Material Supply Risk
NZE	Net Zero Emission
PEMEC	Proton Exchange Membrane Electrolyzer
PV	Photovoltaic
REE	Rare Earth Element
RES	Renewable Energy Supply
SOEC	Solid Oxide Electrolyzer
SOFC	Solid Oxide Fuel Cell
SR	Supply Risk
SS	Self Sufficiency
TPES	Total Primary Energy Supply
VRFB	Vanadium Redox Flow Battery
WSR	Water Stress Region

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Acronym	Meaning
Symbol	Meaning
$B\$$	Billion US Dollars
Cap	Capacity
c_i	Global Material Consumption
ESI	Energy Security Index
$f_{i,t}$	Specific Material Consumption
IMP	Import Fraction in the TPES
MIN	Mining Fraction in the TPES
p_i	Primary Energy Sources
PJ	Unit of Measure for Petajoule
RNW	Renewable Fraction in the TPES
w	Weight
χ	Indicator
$\overline{\chi}$	Normalized Indicator

1. Introduction

The recent energy crisis highlighted the need for resilient energy systems, especially in energy-importing regions like the European Union (EU) [1] and Italy [2]. Policymakers are focusing on sustainable Energy Security (ES) policies to reduce import dependence by increasing low-carbon domestic production. For example, the EU targets 42.5 % renewable energy in final consumption and an 11.7 % energy use reduction by 2030 [3], while Japan aims for 38 % renewable and 22 % nuclear generation by 2030 [4]. Measures like the 2022 REPowerEU plan seek to cut Russian gas imports by two-thirds [5]. This is complemented by goals for 10 million tons of renewable hydrogen and 35 Bm3 of biomethane by 2030 [5]. ES also includes uninterrupted supply and affordable costs [6]. Enhanced ES promotes equitable energy access [7], supports economic welfare, mitigates climate change, reduces price volatility, and fosters economic growth [8].

Current ES policies aim to diversify energy supply and increase renewable energy adoption to enhance energy independence [9]. However, this transition can create ES trade-offs due to supply chain bottlenecks [10]. Clean energy technologies like wind turbines, solar PV, and BEVs require more minerals and metals than fossil-based systems, many of which are Critical Raw Materials (CRMs) [11,12]. CRM demand is expected to surge, with lithium demand projected to increase over fivefold by 2030 and tenfold by 2040 [13,14], leading to potential supply-demand imbalances [15]. Dependence on unstable regions, such as China for lithium and the Democratic Republic of Congo for cobalt, further increases risks [16]. Manufacturing is also geographically concentrated, with China projected to control 60–80 % of the global market for solar PV modules, wind nacelles, and batteries by 2030 [17]. Future material needs and supply concentration contribute to Supply Risk (SR), the likelihood of supply disruptions [12,13]. Policymakers are responding with initiatives like the EU Net-Zero Industry Act [18] and the U.S. Inflation Reduction Act [19], aimed at boosting domestic clean energy manufacturing.

SR linked to clean energy technologies should be included in energy system security assessments [20,21]. ES metrics support decision-making and can integrate with energy scenarios, often derived from Energy System Optimization Models (ESOMs) [22]. ESOMs test energy policies by identifying cost-effective system configurations over the medium to long term using detailed technology data [23]. However, ES studies face two key limitations. First, ES metrics often overlook SR in clean energy supply chains, missing trade-offs from increased technology adoption [10]. Second, ESOM applications rarely use comprehensive metrics, yielding partial evaluations of future energy systems. Modern ES extends beyond securing fuel access, addressing broader challenges [6]. A multi-dimensional approach is thus essential to tackle diverse ES issues [24].

Most methodologies for evaluating ES use a metric-based approach [25], with proposed metrics analyzing ES as an interconnected concept [26]. Definitions of ES vary: the International Energy Agency defines it as the “uninterrupted availability of energy sources at an affordable price” [27], while [28] emphasizes reliability, recovery from shocks, and minimal supply disruptions. Defining ES universally is challenging due to its multi-dimensional nature [24]. A broad interpretation as the “low probability of damage to acquired values” is applied to energy systems in Ref. [29]. Three ES perspectives – sovereignty, robustness, and resilience – are discussed in Ref. [6]. The “Four As of ES” (Availability, Accessibility, Affordability, Acceptability) from Ref. [24] serve as a foundational framework, as noted in Ref. [30]. Recent studies highlight the need for numerical ES assessments to aid policymaking. For example [25], defines five key dimensions: availability, affordability, technology development, sustainability, and regulation. These dimensions, captured through various indicators, aggregate into an Energy Security Index (ESI) or ES metric [8]. ES also depends on energy system structure, described as “low vulnerability of vital energy systems” [26], where vulnerability combines risk and resilience [29].

Most of existing studies encompass indicators that account for the SR associated with the fossil fuels supply only [29], assigning the risk of supply disruption exclusively to energy supply [22,31]. SR may include supply concentration, political stability, and import reliance factors [13]. These factors can be considered separately or aggregated into a composite SR indicator. On the other hand, the effects that clean energy technologies may have on the security of energy systems are still not considered in the SR [10,32]. Low-emission technologies are typically assessed only in the security of electric grids, considering indicator as capacity factor (CF) [33] or the share of renewable energy consumption [34]. Instead, some studies consider SR indicators also for low-emission technologies. The first group of studies compares the potential materials requirement associated with the energy transition to current geological availability, considering this as a SR proxy. For instance, this is done for: specific materials, like lithium, cobalt, and rare earth elements [21]; single technologies, like wind turbines [35,36], and electric vehicles [37,38]; entire sectors as in Refs. [15,39,40,41]. Then, a second group of studies considers SR indicators like the ones adopted for fossil fuels, which are typically used in materials criticality assessments [12]. Building upon these indicators (i.e., supply concentration, import reliance), a few studies estimate future risks associated with CRMs required for the energy transition [42,43,44]. For instance, the authors of [45] examines the impact of the Chinese transport electrification on the lithium supply chain concentration. Instead, other studies consider more composite SR indicators and focus on single materials [46] or technologies (e.g., solar PV [47], cars [48] and wind turbines [49,50]). Then, a similar composite SR indicator is evaluated along the whole technologies supply chain to assess current and future risks both at EU [13] and global level [51]. Finally, the SR of single materials are aggregated at technology level in Ref. [52], developing a technology SR which is then applied to European energy scenarios in Refs. [53,54]. However, the existing literature focuses on single materials or technologies, without providing broader insights on the energy systems security evolution. To address this weakness, preliminary attempts to incorporate materials and technologies SR in ES indexes are presented in Refs. [10,32]. The former proposes a security index encompassing indicators for materials internal reliability (IR) and political stability of supplier countries, in addition to more traditional measures of reliability and shortage risk. Then, the index is included in a more comprehensive sustainability metric, which is applied to Italian decarbonization scenarios. Instead, the authors of [32] evaluate SR for both materials and energy commodities using a multi-objective energy system optimization approach. However, both the studies lack a comprehensive evaluation, focusing on single or few security aspects.

Lastly, the studies that evaluate ES through ESOMs encompass different metric definitions. For instance, in Ref. [55] the ES evaluation is endogenously integrated into ESOM by evaluating the fraction of electricity demand satisfied by renewable sources. This methodology encompasses the definition of a renewable energy security index. Instead, the study presented in Ref. [56] connects the model results with an ESI encompassing a simple taxonomy, which only considers the diversification of energy sources. A simple ESI definition produces more interpretable results at the expense of other crucial ES aspects. For this reason, other studies (e.g., Refs. [57,58,59]) consider metrics composed by a broad set of indicators, which are then connected with the model outcomes. However, none of the existing studies incorporate a comprehensive definition of SR.

To address the aforementioned research gaps, this paper proposes an ES metric to study the impact of potential materials supply chain bottlenecks on future energy systems, aiming at:

- Developing a suitable indicator to assess material supply risk of energy technologies.
- Integrating the SR indicator in a comprehensive ES metric accounting for several security dimensions.
- Applying the developed ES metric to materials supply disruptions scenarios to generate policy-relevant insights on the security of decarbonized energy systems.

