Politecnico di Torino

Master’s Degree in Energy and Nuclear Engineering
A.Y. 2023/2024
Graduation Session July 2024

How may the availability of critical raw materials affect the deployment of material-intensive technologies and the security of energy systems?

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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 thesis proposes a metric to evaluate the security of energy systems under medium-to-long term energy scenarios generated by the energy system optimization model TEMOA-Italy. Such a metric consists of an index covering several dimensions of energy security, encompassing the security of energy supply and the internal reliability of the system. Among these dimensions, the inclusion of the supply risk of critical raw materials represents a novelty compared to the existing literature. It enables to account for the possible risks due to the disruption of the minerals supply chains. The latter are the focus of the scenario analysis performed through the TEMOA-Italy open-source model, after the definition of the energy security index. The developed scenarios encompass several geopolitical perspectives, by considering different constraints on the minerals' consumption. It results that the energy supply mix does not considerably change across the various scenarios. In the low-emissions scenarios, the main contribution from gas supply is replaced by renewable sources such as bioenergy, solar, and wind. Similarly, also the power sector composition is almost unchanged, resulting in a similar future trend for the indicators that mainly depend on its composition, such as CF and CC. In the analysis on energy security a higher weight is assigned to the materials supply risk indicator, which variation results in having more influence on the energy security index time evolution than the other indicators. The minerals consumption in the different scenarios is also evaluated, analyzing how the latter can affect the materials supply risk. The highest consumption occurs for the net-zero emission scenario, with almost 21 Mt. In the water stress regions scenario, the materials consumption is much lower, reaching 9 Mt, and this is associated with the highest value of energy security. This result is mainly due to the transport sector technology mix, which does not include electric cars only as low carbon alternative. Lastly, this work provides a quantification of the cost of energy security. It results that the additional cost per percentage security unit earned is equal to 8.7 B€/%, while the additional cost to reduce the material supply risk is about 2.1 B€/%.

List of acronyms

ALK	Alkaline
BAU	Business As Usual
BEV	Battery Electric Vehicle
BEV	Battery Electric Vehicle
CC	Capacity Credit
CCUS	Carbon Capture Utilization and Storage
CF	Capacity Factor
CRM	Critical Raw Material
CSD	Chinese Supply Disruption
DEV	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
EV	Electric vehicle
FC	Fuell Cell
FCV	Fuel Cell Vehicle
FEC	Final Energy Consumption
FHEV	Full Hybrid Electric Vehicle
GDP	Gross Domestic Product
GHG	Green House Gass
GSI	Gini-Simpson Index
HHI	Herfindahl-Hirschman Index
IEA	International Energy Agency
IR	Internal Reliability
JRC	Joint Research Center
LCA	Life Cycle Assessment
LGR	Low Governance Region
LIB	Lithium Ion Battery
MSR	Material Supply Risk
NREL	National Renewable Energy Laboratory
NZE	Net Zero Emission
PEM	Proton Exchange Membrane
PHEV	Plugin Hybrid Electric Vehicle
PV	Photovoltaic
RDC	Republic Democratic of Congo
REE	Rare Earth Element
RES	Renewable Energy Supply
RESI	Renewable Energy Security Index
SO	Solid Oxide
SR	Supply Risk
SS	Self Sufficiency
SWI	Shannon-Wiener Index
TPES	Total Primary Energy Supply
VRFB	Vanadium Redox Flow Battery
WSR	Water Stress Region

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Chapter 1

Introduction

The recent energy crisis emphasized the urgent need for more resilient energy systems. This is specifically important for regions, such as Italy, relying on relevant energy imports. Italy imported more than 4,300 PJ of natural gas and oil in 2022 [1]. It is pointing to energy security (ES) as one of the priorities in the energy decision making processes. The current European Union (EU) ES policies aim at reducing the risk of energy supply disruption [2], defining the ES as a multidimensional target [3], with a close linkage to other energy policies, such as the ones dealing with equitable access to energy supply and the mitigation of climate change [4]. 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 [5]. Indeed, an affordable and sustainable energy supply can reduce the risk of prices volatility and the energy cost for strategic sectors, as the industrial one and enabling further investments. Trying to implement adaptive energy-policies, recently different regions have investigated the possibility of increasing the independence of energy supply, or at least increasingly diversifying the supply imports, due to the benefits that a higher penetration of renewable energy sources may provide to the ES of the system. In this regard, different analyses [6] pointed out how the energy transition may switch the dependency from fossil fuels to the so-called critical raw materials (CRMs). Indeed, such materials are necessary for the deployment of low carbon technologies, but their supply result highly concentrated [7]. For instance, the global lithium and rare earth elements (REEs) supply is mostly provided by China, inducing the risk of disruption for other regions (e.g., Europe) which cannot rely on relevant domestic extraction and processing [7]. Moreover, China also leads the supply along other steps of transition technologies (e.g., components manufacturing) such as solar photovoltaic (PV), wind nacelles, lithium-ion batteries [8], [9].

Policymakers are starting to be concerned about the access to the supply chains of transition materials and technologies [8]. Indeed, the high concentration characterizing them is considered a potential supply chain bottleneck [8], [9] that may limit the transition to a low-carbon economy [10]. Therefore, there is common agreement on the need to include such supply risks (SRs) when formulating ES policies and energy scenario studies [11], [12]. In this regard, Energy System Optimization Models (ESOMs) are suitable tools supporting policy makers in identifying the effects of possible future energy policies on the evolution of the system, also regarding the improvement of ES [13], especially due to the possibility of analyzing future energy scenarios, which can be implemented considering specific constraint aimed to represent future geo-political perspectives. 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 [14].

The conceptualization of ES is broadly discussed in literature, investigating several definitions. For instance, "uninterrupted availability of energy sources at an affordable price" is proposed by [15] and "measures a nation's capacity to meet current and future energy demand reliably, withstand and bounce back swiftly from system shocks with minimal disruption to supplies" by [16].A comprehensive description of ES may result particularly challenging due to the multidimensional nature of the theme and being ES highly context dependent [17]. During the 'oil crisis' period in the '70s, ES was mainly focused on the security of energy supply, promoting this aspect as the major objective of energy policies. In the next years the definition of ES was widened over time and four main elements or dimensions were identified [17]: availability, accessibility, affordability and acceptability.

This definition of ES is known as "the Four As" of ES and is a frequent starting point of contemporary ES studies, such as for [18], which used this framework for its study on ES in Asia. The analysis done by [19] provides a broader consideration of ES, analyzing it as an interconnected and synergic concept and underling that the presence of different definition of ES does not necessarily imply the existence of different concepts of ES, therefore the same concept finds different expressions under different conditions. Being an extensively and intangible interconnected concept, ES generated several misleading in literature. To provide an essential definition of ES, [20] started from defining the security as a "low probability of damage to acquired values" [20] it applied a more specific contextualization answering to the following questions:

- Security for whom?
- Security for which values?
- From what threats?

However, being these questions rarely explicitly asked in the ES literature, other methodologies were investigated, such as the one analyzed by [21] in which three different perspectives of ES emerged, sovereignty, robustness, and resilience.

The main objective of the contemporary studies literature is to determine a methodology able to quantitatively evaluate the level of ES of a region [22], [23]: in this regard, ES is conceptualized through the definition of several dimensions, emphasizing the important role covered by the independence and diversification of energy sources. Trying to provide a further support to the quantification of ES, the approach proposed by [3] represents another important reference for the studies on ES, introducing a multidimensional analysis based on the definition of five key dimensions, which can be connected to a metric composed by a diversified collection of indicators. The dimensions proposed are presented in Table 1.

Table 1. Dimensions considered to analyze the energy security.

Dimension	Explanation	Component
Availability	Having sufficient supplies of energy. Being energy independent. Promoting a diversified collection of different energy technologies.	Security of Supply and Production, Dependency and Diversification.
Affordability	Producing energy services at the lowest cost, having predictable prices for energy fuels and services, and enabling equitable access to energy services.	Price Stability Access and Equity, Decentralization and Affordability.
Technology development	Capacity to adapt and respond to the challenges from disruptions, delivering high quality and reliable energy services.	Safety and Reliability, Resilience, Efficiency and Energy Intensity.
Sustainability	Minimizing ambient and indoor pollution, mitigating GHG emissions associated with climate change, adapting to climate change.	Land Use, Water, Climate Change, Pollution.
Regulation	Having stable, transparent, and participatory modes of energy policymaking, competitive markets, promoting trade of energy technology and fuels.	Governance Trade and Regional Interconnectivity, Competition and markets Knowledge.

A simple indicator generally focuses on a narrow aspect of ES, while compound indicators cover more relative considerations in terms of analysis [5]. Therefore, the methodologies that quantitatively evaluate the ES adopting the definition of an energy security index (ESI), commonly known as a metric, refer to a set of several indicators. However, as reported by [3], the availability of data and the diversity of concepts and dimensions related to ES can significantly affect the selection of ES indicators. These elements are extensively investigated in [3] and [20], in which result that an excessive number of indicators can affect the clearness of the analysis, with a possible overlapping of meanings, reducing the validity of the study.

In addition, the concept of ES is also commonly associated with the characterization of the energy system. For this purpose, ES is defined by [19] as “low vulnerability of vital energy systems”, in which the vulnerability is a combination of risk and resilience [20]. Starting from the concept of vulnerability of an energy system and introducing the approach of metric and indicators definition, aimed to support the energy policy-making process, several studies analyzed the ES of energy systems with the adoption of ESOMs, introducing the possibility to investigate the future perspectives of ES.

The relevant methodologies found in literature are based on the selection of different indicators used for the construction of a comprehensive metric and subsequently applied to the scenarios generated with ESOMs, which allow to evaluate the ES on a medium-long term time scale [14]. These kinds of applications can produce interesting results, such as for [24], in which the evaluation of the ES is endogenously integrated in the models through the definition of a Renewable Energy Security Index (RESI), that mainly accounts for the electricity production mix. Similarly, the ESI proposed by [25] is connected to ESOMs results, using a simple taxonomy to define the ES, accounting for the diversification of energy sources only. That approach can produce much more interpretable results, with the drawback, as mentioned before, of losing some relevant aspects of ES. For this reason, several other studies (e.g. [26], [27], [28]) consider metrics composed by a higher number of indicators.

As mentioned by [5], the considerations on ES should refer to the entirety of the energy system instead of focusing on its selected aspects, in addition to this analysis, considering the possibility of a high renewable technologies penetration in the energy system aimed at reducing greenhouse gasses (GHGs) emission, a contemporary and always more critical factor must be considered in the evaluation of the ES: the possibility of material supply chain disruption. Noticing the results obtained by the European Joint Research Center (JRC) [8], in which a set of critical materials necessary for the energy transition is provided, and being the renewable technologies more material intensive than the traditional one [6], the occurrence of shortages on the supply chain of some of these relevant materials may produce critical delays in the energy transition, also resulting in disruptive effects on the ES.

The implications that emissions restrictions may have on the energy transition sustainability are deeply analyzed in [29], in which a metric composed by three dimensions (environmental, security and social) is applied to scenarios generated by ESOMs. Providing a first analysis on the effects that a sustainable energy transition could have on ES. The contribution of the material supply risk (MSR) is still not considered in the present literature on ES, but it may play a critical role for the future ES perspectives. For this reason, the energy security metric proposed in this thesis also includes a MSR component, as presented in Section 2.1.

The future evolution of energy systems is generally expected to be more material intensive, due to dependence on the previously mentioned Critical Raw Materials (CRMs) of many energy transition technologies [30], but the effects of possible supply chain disruptions of CRMs is still not explicitly investigated in the analyses on ES, as well as in ESOMs frameworks[31]. To the authors knowledge, [29] proposes among the first ESOMs integrated security metrics including CRMs aspects. Facing this lack, this work aims at providing a comprehensive metric to evaluate the ES, accounting also for the SR associated with CRMs. The proposed case study focuses on future energy scenarios generated using the TEMOA-Italy model [32], [33].

In Chapter 2 is extensively described the methodology applied in the ESI definition, focusing on the single indicators and investigating their own features and contribution to the metric. Moreover, the normalization and aggregation methodologies for the final ESI evaluation are analyzed. Chapter 3 investigates the scenarios modelled in this study. It begins with a general overview of the different scenarios, focusing later on the material disruption scenarios, which are based on specific geopolitical considerations. Finally, Chapter 4 provides several insights and results on the energy system and the application of the metric to the geopolitical scenarios.

Chapter 2

The energy security metric

A crucial step of the analysis on ES is related to the selection of the dimensions used to characterize the comprehensive metric. Since this study aims at evaluating the ES of the energy systems, the dimensions considered are limited to the aspects with a direct influence on the systems themselves. In addition, as noticed by [33], the definition of internal and external factors that could threaten the system is crucial. On this basis, the dimensions considered in the analysis are three, the material supply risk, the energy supply risk and the reliability, which account, respectively, for the physical and energy sources that are introduced in the system and for the internal reliability of the energy system.

- The **material supply risk dimension** considers the physical input to the system, in particular the material consumption of the technologies which compose the energy system.
- The **energy supply risk** accounts for the risks associated with the various energy sources that supply the system, e.g. the energy imports to the system. Said that, these two dimensions include a set of indicators able to analyze the different effects on ES due to a variation in the external inputs to the system.
- The **internal reliability dimension** accounts for the internal reliability of the system, including aspects, such as robustness and resilience, which can define its capacity to provide energy with a high level of continuity. This dimension, on the other hand, considers the internal factors that can threaten the ES of a system.

As previously said, each dimension must include an adequate set of indicators to provide a comprehensive interpretation of ES. To reach this objective, the indicators selection should be supported by proper literature. In Table 2 the list of indicators selected to evaluate the ES and their own dimensions is reported.

Table 2. Selected ES dimensions, indicators, their qualitative description and the related references.