The Italian energy system serves as a case study. With a net energy import of nearly 84 % in 2022 [2], Italy is one of the EU's largest energy importers [60]. Recent ES objectives focus on diversifying and reducing imports and enhancing grid stability, a key measure tied to the increasing adoption of clean energy technologies [61]. The lack of low-carbon baseload generation (e.g., nuclear) accelerates Italy's investments in variable renewables like solar PV and wind, alongside higher battery storage needs, especially with end-use electrification (e.g., EVs). However, discussions on potential supply chain bottlenecks and material needs for these technologies are limited. Italy's first CRM-specific law offers only a preliminary framework with respect to other countries worldwide [17] and do not account for specific measures and targets considering the energy transition [62], thus making the Italian case study valuable for such an analysis.

The ES metric definition is provided in Section 2, while the Italian case-study and the adopted disruption scenarios are described in Section 3. Then, results are presented and discussed in Section 4.1. Lastly, Section 6 concludes the work.

2. The energy security metric

The ES metric proposed in this work encompasses the dimensions and associated indicators reported in Table 1. They are chosen to consider the potential risks associated with both external and internal factors and how they impact the energy system [63]. The Material Supply Risk (MSR) dimension accounts for the potential materials supply chain disruption. Instead, the risks associated with the diversification of the primary energy supply, the renewable energy fraction, and the import dependence, are included in the Energy Supply Risk (ESR) dimensions. Both MSR and ESR consider external threats, since they are associated with the energy system supply chains until the primary energy supply [63]. Conversely, the IR accounts for the impacts on ES of the energy system internal consumptions and configuration, by considering the end-uses energy efficiency, and the continuity and adequacy of the electricity generation mix. While the MSR dimension represents a novelty compared to the existing literature, the other dimensions and indicators are considered building upon the well-established ES metrics extensively presented in the supplementary material.

Table 1
Selected ES dimensions, indicators, their qualitative description and the related references.

Dimension	Indicator	Description	References
Material supply risk (MSR)	Material Supply Risk (MSR)	Risk of materials supply chain disruption	[52,53,54,64]
Energy supply risk (ESR)	Renewable Energy Supply (RES)	Fraction of renewable energy supply to the system	[8,65,66]
	Diversification of Energy Supply (DES)	Diversification of energy sources which supply the system	[56,66,67,68]
	Self-sufficiency (SS)	Fraction of energy domestically produced in the system	[24,57,58,68]
Internal reliability (IR)	Energy Intensity (EI)	Efficiency of energy consumption from the end use sectors	[24,58,69,70]
	Capacity Factor (CF)	Continuity in the energy supply	[71,72]
	Capacity Credit (CC)	Resource adequacy of the system	[70,73,74]

Fig. 1 shows the workflow of the methodology adopted to build the ESI. The selected indicators are defined building upon the results of scenarios derived from an ESOM. In particular, Material Supply Risk (MSR), Capacity Factor (CF), and Capacity Credit (CC) indicators are associated with the new installed capacity of technologies, while Renewable Energy Supply (RES), Diversification of Energy Supply (DES), Self Sufficiency (SS), and Energy Intensity (EI) with their activity. Capacity and activity are the decision variables of the linear programming problem typically solved within ESOMs framework. The former is defined as the nominal production capability as if the technology was continuously operated at full load (e.g., the nominal power of a power plant). On the other hand, the latter refers to the total flow of output commodities of a technology (e.g., the electricity production of power plants). For more details on their definitions in ESOMs, see e.g., Refs. [75,76]. Moreover, further parameters are needed to define some indicators. Some parameters are among the input data characterizing the energy system under analysis, as in the case of CF, CC, and EI. Instead, others are taken from third party databases, such as for MSR. The supplementary material presents the indicators related to the MSR, ESR, and IR dimensions.

The composition of the overall ESI requires then the normalization of the indicators and a proper aggregation, as discussed in Refs. [32,77]. The normalization procedure, the weight assignment, and the aggregation method are explained in the supplementary material.

3. Scenarios definition

The objective of the scenarios modeled in this work is investigating the effects that potential materials supply chain disruptions may have on the security of the Italian energy system, especially in the condition of a net-zero emissions target. Indeed, the constraints imposed to the model refer to the total CO2 emissions and the materials supply. Fig. 2 schematically represents the various scenarios and their main features. The first branch concerns the possible application of a CO2 emissions constraint. Then, the second branch considers whether a material supply disruption constraint is imposed. In this regard, the disruption factors and the corresponding maximum availability in unit mass are shown by material and by main suppliers (i.e., countries providing at least the 50 % of global mining or processing).

The Business-As-Usual (BAU) scenario is modeled only considering technical constraints that guarantee the model calibration and the future evolution of the energy system according to the minimum cost criterion. On the other hand, the Net-Zero Emissions (NZE) scenario encompasses a set of constraints on the total CO2 emissions of the system (extensively analyzed in Refs. [78,79]). The outcomes of the European Commission Fit for 55 package [80] are taken as reference for the 2030 emission reduction target, while the constraint imposed to reach the carbon neutrality in 2050 is derived from the long-term Italian strategy on greenhouse gasses emission reduction [81].

A set of materials supply disruption scenarios are defined considering the effects of potential material shortages on both short- and long-term investments in the energy system [82,83], especially concerning clean energy technologies. The material shortages are evaluated by applying

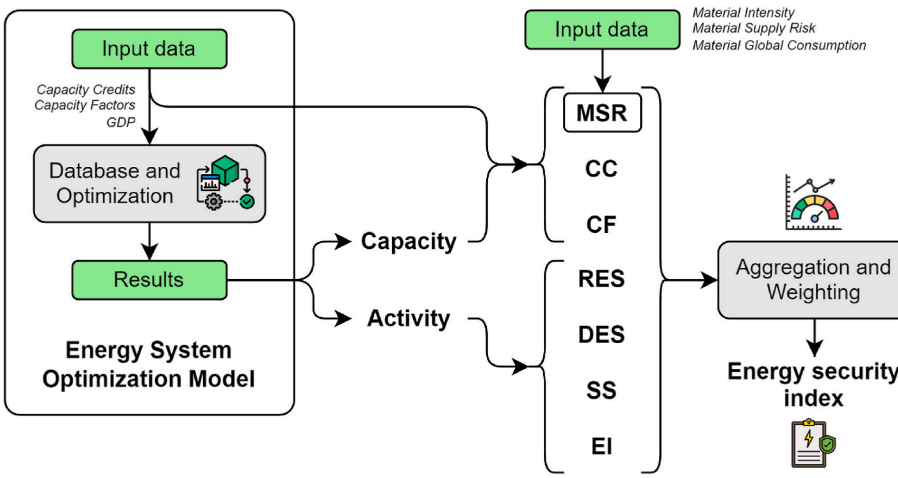

Fig. 1. Computational flowchart representing the connection between the ESOM input and output data, the ES indicators, and how they are aggregated to evaluate the ESI. The indicators composing the ESI are the Material Supply Risk (MSR), the Capacity Factor (CF), the Capacity Credit (CC), the Renewable Energy Supply (RES), the Diversification of Energy Supply (DES), the Self Sufficiency (SS), and the Energy Intensity (EI).