Dimension	Indicator	Description	References
Material supply risk (MSR)	Material Supply Risk (MSR)	Risks of material supply chain disruption	[8], [34], [35], [36]
Energy supply risk (ESR)	Renewable Energy Supply (RES)	Fraction of renewable energy supply to the system	[5], [37], [38]
	Diversification of Energy Supply (DES)	Diversification of energy sources which supply the system	[25], [38], [39], [40]
	Self Sufficiency (SS)	Fraction of energy internally produced in the system	[17], [26], [27], [40]
Internal reliability (IR)	Energy Intensity (EI)	Efficiency of energy consumption from the end use sectors	[17], [27], [41], [42]
	Capacity Factor (CF)	Continuity in the energy supply	[43], [44]
	Capacity Credit (CC)	Resource adequacy of the system	[42], [45], [46]

Once the indicators are selected, the next crucial step is to identify the best procedure to connect the model results with them. For the purposes of this analysis, only the activity and the capacity are directly involved in the quantification of the ES. In an ESOM, the capacity is defined as the nominal production capability as if the technology (or group of technologies) was continuously operated at full load (e.g., the nominal power of a power plant). While the activity refers to the total flow of output commodities of a technology (see [47], [48]) (e.g., the electricity production of power plants). In the metric, the capacity is linked to the MSR, CF and CC indicators, while the activity to the RES, DES, SS and EI indicators.

Subsequently, the composition of the ESI requires the normalization of the indicators and a proper combination methodology, as discussed in [29] and [49]. The normalization procedure, the weight assignment and the aggregation method, which represent the last steps for the construction of the ESI, are explained in Section 2.8.

2.1 Material Supply Risk

Analyzing more in detail the indicators composing the ESI, it is observed from results obtained by [50] that a scenario in which the energy system is characterized by a strong penetration of renewable energy sources presents a higher material consumption. This is because renewable energy technologies are much more material intensive than the traditional ones. This aspect becomes particularly relevant in the low GHGs emission scenarios, in which renewables typically play an important role in the energy system. Being the material and renewable technologies production strongly concentrated in few regions (e.g. China), the MSR can represent a possible bottleneck to the renewable transition. In addition, a variation in the actual geopolitical state could leads to a disruption of the supply chain of these resources. It is a theme gaining always more importance in the perspective of energy policies and it is necessary to include this aspect in the evaluation of ES.

To include in the evaluation the risk of material supply disruption, this analysis considers the methodologies proposed by [34], in which a set of material metabolism indicators are applied to the case study of wind and PV technologies, [35], that analyzes three indicators relating the raw materials supply and a specific production process. In [36], it integrates a broad range of environmental, material end socio-economic indicators into energy modelling. All these studies are based on the traditional SR index usually adopted in materials criticality assessments, which includes supply concentration and import dependence aspects [31], [51], [52], [53]. Such an index is adopted to identify the materials considered particularly important for the economy of the region under analysis. Above certain SR thresholds, the SR indexes are traditionally applied to materials extraction and processing phase [51], [52]. However, since transition technologies usually require several materials with high SRs [54], a technology material SR index was considered as the most suitable indicator to include in the ES metric. In this regard, the only quantitative approach is proposed by [35] and adopted in [34], [36], [31]. First, two possible definitions are considered. They are reported in Equation (1) and Equation (2), both aimed to quantify the MSR of a certain technology of the energy system, starting from the n materials composing the technology itself. In Equation (1) the material intensity (m_i) accounts for the material consumption of the technology and it is expressed as $\frac{\text{kg}}{\text{Cap}}$, where kg is the quantity of material consumed and Cap is the technology capacity [6], [34]. The supply risk (SR_i) of the material is a dimensionless quantity and it also includes the global material consumption (c_i), expressed as $\frac{\text{kg}}{\text{year}}$ and accounting for the material availability in the global market [55], giving more importance to materials consumed in smaller amounts by technologies, but usually associated with smaller markets and higher SR_m, than bulk materials [35].

To assess the indicator sensitivity on the global materials consumption (c_i), Equation (2) does not include them, resulting in a different contribution of the materials to the MSR of the technology, as it is shown in Figure 2b.

$$SR_{tech_j,cons} = \sum_{i}^{n} m_i \cdot \frac{SR_i}{c_i} \left(\frac{year}{cap}\right) \tag{1}$$

$$SR_{tech_j} = \sum_{i}^{n} m_i \cdot SR_i \left(\frac{kg}{Cap}\right) \tag{2}$$

Equation (1) also requires the introduction of an assumption on the future evolution of the global material consumption. Indeed, the values of c_i are provided by the European Commission [7] and refer to the 2023 historical values. Noting that the analysis done in this study is applied to future values for the technologies' capacity, the future projection of the global material consumption is in principle necessary among the inputs. Since its evaluation is complex and out of the scope of this thesis, the same 2023 level of global consumption (c_i) are assumed to remain constant in the future. However, it should be notice that, thanks to the normalization process, this hypothesis only introduces the simplification of keeping constant the consumption shares among the different materials at global level (which may be not verified in the future), while the absolute consumption values do not influence the MSR evaluation per se. While the latter would have been a much stronger assumption prejudicing the reliability of the analysis, the first only introduces a minor simplification.

Once the MSR for the single technologies is defined, the subsequent step is evaluating the MSR of the entire system. This is done considering the installed capacity (Cap_j) of the technologies analyzed and if a technology consumes materials only when new capacity is added. Therefore, the MSR of the system is evaluated as reported in Equation (3) and Equation (4), accounting for the k technologies constituting the energy system, in which Equation (3) also includes the global material consumption.

$$MSR = \sum_{j}^{k} SR_{tech_j,cons} \cdot Cap_j \ (year) \tag{3}$$

$$MSR' = \sum_{j}^{k} SR_{tech_j} \cdot Cap_j \ (kg) \tag{4}$$

As represented by the equations above and reported in the previous paragraphs, the resulting indicator of MSR is not a dimensionless indicator, meaning that it needs a normalization procedure to be comparable with the other indicators. The approach applied in this work considers the maximum value across all scenarios and over the entire time period (2007 – 2050), assuming, respectively, 0 and 1 for the minimum and maximum value of the normalized indicator.

An example of technology material consumption is reported in Figure 1 showing the material consumptions associated with solar PV and wind technologies (a) and battery electric vehicles (BEVs) (b), among which this study considers car only.

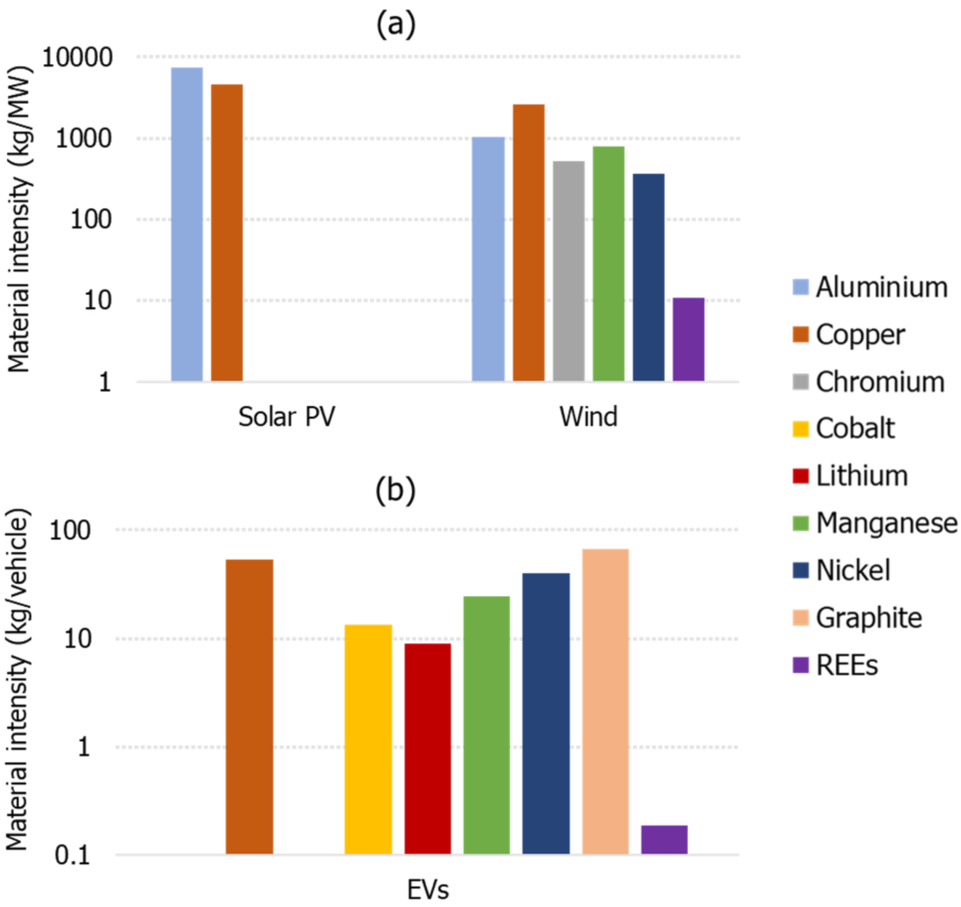

Figure 1. Material intensity for low carbon technologies (a) and electric vehicles (b).

Focusing on BEVs, in Figure 2 presents how the use of Equation (1) or Equation (2), alternatively, can influence the analysis. In particular, Figure 2a shows the values of the SR index for the mostly consumed materials by the BEVs. On the other hand, Figure 2b shows the impact of each material on the evaluation of the SR for BEVs. It is noticed that for the method reported in Equation (1) ($SR_{tech_j,cons}$), materials consumed less, usually associated with smaller markets and higher SRs, influence more the assessment of the MSR. On the other hand, in the method represented by Equation (2) (SR_{tech_j}), a higher effort is done by materials consumed more from the technology, hiding the effect related to the most critical materials. This outcome is supported by LCA literature that carried out a similar comparison [56].

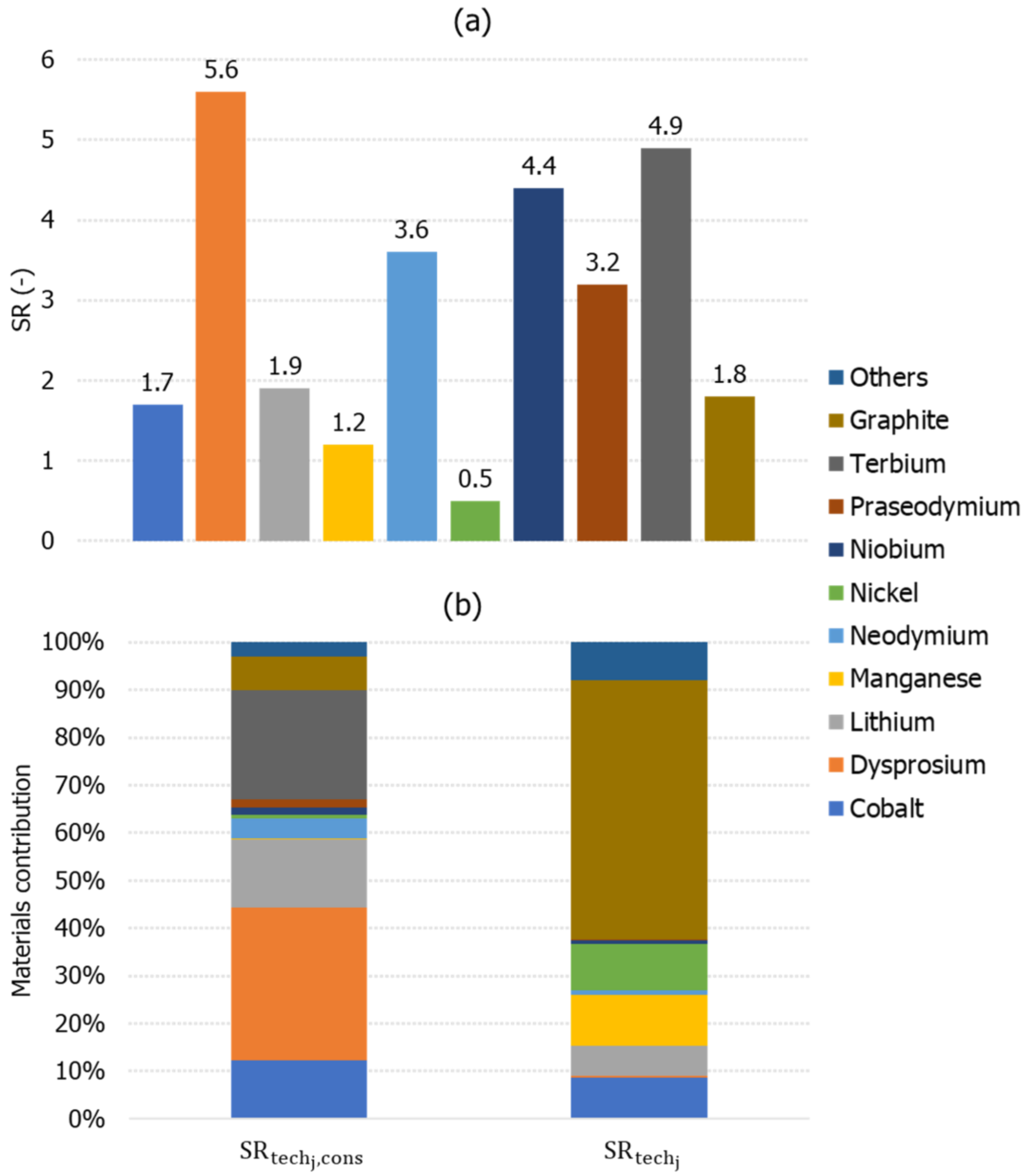

Figure 2. Supply Risk (SR) index (a), weight comparison of the different materials in the SR of the technology (b).

Considering the results obtained from the analysis on the two methodologies, the approach selected to evaluate the indicator is $SR_{tech_j,cons}$ (1), which includes the global material consumption and emphasizes the efforts of poorer materials.

Going more in details with the analysis of this indicator, in Table 3 is reported the list of the CRMs investigated from the European JRC [7] and its values of SR index.

Table 3. SR index of the different materials analyzed by the JRC [7].