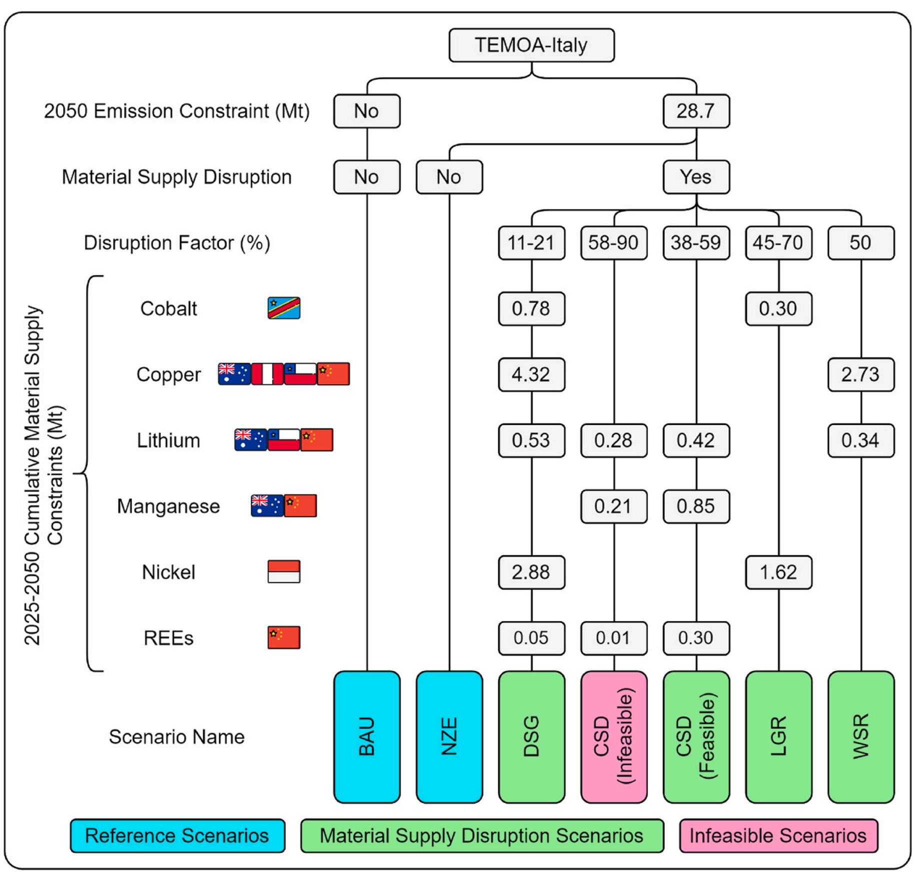

Fig. 2. Schematic representation of the analyzed scenarios and their features. The first branch considers the possible introduction of CO2 emission constraint. Instead, the second one distinction refers to the assumptions on the material supply disruption. In this regard, the range of disruption factors applied to the materials involved is reported at the beginning of each branch. In addition, the maximum availability is reported by material and main supplier countries.

disruption factors to the cumulative materials demand (from 2025 to 2050) of the NZE scenario.

The **Demand-Supply Gap (DSG) scenario** considers that a strong demand growth of renewable sources is not adequately supported by an equivalent scaling up of the mining industry investments [51]. Indeed, despite materials reserves and resources are sufficient to meet the growing demand due to the energy transition [84], possible bottlenecks on the CRMs supply-chains might occur if the demand growth outpaces the industry expectation [15]. The constraints applied to the model are derived from the analysis conducted by Ref. [15], which provides a range of materials supply-demand unbalance for alternative scenarios. Among them, the “achievement commitments” scenario is considered, which encompasses the operating mines and projects under construction, together with projects for which a feasibility study has been conducted or is currently ongoing. Considering that [15] envisages a time horizon up to 2030, when a higher disparity between demand and supply is expected with respect to the improved adequacy foreseen for the 2030–2050 period [41], the lowest values of the supply-demand balance range are taken. These disruption factors are reported in Table 2 and affect the supply of cobalt, copper, lithium, nickel and rare earth elements (REEs) (i.e., dysprosium, terbium, neodymium and praseodymium).

The current mineral industrial conditions may pose strong uncertainties in the future market perspectives for scenarios facing the decarbonization of the energy system. The higher request of clean energy technologies can further boost a concentration of the market toward China [11,83], resulting in a dramatic market uncertainty and price peak volatility. The growing CRMs demand can also lead to export restrictions affecting developing countries that account for most materials reserves and processing. All these factors are considered in the **Chinese Supply Disruption (CSD) scenario**, which investigates the implications of a complete supply disruption from China. As pointed out in Fig. 2, this disruption leads to an infeasible scenario, making the decarbonization of the energy system impossible. In this regard, the maximum acceptable material disruption factor that allows the system decarbonization is investigated, resulting in a maximum of 65 % of supply disruption from China.

The mineral industries are mainly concentrated in regions categorized as either extremely unstable or unstable in the Worldwide Governance Indicators [84]. In particular, the nickel and cobalt supply chains are concentrated in regions with a significant governance instability [11]. Today, Indonesia and the Republic Democratic of Conge represent the main suppliers of nickel (50 %) and cobalt (70 %), respectively [83]. The **Low Governance Region (LGR) scenario** investigates the possibility of a complete disruption of nickel and cobalt from such regions.

Lastly, the **Water Stress Region (WSR) scenario** encompasses the potential effects of climate change on materials supply. In particular, the water needed in mining and processing of critical minerals is often very high, especially for lithium and copper mining [51]. For instance, more than 50 % of lithium and copper production is concentrated in areas of high or extremely high-water stress, such as Chile and China [11]. The WSR scenario investigates the disruption of copper and lithium, considering a reduction of 50 % in the global supply.

Table 2 reports the disruption factors implemented to model the discussed disruption scenarios. Such factors assume that the disruption at global level affects the Italian supply with the same percentage, being Italy a region without many mineral resources and heavily dependent on imports [85].

Table 2
Material supply disruption factors for different scenarios and materials.

Scenario	Infeasibility	Material	Disruption factor (%)
DSG		Cobalt	21
		Copper	21
		Dysprosium	50
		Lithium	21
		Neodymium	21
		Nickel	11
		Terbium	50
		Praseodymium	21
CSD	X	Dysprosium	90
		Lithium	58
		Manganese	90
		Neodymium	85
		Dysprosium	59
		Lithium	38
		Manganese	59
		Neodymium	55
LGR		Cobalt	70
		Nickel	45
WSR		Copper	50
		Lithium	50

4. The Italian case study

The TEMOA-Italy version used for this work, including the technologies material intensity, is available at [86], based on the TEMOA version available at [87].

TEMOA is an ESOM that allows to build complex model instances modeling both sectors devoted to energy primary supply, transformation processes, and end-use sectors. The representation of the modeled energy system is based on the construction of a network of technologies and commodities, representing existing and future processes and material, energy, and greenhouse gasses emissions flows, respectively [88]. The model aims at minimizing the total economic cost of the system over long-time horizons (e.g., up to 2050), producing the optimal feasible evolution of the system in the investigated future scenarios, represented by alternative sets of model inputs. TEMOA is mainly oriented to capacity expansion and investments, although it also includes items to model the operation of technologies over shorter time steps than the annual one. For these reasons, it is particularly suited for evaluating the possible future consumption of CRMs for energy system technologies due to new capacity deployment.

TEMOA-Italy is a model instance focused on the representation of the Italian energy system, as accurately described in Ref. [89]. The supply-side of the system encompasses the upstream sector (see Ref. [90] for more details) and the power and heat production one (see Ref. [91] for more details). The model includes technology modules for hydrogen production, as reported in Refs. [92,93], as well as carbon, capture, utilization, and storage options (see Refs. [78,79]). On the other hand, the demand-side encompasses the agriculture, residential and commercial buildings, transport, and the industrial sectors aimed to satisfy the end-uses. The transport and power sectors are the main subject of this analysis, since the materials consumption due to hydrogen production technologies turned out to be negligible in the considered scenarios [94]. The power sector encompasses a broad distribution of supply sources (e.g. fossil fuels, biofuels, renewables, and hydrogen) to the power plants, cogeneration heat and power plants, and pure heat plants. Subsequently, these plants produce intermediate commodities such as electricity and heat. The structure of the transport sector is based on two main transport categories, namely road and non-road transport. Each of these categories encompasses different sub-sectors that must satisfy the associated final service demands, projected according to Ref. [95]. The focus of this analysis is on road transport, specifically on cars [96,97].

4.1. Energy security indicators

As pointed out in Section 2, some indicators are defined by considering parameters in addition to the model results about technologies capacity and activity.