Material	SR (-)	Material	SR (-)	Material	SR (-)
Dysprosium	5.6	Gadolinium	3.3	Palladium	1.5
Erbium	5.6	Phosphorus	3.3	Silicon metal	1.4
Europium	5.6	Praseodymium	3.2	Tantalum	1.3
Holmium	5.6	Strontium	2.6	Aluminum	1.2
Lutetium	5.6	Rhodium	2.4	Helium	1.2
Thulium	5.6	Scandium	2.4	Manganese	1.2
Ytterbium	5.6	Vanadium	2.3	Tungsten	1.2
Terbium	4.9	Platinum	2.1	Fluorspar	1.1
Gallium	4.8	Bismuth	1.9	Coking coal	1.0
Niobium	4.4	Lithium	1.9	Tin	0.9
Magnesium	4.1	Antimony	1.8	Molybdenum	0.8
Cerium	4.0	Beryllium	1.8	Silver	0.8
Iridium	3.9	Germanium	1.8	Zirconium	0.8
Boron	3.8	Natural graphite	1.8	Chromium	0.7
Ruthenium	3.8	Cobalt	1.7	Indium	0.6
Neodymium	3.6	Arsenic	1.6	Nickel	0.5
Lanthanum	3.5	Titanium metal	1.6	Titanium	0.5
Samarium	3.5	Feldspar	1.5	Copper	0.1
Yttrium	3.5	Hafnium	1.5		

Four groups of technologies are then characterized by material intensity in this study: power plants, storage technologies, hydrogen technologies and cars transport. The assigned values are reported in the tables below.

In Table 4 are represented the various values of material intensity for the power plants technologies, including both the low carbon technologies, which encompass renewables and CCUS plants and the traditional power plants.

Table 4. Power plants material intensity.

Sector	Technology	Material	Material Intensity $\left(\frac{kg}{MW}\right)$	Data sources
Low carbon power technologies	Solar PV	Aluminum	7.50E+03	[6], [10], [12], [34]
		Cadmium	2.00E+00	
		Copper	4.60E+03	
		Silicon	3.80E+00	
		Silver	1.90E+01	
		Tellurium	2.08E+00	
	Wind onshore	Aluminum	1.25E+03	[6], [10], [12], [34]
		Boron	9.40E-01	
		Chromium	4.92E+02	
		Copper	1.80E+03	
		Dysprosium	4.74E+00	
		Manganese	7.84E+02	
		Molybdenum	1.03E+02	
		Neodymium	4.04E+01	
		Nickel	3.99E+02	
		Praseodymium	5.84E+00	
		Terbium	1.14E+00	
		Zinc	5.50E+03	

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Continued from page 15

	Wind offshore	Aluminum Boron Chromium Copper Dysprosium Manganese Molybdenum Neodymium Nickel Praseodymium Terbium Zinc	6.65E+02 5.25E+00 5.33E+02 2.69E+03 1.54E+01 7.92E+02 1.11E+02 1.61E+02 2.70E+02 3.04E+01 6.10E+00 5.50E+03	[6], [10], [12], [34]
	Hydropower	Copper Manganese Nickel	1.05E+03 2.00E+02 3.00E+01	[6], [50]
	Bioenergy	Copper Titanium	2.27E+03 4.00E+02	[6], [50]
	Geothermal	Chromium Nickel	6.20E+04 1.20E+05	[6], [50]
	Coal & NGA with CCUS	Chromium Cobalt Copper Manganese Molybdenum Nickel Niobium Vanadium	3.26E+02 7.50E+00 6.92E+02 3.76E+03 7.50E+00 1.15E+03 1.00E+02 1.00E+02	[57], [58], [59]
Traditional power technologies	Coal power plant	Chromium Cobalt Copper Molybdenum Nickel	3.08E+02 2.02E+02 1.15E+03 6.63E+01 7.21E+02	[57], [58], [59]
	NGA power plant	Chromium Copper Nickel	4.83E+01 1.10E+03 1.58E+01	[57], [58], [59]

The storage technologies are included in Table 5, considering the traditional lithium-ion batteries (LIBs) and the vanadium-redox-flow batteries (VRFBs).

Table 5. Storage technologies material intensity.

Sector	Technology	Material	Material Intensity $\left(\frac{kg}{MW}\right)$	Data sources
Storage technologies	LIBs	Aluminum	1.35E+04	[59], [60], [61], [62], [63]
		Cobalt	6.22E+02	
		Copper	5.05E+03	
		Fluorspar	2.31E+01	
		Graphite	7.31E+03	
		Lithium	8.68E+02	
		Manganese	7.03E+02	
		Nickel	2.00E+03	
		Phosphorus	4.14E+03	
	VRFBs	Copper	2.23E+03	[6], [64], [65], [66], [67]
		Graphite	1.98E+03	
		Vanadium	2.03E+04	

Additionally, in the material intensity characterization is considered also a group of hydrogen technologies. In particular, the alkaline (ALK), proton exchange membrane (PEM) and solid oxide (SO) electrolyzer are expressed in $\frac{kg}{GWh}$, while the solid oxide fuel cell (FC) is expressed in $\frac{kg}{MW}$. Their values are shown in Table 6.

Table 6. Hydrogen technologies material intensity.

Sector	Technology	Material	Material Intensity $\left(\frac{kg}{Cap}\right)$	Data sources
Hydrogen technologies	ALKEC	Nickel	8.93E+00	[6], [59], [65]
		Zirconium	1.12E+00	
	PEMEC	Platinum	2.20E-03	[6], [59], [65]
		Palladium	2.20E-03	
		Iridium	8.00E-04	
	SOEC	Nickel	1.36E+00	[6], [59], [65]
		Zirconium	3.57E-01	
		Lanthanum	2.00E-01	
		Yttrium	2.55E-02	
	SOFC	Nickel	2.00E+02	[6], [59], [65]
		Zirconium	4.00E+01	
		Lanthanum	2.00E+01	
		Yttrium	5.00E+00	

Eventually, in Table 7 the values of material intensity for the cars transport technologies are reported for four sub-sectors: traditional cars, BEVs, plugin hybrid electric vehicles (PHEVs), full hybrid electric vehicles (FHEVs) and fuel cell vehicles (FCVs).

Table 7. Cars transport technologies material intensity.

Sector	**Technology**	**Material**	**Material Intensity $\left(\frac{kg}{vehicle}\right)$**	**Data sources**
Transport technologies (car)	Traditional car	Copper	2.23E+01	[6]
		Manganese	1.12E+01	
	BEVs	Chromium	9.91E+00	[6], [10], [12], [68], [69]
		Cobalt	1.33E+01	
		Copper	5.32E+01	
		Lithium	8.90E+00	
		Manganese	2.45E+01	
		Nickel	3.99E+01	
		Graphite	6.63E+01	
		REEs	8.17E-01	
	PHEVs	Chromium	1.07E+01	[6], [10], [12], [68], [69]
		Cobalt	4.60E+00	
		Copper	3.00E+01	
		Lithium	4.56E+00	
		Manganese	1.48E+01	
		Nickel	2.56E+01	
		Graphite	1.11E+01	
		REEs	1.28E+00	
	FHEVs	Chromium	1.07E+01	[6], [10], [12], [70], [71]
		Cobalt	5.52E-01	
		Copper	2.32E+01	
		Lithium	5.47E-01	
		Manganese	1.16E+01	
		Nickel	3.07E+00	
		Graphite	1.33E+00	
		REEs	9.75E-01	
	FCVs	Chromium	5.60E-01	[6], [10], [12]
		Cobalt	6.77E-01	
		Copper	2.97E+01	
		Lithium	1.92E-01	
		Manganese	1.04E+01	
		Nickel	4.00E+01	
		Vanadium	5.13E+01	
		REEs	3.04E+00	

For most of the analyzed technologies the material intensity was obtained from the literature. On the other hand, for LIBs, VRFBs and FHEVs, the evaluation of the material consumption required an elaboration of the available data.

Specifically, for LIBs the material intensity has been estimated as the ratio between the values of material demand in t (tons) and the projections of installed capacity in GW by the European Joint Research Center (JRC) [7], [8], [63], which analyze different scenarios of LIBs penetration. Completely different was the approach used for the VRFB, in which starting from the results obtained by [65], [72] the amount of vanadium required from the battery has been evaluated, following the procedure represented by Equation (5), in which M is the molar weight of Vanadium (0.051 kg/mol), U is the open circuit voltage of the cell (1.4 V) [66], X is the depth of discharge (assumed equal to 0.8), F is the

Faraday constant (96,485 C/mol(e^-)), n_e is the electron transferred per mol of V (1 mol(e^-)/mol(V)), considering for both LIBs and VRFBs a storage capacity of 6h.

$$MI = \frac{2M}{n_e \cdot F \cdot U \cdot X} = 3.4 \cdot 10^3 \left(\frac{kg}{MWh}\right) \quad (5)$$

Once the amount of vanadium consumed by the VRFBs is defined in $\frac{\mathrm{Kg}}{\mathrm{MW}}$, the consumption shares provided by the IEA [6], [67] for the other materials associated with VRFBs were used to evaluate the material intensity of graphite and copper. The adopted consumption shares are 83% for vanadium, 8% for graphite and 9% for copper in weight.

Finally, the values applied to the FHEVs are obtained resizing the data of material consumption of plug-in-hybrid electric vehicles reported by [10] and considering a different scaling factor for the materials concerning the battery and the electric motor, referring to an average size of these components represented in Table 8, whose values are derived from the considerations done by [70], [71].

Table 8. PHEV and FHEV, reference components size and related materials.

Technology	Component	Size	Material
PHEV	Battery	12.5 kWh	Co, Cu, Li, Ni, Mn
	Electric motor	48 kW	REEs
FHEV	Battery	1.5 kWh	Co, Cu, Li, Ni, Mn
	Electric motor	32 kW	REEs

One last consideration about the vehicle's material intensity, expressed in $\frac{\mathrm{Kg}}{\mathrm{v}}$ (kilograms per vehicle), concerns the connection to the model results. This requires a proper conversion of the units of measures, since a different unit with respect to the number of vehicles is typically adopted to express the capacity of vehicles. In particular, the capacity of the transport sector provided by the model is often expressed in Bvkm (billion vehicles kilometers), which must be divided by the average mileage (annual travelled kilometers) to obtain the resulting number of vehicles. Being the analysis on transport sector limited to car vehicles, the average daily distance travelled for Italy was obtained from [73] and it is equal to 32.25 km/day (11,771 km on annual basis).

2.2 Renewable Energy Supply

Modern perspectives on ES define it as a multidimensional theme, which is interconnected with other policy objectives such as economic development and climate change mitigation. Concerning the latter, it is noticed by [5] that current EU priorities focus on measures to fight climate change, which has far-reaching implications for the concept of ES, supporting that issues on ES and climate changes should be investigated in an integrated manner. In 2007, the IEA published a study [38] aimed at analyzing the possible contribution of renewable energy to the ES. It resulted that they could contribute to an enhancement of the ES of an energy system introducing different benefits. These benefits were subsequently analyzed in a study conducted by the National Renewable Energy Laboratory (NREL) [37] and mainly resulted in:

- A reduction of the CO2 emission produced by the energy system. As reported from the World Economic Forum "The sustainability and security of the energy system are closely intertwined, as an unsustainable energy system can pose a long-term threat to energy security" [74]. Therefore, environmental sustainability has been added to the indicators comprising the ES [40], considering the supply of renewable sources associated with a reduction in the GHGs emissions, inducing positive effects on the mitigation of climate changes and long-term ES.

- Spatial distribution of the resources. A more spatially diversifies generation of energy can better withstand shocks to the system and can also provide a smoothing effect across variable generation resources, improving the supply diversification and allowing energy supply also in hard-to-reach locations.
- Modularity of the generation system. Instead of having a single large-scale system, big renewable generation systems are based on modules, that allows to increase the flexibility of the system.
- Distributed generation. Instead of having a few large generation systems, renewables introduce the possibility of a more distributed and local energy generation, reducing the risk of disruption due to possible failures of the transmission and distribution infrastructure. This feature may find a particular relevance when the main grid is compromised, in this case the system can locally operate in islanding condition.
- Water intensity. Renewable sources are not water intensive technologies. On the contrary, technologies with high water requirement, as for cooling system, are vulnerable to climatic events as drought. Therefore, renewable energy can be considered as an alternative for adaptation to climate changes, allowing a better utilization of the water resources.

This indicator is aimed at evaluating the fraction of renewable energy supply (RES) with respect to the total primary energy supply (TPES), as reported in Equation (6), which is evaluated considering the primary renewable energy (*RNW*), the energy imports (*IMP*) (i.e., fossil fuels, bioenergy and electricity imports), and the internal fossil fuel extraction (*MIN*) of the region.

$$RES = \frac{Primary\ Renewable\ Energy}{TPES} = \frac{RNW}{RNW + MIN + IMP} \tag{6}$$

The indicator is connected to the model results through the activity of the upstream sector, which is graphically represented in Figure 3.

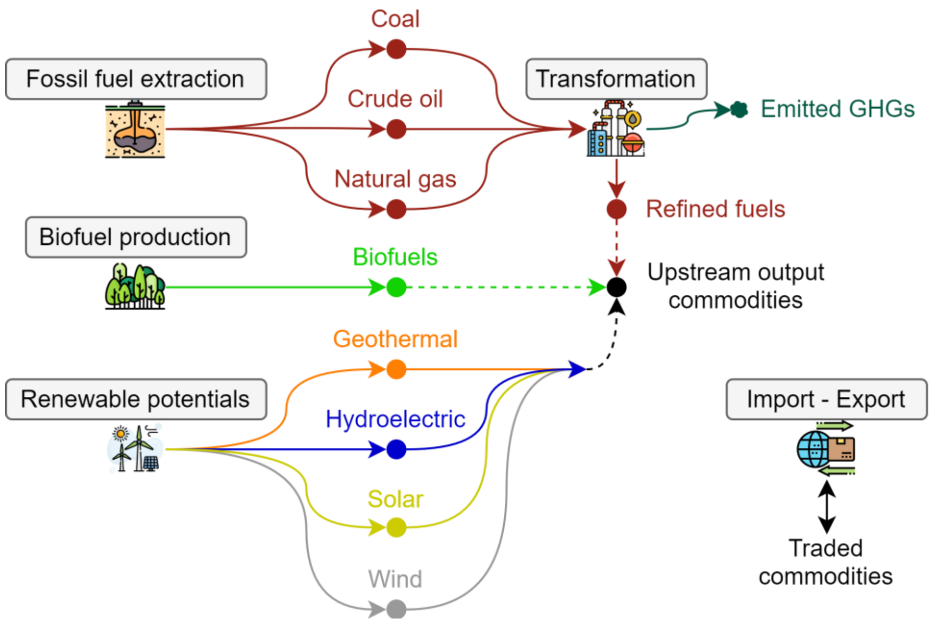

Figure 3. Schematic overview of the main technology and commodity groups typically included in the upstream sector of an ESOM: fossil fuels primary extraction and secondary transformation, renewable resources potentials, import and export.