The evaluation of MSR relies on many data. The complete set of data and assumptions are available in Ref. [94] and in the supplementary material of this article. Firstly, CRMs considered critical for the EU economy were included, given the lack of specific studies for Italy. The single materials SR_i are obtained from the latest study on CRMs conducted by the European Joint Research Center [16]. Then, the specific consumption $f_{i,t}$ encompasses four groups of technologies: power, storage, hydrogen, and transport technologies. Table 3 reports the involved technologies, showing also the data sources used in the evaluation of the technology specific material consumption [94].

Lastly, the global material consumption c_i referring to the 2023 values is used as normalization factor [13] (see the supplementary material). As a first hypothesis, the share of global consumption is considered constant over the entire 2025–2050 period. This assumption and its effects on the MSR are extensively investigated in Refs. [94,109], which points out that more consistent results on the MSR analysis are

Table 3
Technology groups and technologies considered for material consumption and their data sources.

Technology group	Technologies	Data sources
Traditional power technologies	Coal and gas power plants	[39,98,99]
Low carbon power technologies	Solar PV, wind onshore, wind offshore, hydropower, bioenergy, geothermal, coal and gas with CCS	[11,21,39,41,42,52,98,99]
Storage technologies	LIBs and VRFBs	[11,51,99,100,101,102,103,104,105,106]
Hydrogen technologies	ALKEC, PEMFC, SOEC, SOFC	[11,99,105]
Transport technologies (cars)	ICEs, FHEVs, BEVs, FCVs	[11,21,42,107,108]

obtained when applying the same disruption factors (see Section 3) also to global material consumptions c_i.

Fig. 3 graphically represents the SR_t of the various technologies expressed in a logarithmic scale. In Fig. 3a, the values for power plants and storage technologies are reported, in which the higher SR_t values are reached by wind technologies. The latter present huge consumption of REEs which are almost entirely supplied to EU by China. In the power sector, also geothermal technologies show a high SR_t due to the high consumption of chromium and nickel alloys and this is in accordance to the outcomes of [54]. On the other hand, both the storage technologies, lithium-ion batteries (LIBs), and vanadium-redox-flow batteries (VRFBs) present high values of SR_t. For the LIBs this is due to the consumption of CRMs such as cobalt, graphite, lithium and manganese, while in the VRFBs the SR_t is mainly influenced by the vanadium, presenting a $f_{i,t}$ equal to 2.03E+04 kg/MW and a SR_i equal to 2.3 (see the supplementary material). It should be noted how the SR_t vary on a range of values covering several orders of magnitude, due to the different material intensities and SRs.

The low carbon vehicles present much higher SR_t values than the traditional ones (see Fig. 3b). Similarly to wind technologies, BEVs consume important quantities of REEs in the electric motors, in addition to the CRMs consumed in the batteries. Instead, the fuel cell vehicles (FCVs) encompassed higher consumption of vanadium and yttrium. Full hybrid electric vehicles (FHEVs) consume less CRMs than the other low carbon vehicles, leading to a SR_t 2.5 times lower than BEVs. Note that plug-in hybrid electric vehicles and their CRMs consumption are not considered in the technology inventory of TEMOA-Italy. Proton exchange membrane electrolyzer (PEMEC) shows the highest value of SR_t in the hydrogen sector, due to the platinum group metals consumption. Then, the SR_t of the solid oxide electrolyzer (SOEC) is mainly influenced by the yttrium consumption, while the alkaline electrolyzer (ALKEC)

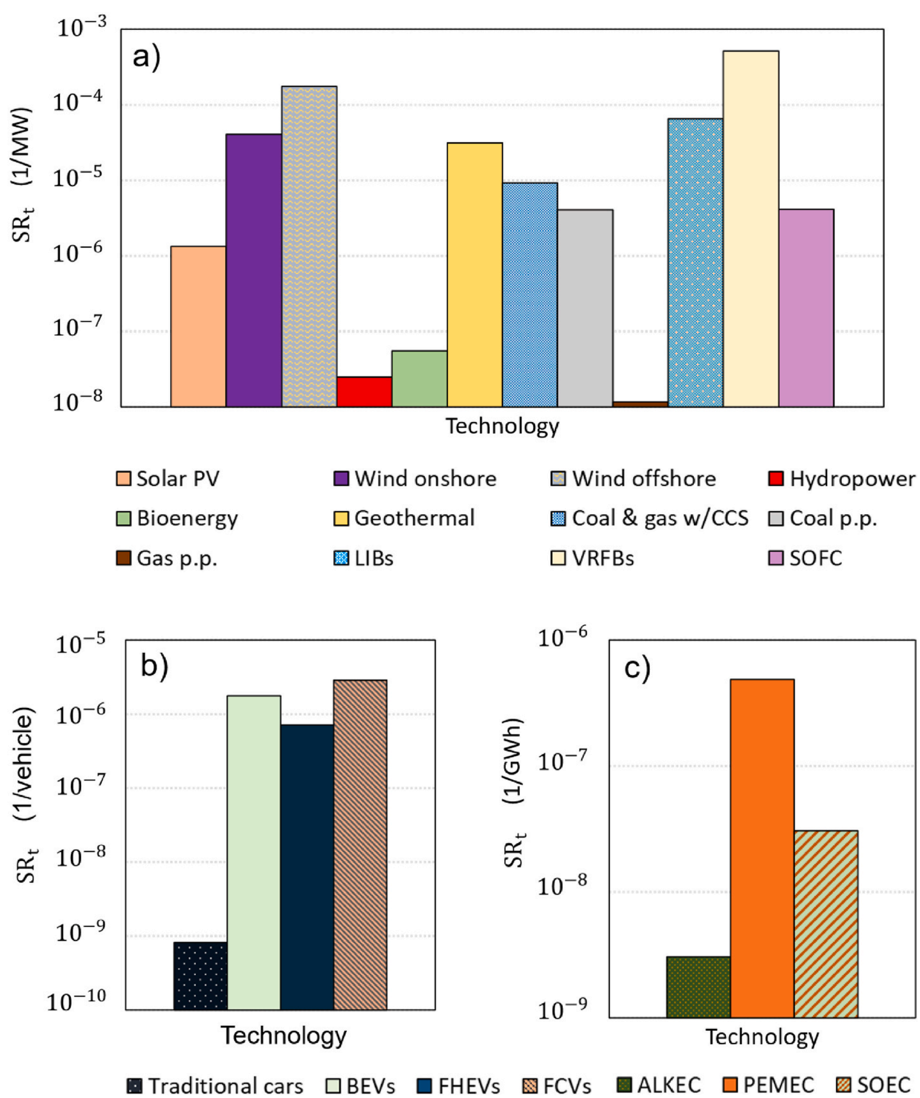

Fig. 3. Graphical representation of the SR_t for the power and storage sectors (a), transport sector (b) and hydrogen (electrolyzer) sector (c).

represents the hydrogen technology consuming the lowest amount of CRMs.

The EI indicator is evaluated as the ratio between the total energy consumed by the end-use sectors and the GDP of the country. The latter is typically used to project some of the final service demands modeled in ESOMs [95]. In Ref. [94] the values of GDP imposed to the TEMOA-Italy model are compared with the values provided by the World Bank historical data [110], observing a converging trend in the closer years. The observed convergence leads to greater reliability to the future GDP values applied to the model. Indeed, for the sake of the analysis coherence, the future evolution of EI indicator involves the GDP values introduced in the model.

Similarly to the GDP, also the technologies capacity factors and credits are input parameters for the model. As discussed in the supplementary material, these parameters are used to define the CF and CC indicators, which refer to the reliability of the electricity grid. Hence, only power sector technologies are considered. Table 4 reports average capacity factor and credit for the technology groups taken from Ref. [111].

5. Results and discussion

The results presented in this section concern the energy system composition, the ES of the system, and the material consumption in the different scenarios. Lastly, the costs of security are also analyzed.