2.3 Diversification of energy supply

A high diversification of energy supply (DES) can significantly reduce the possibility of energy supply disruption, by limiting the dependency on a specific source of energy. That improves the ES of the system and reduces the risk of price volatility. Similarly to the previous indicator, also DES is connected to the model output through the activity of the upstream sector. However, the distinction between internal production and imports from abroad was not considered.

In literature, different methodologies are proposed to evaluate the diversification of energy supply, in particular the standard Herfindahl-Hirschman Index (HHI) [40] and the Shannon-Wiener Index (SWI) [75] represent the main approaches in the analysis of ES. Both refer to the share with respect to the TPES of the n primary energy sources (p_i) composing the energy portfolio. The indexes present different features. The standard Herfindahl-Hirschman index (*HHI*), which its evaluation is represented by Equation (7), provides values between 0 and 1, in which a lower value of the index corresponds to a higher value of diversification, giving more emphasis to larger suppliers.

$$HHI = \sum_{i}^{n} (p_i)^2 \tag{7}$$

SWI, which attributes higher importance on the impact of smaller suppliers, can provide results higher than 1, reaching its maximum value when the sources are equally distributed, in which a higher value of the index corresponds to a higher level of diversification, as it is possible to notice from the Equation (8) . Considering the assumption made in this study about the construction of the metric, if this approach is considered a normalization is required to make it comparable with the other indicators.

$$SWI = -\sum_{i}^{n} p_i \cdot ln(p_i) \tag{8}$$

[39] suggests the use of the Gini-Simpson Index (GSI) to evaluate the diversification and the proportionality of the elements, i.e. energy sources, as represented in the Equation (9). The GSI is characterized by a higher normalized standard deviation, with respect to the HHI and the SHI, resulting in a better representation of the elements diversification.

$$DES = GSI = 1 - HHI = 1 - \sum_{i}^{n} (p_i)^2 \tag{9}$$

The GSI, the complement to one of the standard HHI, provides higher values when the energy supply is more diversified.

2.4 Self Sufficiency

The last indicator attributed to the energy supply risk dimension is self sufficiency (SS), which aims to account for the energy dependence of the analyzed region from the exporting countries. This aspect has aroused more interest in the last years, in particular in Europe, where the disruption of energy imports from Russia have undoubtedly had an impact on ES [16]. This is particularly true for countries (Italy included) whose energy system is strongly reliant on fossil fuel imports from the Russian Federation, which presents a higher source of supply uncertainty [76]. Focusing on the Italy's energy sector, which in 2021 accounted for one third of the TPES of fossil fuels [77], an increase in the amount of indigenous sources that can contribute to the energy supply would directly reduce the needs of energy imports, limiting the contribution of third parts to the supply of energy.

Therefore, an increment of the internal energy production induces a lower uncertainty of energy supply, reducing the risk of service disruption and the price volatility of energy services, being the indigenous sources independent from the decisions and actions of exporting countries [28].

This indicator is evaluated following the same procedure of the RES but considering both primary renewable energy and the fossil fuel extraction, as reported in Equation (10).

$$SS = \frac{Primary\ Renewable\ Energy + Fossil\ Fuel\ Extraction}{TPES} = \frac{RNW + MIN}{RNW + MIN + IMP} \quad (10)$$

It is noticed that the RNW component is included in two different indicators. That is done because, as discussed in Section 2.2, in the evaluation of modern ES it provides different benefits that are not strictly related to the supply of indigenous energy sources, considering also that the renewable sources are not equally available in every region.

2.5 Energy Intensity

Analyzing the indicators associated with the reliability dimension, it is observed from the literature [78], [79] that the evaluation of ES includes the aspect of energy efficiency. In particular, it is commonly defined as the energy intensity of the reference energy system. Considering what is reported by IEA [78], the energy efficiency has the unique potential to simultaneously contribute to long-term ES and economic growth, in which Equation (11) represents the definition of energy efficiency provided from the IEA, which is the amount of energy consumed to produce a certain quantity of service.

$$Energy\ Efficiency = \frac{Energy\ Consumed}{Service\ Produced} \quad (11)$$

Appling this definition at a high disaggregated level of technologies, such as for ESOMs, is a complex issue. In addition, in the ESOMs the efficiency may not be a dimensionless parameter, presenting different unit of measure for the different sectors and technologies analyzed, requiring a normalization of the parameters that can conduce to misleading results. Therefore, the Energy Intensity is often considered as energy efficiency proxy [80]. It is important to remark that the energy intensity does not include only the pure efficiency of the energy system, but also other aspects not related to the efficiency, such as the economic structure of the country, that can bring to less precise results [41].

The energy intensity presents also different advantages, considering the energy system as an aggregated object and allowing a simplified and immediate evaluation of the indicator. In this study it is focused on the energy intensity of the end use sectors of the system, calculated as the final energy consumption (FEC) with respect to the Gross Domestic Product (GDP) of the system (see Equation (12)). Having considered in the energy supply dimension the results uniquely provided from the upstream sector, the analysis of the end use sector allows to introduce a more comprehensive characterization of the energy system in the ES evaluation.

$$EI = \frac{Final\ Energy\ Consumption}{Gross\ Domestic\ Product} = \frac{FEC}{GDP} \quad (12)$$

The GDP represents an input parameter of the model which characterizes the demand of the end use sectors. Being an input parameter, it is defined a priori, and it is independent from the model optimization. To better appreciate the consideration about the GDP, a comparison between the GDP applied in the definition of the index and the one provided by the World Bank historical data [81] is represented in Figure 4. A certain difference is noticed from the base year 2006 up to 2016, due to the selected time steps and the necessity of deriving average values on more years, while similar trends are highlighted in the last part of the period. This convergency of GDP can represent a positive result from the perspectives of the analysis, considering an expected GDP closer to the real one.