Fig. 4 represents the computed TPES in the BAU and NZE scenarios. The reducing trend observed in the decarbonization scenario is due to an increase in the electrification of end-uses and in the efficiency of demand-side technologies. The NZE scenario shows a significant reduction in the natural gas supply, while the penetration of biogas is increasing. This trend is also observed in the materials supply disruption scenarios, which include the same decarbonization targets as the NZE. Indeed, the TPES composition does not significantly vary with respect to NZE.

Fig. 5 shows the sectorial energy and technology mixes computed in 2050 across the studied scenarios. The composition of the power sector is similar between the different decarbonization scenarios, as shown in Fig. 5a. The power mix presents a strong penetration of solar, wind, and hydropower technologies, at the expense of natural gas plants, which are the main electricity sources of the BAU [94]. Power production technologies require materials which are less threatened by supply chain disruptions than other sectors and this leads to few technological variations across the decarbonization scenarios. Indeed, in such scenarios the composition of the power sector is mainly driven by the emission constraint application, while the constraints on the availability of CRMs mainly affect cars, which are more material intensive. The only relevant difference refers to the electrification level, which is much higher in the NZE scenario, almost 20 % more than BAU in 2050 (see Fig. 5a), due to higher BEVs penetration as depicted in Fig. 5b. Fig. 5a also shows the storage usage. LIBs represent the main solution in all the scenarios, reaching the peak in the DSG with 19 GW of storage capacity installed. On the other hand, the LIBs penetration in CSD and WSR scenarios is quite reduced, because of the much stricter constraints on lithium supply. This condition leads to the penetration of VRFBs as storage alternative.

Fig. 5b shows the computed technology mix satisfying the cars transport demand. The BAU mix is completely dominated by traditional vehicles, mainly composed of gasoline, diesel, NGA, and LPG cars, while BEVs satisfy the whole demand in the NZE scenario. On the other hand, the material supply disruption scenarios encompass a more diversified portfolio, especially in the WSR scenario. The latter is characterized by strong constraints on lithium and copper supply. These materials are hugely consumed in batteries, leading to different alternatives, such as

Table 4
Average capacity factor and credit of the TEMOA-Italy power sector technology groups.

Technology Group	Average CF	Average CC
Bioenergy	≈0.60	≈0.60
Coal	0.76	1.00
Geothermal	0.88	1.00
Hydroelectric	≈0.23	0.50
Hydrogen	0.90	1.00
Natural Gas	≈0.90	1.00
Oil	0.85	1.00
Solar PV	≈0.23	≈0.20
Wind	≈0.17	≈0.30
LIBs		0.70
VRFBs		0.70

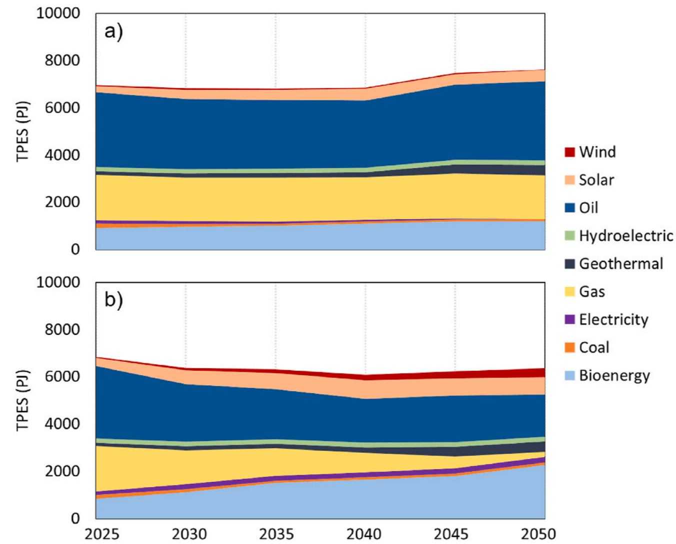

Fig. 4. Computed TPES for BAU (a) and NZE (b) scenarios.

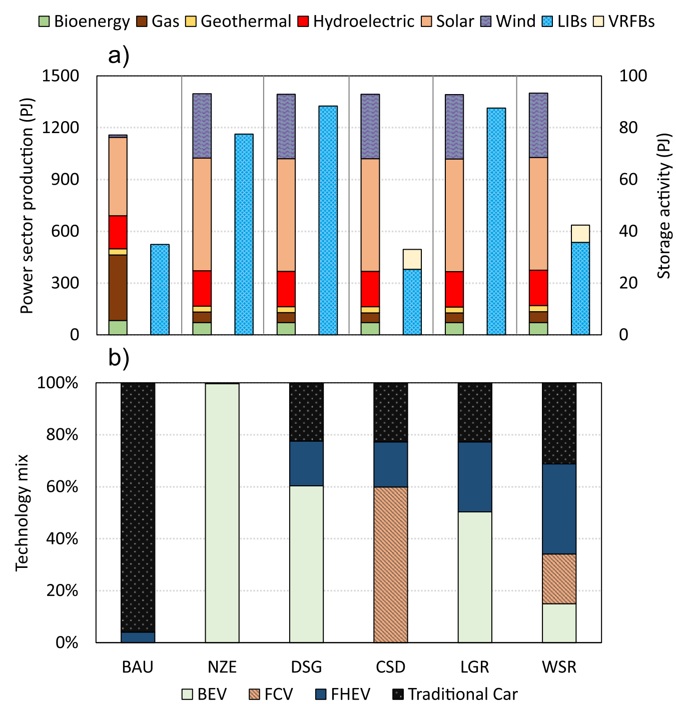

Fig. 5. Power sector electricity production (left-y axis) and storage activity (right-y axis) (a) and cars technology mix (b) computed in 2050 across the different scenarios.

FCVs and FHEVs, less dependent on these CRMs. Similarly, the CSD scenario presents a much higher introduction of FCVs. Indeed, the REEs constraints involved mainly the materials consumed in electric motors, which are not present in FCVs. The penetration of traditional vehicles also in the low emission scenarios is related to an increase in the consumption of biodiesel, which in 2050 reaches 30 % of the whole diesel consumption by cars.

The materials disruption constraints influence the technological mixes which affect, in turn, the amount and type of consumed materials. In this regard, Fig. 6 shows the cumulated materials consumption from 2025 to 2050 by specific materials across the scenarios. The least materials consumption is associated with the BAU scenario, being its energy system based on traditional and less material intensive technologies. In particular, the BAU demand is on average 1.3 times lower than the one of the decarbonization scenarios. This is in line with other studies such as [11,13], and [112]. Then, the overall materials consumption across the decarbonization scenarios is between 3 and 5 Mt in the power and storage sectors (see Fig. 6a), while cars require much more materials (see Fig. 6b). In particular, the NZE scenario reports the highest value of cars cumulative consumption, exceeding 16 Mt. This is related to the strong penetration of BEVs, which present higher material intensities with respect to other vehicles. This points out that the higher the diversification, the lower the materials consumption across the disruption scenarios.

Focusing on the single materials, the demand for aluminum and copper roughly covers 70 % of the total demand in the power and storage sectors. Instead, their demand of lithium and cobalt, for the decarbonization scenarios, is much lower than in the transport sector (see Fig. 6b). This is because such scenarios encompass a strong penetration of electric vehicles, whose batteries require high amounts of lithium and cobalt. In particular, the average cars lithium and cobalt consumptions across the decarbonization scenarios are, respectively,

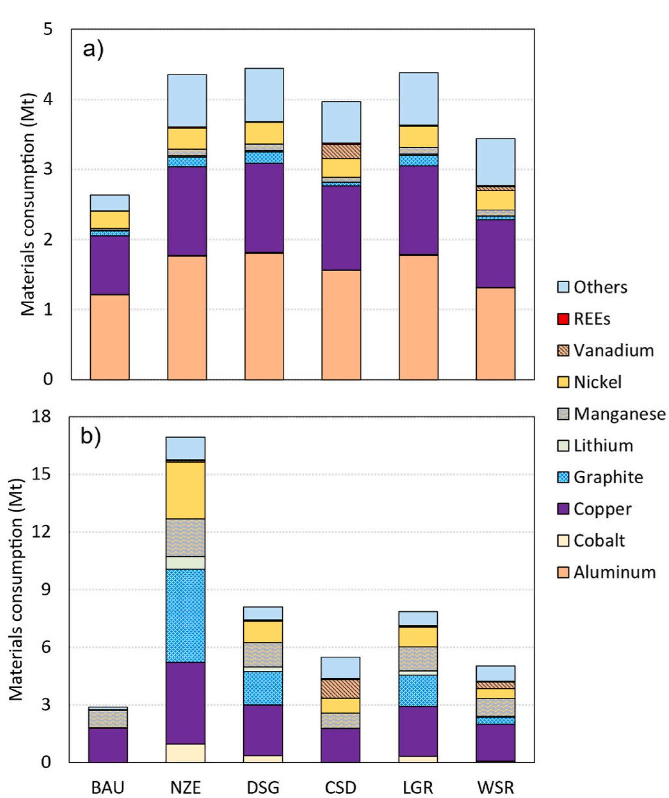

Fig. 6. Cumulated (from 2025 to 2050) material consumption for specific minerals in the different scenarios, for power and storage sector (a) and transport sector (b). "Others" refers to materials whose consumption is on average less than 15 % of the total consumption.

sixteen and thirty times higher than in the power sector. Moreover, the introduction of low emission vehicles also induces higher consumption of REEs. Being these CRMs subjected to strict constraints and highly consumed by BEVs, the cars technology mix is strongly influenced by the related supply constraints. In this regard, the average REEs demand by cars across the decarbonization scenarios is almost four times than in the power and storage sectors, with an average value of 52 kt. Lastly, the growing material demand in the different decarbonization scenarios is led by the low-emitting vehicles and storage technologies, representing averagely the 73 % of the entire mineral consumption in 2050. This result follows the trends observed by International Energy Agency [11], where the storage technologies and BEVs are responsible of almost half of the material consumption growth in 2040, becoming even more dominant in 2050 [112].

The ES indicators evolution from 2025 to 2050 is shown in Fig. 7. For the MSR (see Fig. 7a) the risk levels in the decarbonization scenarios are much higher than the BAU. This fact is strongly related to the penetration of clean energy technologies, especially low emitting vehicles. In the NZE scenario the BEVs progressively penetrate in the system, resulting in a higher average MSR. Instead, in the materials supply disruption scenarios the installation of low emitting vehicles is softened up to 2035, reaching higher peaks in the CSD and DSG in 2050. The RES and SS indicators are reported in Fig. 7b and c, respectively. They present similar evolution trends in the decarbonizations scenarios, due to the strong introduction of low-carbon sources, while in BAU a relevant fraction of TPES is covered by gas imports. A similar consideration can be done for the DES and EI indicators (see Fig. 7d and e). Concerning the DES, the high natural gas supply observed in BAU is substituted by renewable sources in the low emission scenarios, especially biogas. The penetration of different renewable sources leads to an increment in the DES. On the other hand, the EI of the system is quite reduced in the decarbonization scenarios. This is due to the higher electrification of the end-uses, with the consequent enhancement in energy efficiency with respect to BAU. As for the MSR, the reduction in the EI of the system involves an increase in the final ES. Finally, Fig. 7f and g shows the CF and CC evolutions. Being the technological composition of the power sector similar, CF and CC present similar trends across the decarbonization scenarios. The latter indicators are strongly related to the power sector structure, where a high penetration of variable renewable sources, as in the case of the decarbonization scenarios, significantly reduces the internal system reliability.

Fig. 8a shows the time evolution of the ESI, assigning equal weights to the Material Supply Risk, Energy Supply Risk, and Internal Reliability dimensions, as reported in the supplementary material. The applied aggregation method results in an ESI more sensible to the variation of the MSR indicator, producing the relevant reduction observed in the last part of the time horizon, in accordance with Fig. 8a. On the other hand, in Fig. 8b the average values of the ESI are reported for the different scenarios, offering an overview of the ES for the entire time horizon. Fig. 8b also shows that averagely the MSR indicator exhibits the greatest variability among the scenarios, while the other indicators remain relatively constant.

Considering an ESI ideal maximum value of 1, the NZE scenario provides the average lower value of security, slightly greater than 0.5, due to the strong penetration of BEVs which increases the MSR. On the other hand, the highest value of security is reached in the WSR scenario (0.62), whose energy system encompasses the penetration of both storage technology available and a well-diversified transport sector. On the contrary, BAU is based on more traditional technologies, relying less on CRMs and resulting in a high level of ES. Additionally, Fig. 8 shows that the ES level is slightly changing among the considered scenarios. Most of the indicators depend on the TPES and power sector mixes, whose compositions are roughly unchanged in the material supply disruption scenarios. Indeed, the RES, SS and DES indicators are connected to the TPES of the system. Being the latter subject to strict limitation on CO2 emission, the system is forced to select a combination of

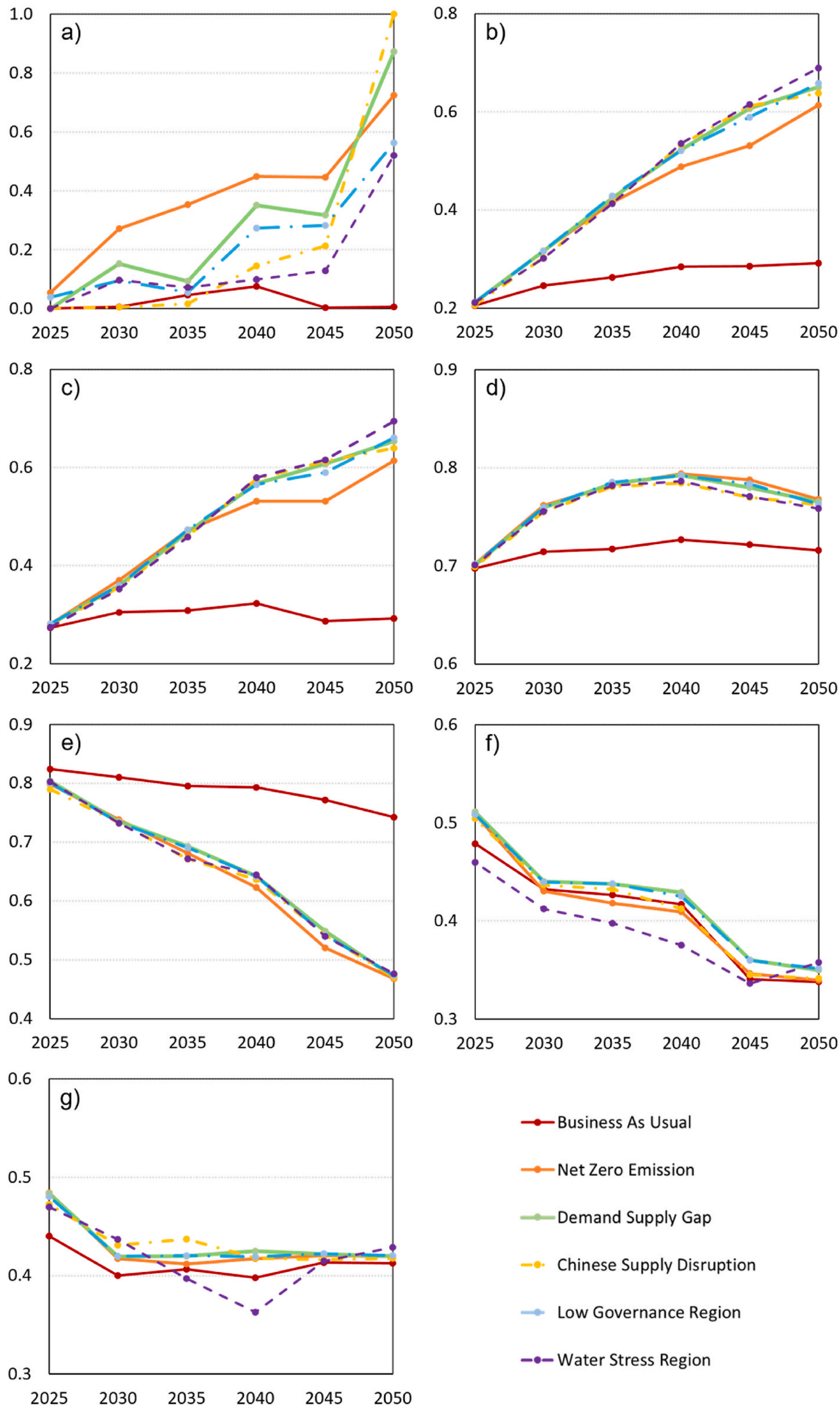

Fig. 7. Time evolution of the ES indicators: Material Supply Risk (a), Renewable Energy Supply (b), Self-sufficiency (c), Diversification of Energy Supply (d), Energy Intensity (e), Capacity Factor (f), Capacity Credit (g).

low emitting primary energy sources, producing a similar TPES in the low emission scenarios. On the other hand, the CC and CF indicators depend on the power sector mixes. Considering the constraint on the emission, the model operates to decarbonize firstly the power sector, producing similar technology mixes (see Fig. 5a) and resulting also in low variations in the CC and CF of the system. While the MSR is the only indicator inducing a significant variation in the ES level (see Fig. 7a). The small variation in most of the indicators results then in an attenuated variation of the average ESI.

Fig. 9 reports the cumulated MSR from 2025 to 2050 for the considered scenarios. The MSR values are normalized with respect to the BAU to show the increment in the decarbonization scenarios compared to the most conservative condition (BAU). In the power and storage sectors (see Fig. 9a) the CSD scenario shows the highest value of MSR,

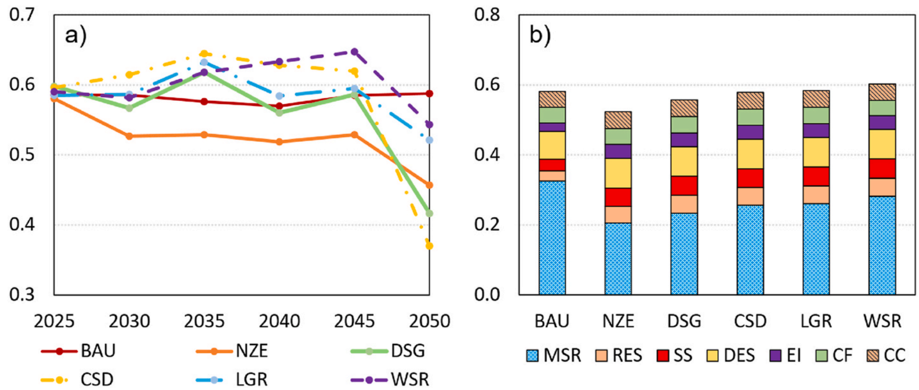

Fig. 8. ESI time evolution (a) and average ESI over the entire time period 2025–2050 (b) for the different scenarios analyzed in the papers.

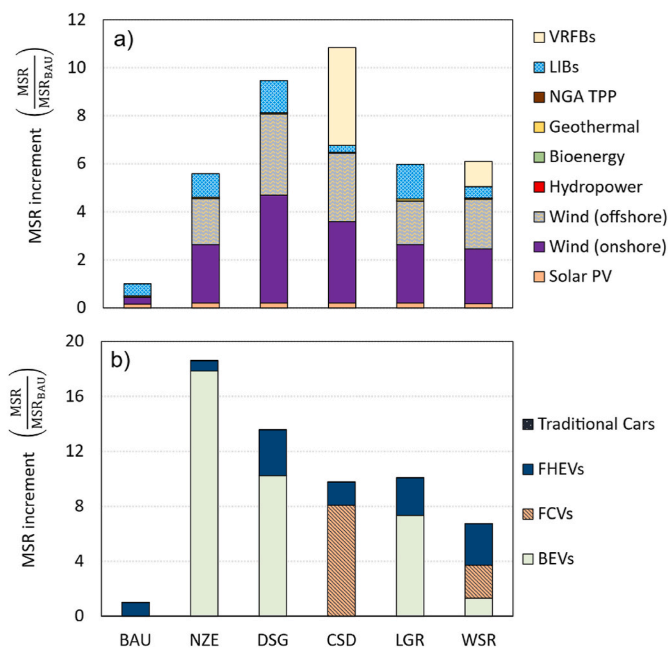

Fig. 9. MSR increment in the power and storage sector (a) and transport sector (b).

where the highest contribution is provided by the VRFBs. While in all the decarbonization scenarios the wind technologies cover always a predominant role, mainly due to the presence of REEs in the permanent magnets of the turbines. On the other hand, the highest value of MSR in the transport rector (see Fig. 9b) is reached by the NZE scenario, due to the highest penetration of BEVs across the decarbonization scenarios. As observed in Fig. 3, the BEVs SR_t is slightly lower than FCVs ones, but their use in the NZE energy system makes the MSR much higher than in the other decarbonization scenarios.

While the aggregated material consumption in CSD scenario is roughly 10 Mt and in LGR scenario exceeds 12 Mt (see Fig. 6), the LGR MSR is lower than the CSD one. This result demonstrates that a higher material consumption is not directly correlated with a higher level of MSR, which is consistent with the technology SR normalization by global material consumption, as discussed in the supplementary material. The latter prevents to lose information about the SR_i of the single material, such as the supply concentration and political instability. This happens when the specific material consumptions are particularly high, such as for copper and graphite, hiding the risk related to more critical materials like REEs.

Fig. 10 represents the system MSR. The main contribution (from 83

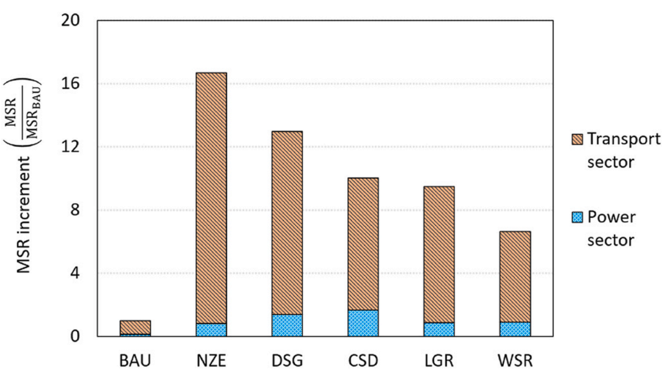

Fig. 10. Total MSR increment of the system.

% to 95 %) comes from the transport sector in all the decarbonization scenarios. This result suggests paying particular attention to the materials demand from low-emitting vehicles. In the materials supply disruption scenarios, the material consumption of power and storage sectors and transport sector (see Fig. 6) are almost comparable. On the contrary, as observed in Fig. 10, the transport sector covers always a much more dominant role in the system MSR than the other sectors. This highlights that this sector relies on a higher consumption of more critical materials, as shown in Fig. 6 (e.g., cobalt and lithium, which are mainly involved in electric batteries).

The last objective of this work is to provide an estimation of the ES cost. Fig. 11a reports the energy system cost expressed in billion euros (B€) and the respective level of ES. The BAU scenario represents the least-cost evolution of the system in the absence of the emission constraints and therefore it presents the lowest cost. Conversely, the decarbonization scenarios are subject to constraints, resulting in an energy system configuration different and more expansive than the BAU. In particular, the materials supply disruption scenarios are modeled considering the potential risk of material supply chain interruptions, providing safer energy system. In this regard, Fig. 11a shows also the regression line of cost and ES for all the scenarios except BAU, noticing that higher final system costs are associated with higher ES level. The slope of the line indicates the additional cost per security unit earned, which corresponds to approximately 8.7 B€/% of ES. This value represents the cost growth relative to the percentage increase in ES, with costs rising by approximately 130 B€ while ES increases by nearly 15 %.

As noted in Fig. 7, the MSR is the main indicator affecting ES and its variation is strongly correlated with the technology investments. In this regard, the cost analysis is performed also considering the MSR variation. The MSR values reported in Fig. 11b are normalized with respect to the NZE value, which is the maximum one. The regression line observed in Fig. 11b presents a ratio of 2.1 B€/% of reduced MSR, which

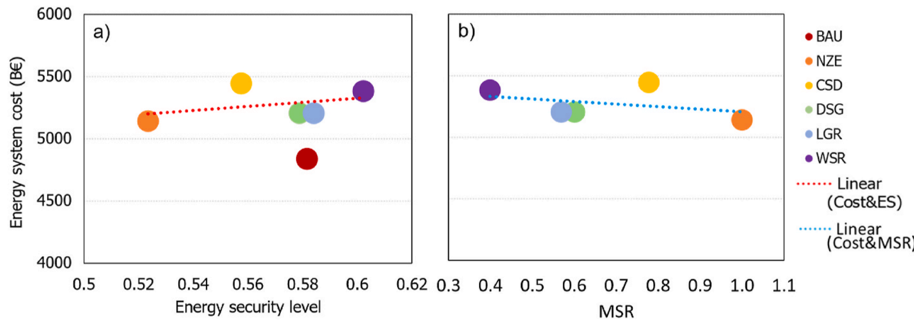

Fig. 11. Energy system cost correlation with the ES (a) and MSR (b), normalized with respect to the MSR associated with the NZE scenario.

corresponds to a reduction of 60 % in MSR and an increase of 130 B€ in the final cost.

5.1. Discussion

The transport sector is the main cause of MSR increment, as observed in Fig. 10, due to higher consumption of more critical materials than in the other sectors. In this regard, the BEVs represent the most efficient and material intensive solution, driving the demand for CRMs in the transport sector. Indeed, by limiting the supply of CRMs consumed from BEVs, such as lithium, REEs and others, the penetration of alternative technologies with higher cost but lower SR_t is observed. Considering a more diversified technology mix, the final cost of the system is expected to increase as reported in Fig. 11, suggesting that higher investments are required to reduce the MSR. Currently, different countries are developing policies focused on the penetration of more efficient and sustainable vehicles [113,114]. In this regard, policy makers can play an important role in defining energy policies aimed at increasing the diversification in the transport sector, incentivizing technologies that rely less on critical materials. While in the medium-to-long term, the reduction of the risk of supply chain disruptions can be achieved by developing an industry specialized in the efficient recycling of materials, reducing the dependency from CRMs import [115]. These measures can represent a first step in the mitigation of threats to ES, enhancing the resilience of the system.

The analysis conducted is subject to several sources of uncertainty which are not directly investigated in this work. Focusing on the methodology, the MSR only considers supply risks associated with the raw materials extraction and processing, while it ignores those related to components production and assembly, whose supply chains is highly concentrated in few and politically unstable countries [13,51]. Instead, DES only considers the diversification of the energy imports in terms of fuel, while it ignores the diversification in the supplier countries since the energy system model adopted does not include such a distinction. However, a high import reliance on a few countries implies higher risks for the ES, as the recent energy crisis highlighted with respect to the gas import from Russia in Europe [116]. In addition, the RES and SS indicators represents a partially overlapped information, as a higher share of renewables in the TPES implies a higher self-sufficiency. Thus, assigning equal weights to these indicators may outweigh the benefits associated with the deployment of renewables. Something similar may occur concerning the impacts of renewables on the power grid reliability, measured by the lower CFs and CCs. More in general, the sensitivity of the evaluated ESI on the adopted weights for the ES indicators and dimensions should be more broadly and rigorously investigated, for instance with a multi-criterial decision assessment, as done in Ref. [32].

To build the case study, many data and assumptions were needed. Although they were all made freely available, thereby improving reproducibility and transparency of the analysis, they represent a relevant source of uncertainty. In this regard, uncertainty analyses might be useful to evaluate how results are affected by input data, such as current and projected values of the parameters used to compute the ES indicators and the factors to build the materials disruption scenarios. Another uncertainty source lies behind the use of global or EU data for the Italian case study. This was primarily due to a lack of Italian devoted data. Concerning the EU data, the lack of current specificities for Italy and the existing legislative framework led us to not consider reasons why there should be different situations in terms of risk and availability of materials. Indeed, EU aims to tackle the CRMs issue through common strategies among the member states [117], while the Italian legislation in terms of CRMs is still not mature if compared to other countries [17]. Concerning material intensities, they does not include all the technologies consuming CRMs modeled in TEMOA-Italy. For instance, freight transport is not included in the materials consumption of the transport sector, which focuses on the CRMs for cars. Moreover, the adopted material intensities are evaluated based on the current features of technologies, ignoring possible material efficiency effects. At the same time, as discussed in Section 4.1, the future global consumption shares of materials are assumed to be equal to the current values, which may be not realistic and significantly influence the technologies SRs. Eventually, the studied scenarios only focus on possible CRMs supply disruption causes and do not consider, for instance, energy supply disruption scenarios or more in general other external issues that may affect the security of energy systems.

6. Conclusions and perspectives

This work presented an energy security metric to evaluate the impact of critical raw materials consumption due to low carbon technology deployment on the security of future energy systems. The considered ES dimensions are Material Supply Risk, Energy Supply Risk, and Internal Reliability. While the MSR is represented by a single indicator, the ESR is evaluated by combining the Renewable Energy Supply, Diversification of Energy Supply, and Self-sufficiency, and the IR includes the Energy Intensity, the Capacity Factor, and the Capacity Credit. The main novelty of the work is the inclusion of a MSR dimension in the ES metric. Indeed, the existing studies typically focus on the dependency on energy imports and the gird reliability issues due to renewables intermittence, without considering the potential bottlenecks associated with materials supply chains. The latter are accounted for by developing a suitable technology supply risk indicator.

The proposed metric is suitable to be applied to ESOMs and the case study investigated in this paper is the Italian energy system, through the TEMOA-Italy open model. The material intensity is considered for power plants, electricity storage technologies, hydrogen production options, and cars. Together with reference scenarios, alternative material disruption scenarios are investigated to assess the impact of possible causes of CRMs supply disruption on the security of the system. Such causes include supply bottlenecks, geopolitical risks, and water scarcity.

The results highlighted a significant impact of cars and electricity storage technologies on the system material consumption and MSR, negatively affecting the overall ESI, in the NZE scenario, which assumes an emissions reduction trajectory up to net zero in 2050. Indeed, the cars fleet is almost completely made of BEVs in the NZE scenarios, while a partial shift towards full hybrid electric vehicles and fuel cell vehicles occurs in the disruption scenarios, which consume less and less critical materials. Concerning the deployment of storage technologies, they are mostly affected by the Chinese Supply Disruption and Water Stress Region scenarios, assuming a partial supply disruption due to geopolitical reasons from China and due to water scarcity, respectively. This behavior is due to the strict constraint on the lithium supply.

Concerning the ESR and IR indicators, the shift from Business As Usual to the decarbonization scenarios improves the former, while the CF and the CC do not significantly change as the variations in the power sector technology mix are minor among the scenarios considered. The overall ESI significantly depends on the MSR in the studied scenarios, also due to the equal weights adopted for the three dimensions.

In perspective, a broader set of technologies with respect to that proposed here could be considered. This would lead to a more comprehensive MSR, for instance including the material intensity of trucks for freight transport. Moreover, the sensitivity of the ESI on the adopted weights for the different indicators may be explored with a multi criteria decision assessment. Finally, the proposed ES metric could be integrated in a ESOM to be evaluated endogenously and possibly in combination with advanced methodologies to improve the results significance, such as modelling to generate alternatives or multi-objective optimization.

CRediT authorship contribution statement

Alessio Vai: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gianvito Colucci:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Matteo Nicoli:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Laura Savoldi:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Data availability

The TEMOA modelling framework including the endogenous materials consumption extension is available at [87], while the Italian model adopted as a case study is available at [86].

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.mtener.2025.101805.

Data availability

Data are fully accessible as described in the Data availability section

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