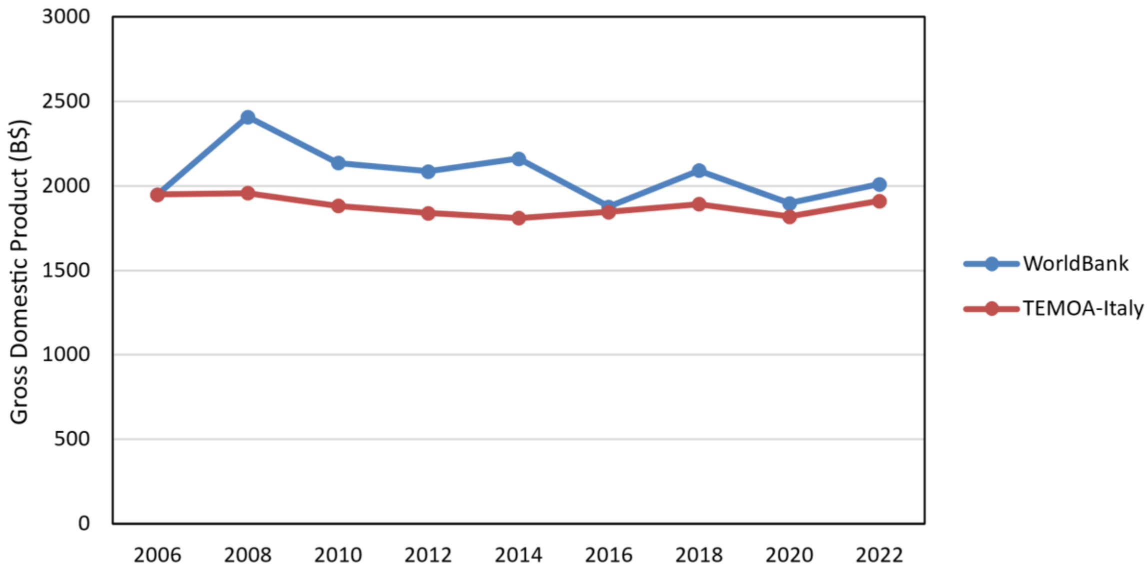

Figure 4. Comparison between the GDP noticed from the World Bank and the GDP obtained applying the TEMOA-Italy factors.

2.6 Capacity Factor

The second indicator which characterizes the reliability dimension is the capacity factor (CF). Considering the continuity in the energy supply one of the pillars which define the ES, the CF is included in the analysis to account for the electricity supply availability of the power sector. Investigating more in details the efforts of this indicator, considering that for the future energy system evolution is noticed a continuously increase in the electricity demand and in an electrification of the power system, moving toward a higher penetration of renewable energy technologies as photovoltaic and wind power plants [82], the CF of the system may be subject to strong variations. Especially, this increment in renewable technologies installation may affects the security of the energy system due to the higher intermittency of power supply, producing also disruptive effect on the electric grid stability [43]. To consider this volatility, the CF is used to directly measure how much electrical power is produced by a plant, in relation to the nominal capacity. Considering the CF of the power sector as a direct measurement of the efficacy of all the power plants suppling the energy system [44] and in view of higher electrification levels of the end uses in low emissions scenarios, the introduction of this indicator in the analysis on ES is considered an important element [83], [84].

Concerning ESOMs, the CF is one of the parameters that characterize the different technologies which compose the energy system and can therefore influence the optimization performed by the model. Referring to this consideration, the CF value considered in the evaluation of the indicator is the nominal CF, is the one provided by the technology in the ideal working conditions, and not the one associated with the model results.

As an example, in Table 9 the average CFs for different groups of technologies as implemented in the TEMOA-Italy power sector are reported, highlighting higher values for thermoelectric groups and lower for renewables.

Table 9. Average capacity factors for power plants.

Technology Group	Average CF
Bioenergy	0.60
Coal	0.73
Geothermal	0.86
Hydroelectric	0.23
Hydrogen	0.90
Natural Gas	0.62
Oil	0.78
Solar PV	0.23
Wind	0.17

Once it is established which values of CF should be considered, the indicator must be connected to the model results to provide an aggregated CF referring to the whole system (CF_{sys}). This is done according to Equation (13) as a weighted average of the technology-specific capacity factors (CF_i) on the capacity of the single technologies (Cap_i) with respect to the total available capacity of the power sector (Cap_{tot}).

$$CF_{sys} = \sum_{i}^{n} CF_i \cdot \frac{Cap_i}{Cap_{tot}} \tag{13}$$

2.7 Capacity Credit

The last indicator included in the reliability dimension is the capacity credit (CC), which in the current literature on quantitative evaluation of ES is still not accounted for. Considering that one of the key aspects of the ES is the reliability of the energy system, which can directly influence the ability of a system to meet the demand consistently and without interruption, it is necessary to provide further consideration on the objective of this indicator.

Starting from an expected increase in the electrification of energy systems, in particular along zero-emission scenarios in which is expected a higher penetration of renewable sources, the reliability of the system becomes critical in the evaluation of the ES. Focusing on this aspect, the reliability of an energy system is strongly connected to its resilience, which represents the ability to respond to shocks, such as demand peak., In literature this feature is attributed to the resource adequacy, which is calculated through the CC [46], [85]. It is noticed by [86] that the reliability of a system can be evaluated measuring its capacity adequacy. Observing that the achievement of a suitable capacity adequacy in a system with a high penetration of renewables is becoming a new challenge, driving to complex problems in the power sector management. Therefore, the inclusion of an indicator that allow to measure the resilience of the energy system, considering the ability to access to resources to provide a stable and uninterrupted supply of energy, is contributing to obtain a more comprehensive view of the ES [84].

Based on those premises, a possible indicator to represent the resource adequacy of the system is the CC. It is considered as a very important parameter to represent the reliability of energy supply [87], and this aspect becomes relevant in the contest of renewable energy sources, in which a high penetration of renewables can impact the reliability and vulnerability of the power system [88].

Similarly to the capacity factor, the evaluation of the CC only considers technologies composing the power sector, i.e., technologies contributing to the reserve margin of the model [89]. Considering this, the capacity credit of the system (CC_{sys}) is evaluated as represented by Equation (14).

$$CC_{sys} = \sum_{i}^{n} CC_i \cdot \frac{Cap_i}{Cap_{tot}} \tag{14}$$

2.8 Weighting and aggregation

As said in the previous sections, some indicators are not dimensionless, in particular the MSR and the EI, requiring them to be normalized before being included in the ESI. The normalization of these indicators is done following a min-max approach (see Equation (15)), in which the normalized value ($\bar{\chi}_{s,t}$), referring to a certain scenario (s) and period (p), it is obtained considering an ideal minimum value (χ_{min}) equal to zero, and the absolute maximum value of the indicator ($\chi_{\max(S,T)}$) which is obtained considering all the scenarios (S) over the entire time period (T).

$$\bar{\chi}_{s,t} = \frac{\chi_{s,t} - \chi_{min}}{\chi_{\max(S,T)} - \chi_{min}} \tag{15}$$

This approach allows to have all comparable indicators, included between 0 and 1. Once the indicators are normalized, the next step for the metric construction is the weights assignment, which is a quite critical phase considering that the weights can emphasize or hide the information provided by the indicators. In addition, the weights are values included between 0 and 1 and their sum must be equal to 1, These considerations imply that the ESI is between 0 (worst case) and 1 (best case) too. In literature it is possible to find several weighting approaches, such as the equal weighting, the expert-based approach, and the stochastic approach, based on a multi criteria decision analysis [49]. Analyzing these different methodologies, for the objective of this study, it was decided to attribute to each dimension the same weight, therefore, being three the dimensions, the weight assigned to each of them is equal to 1/3, and subsequently the weights are equally distributed on the indicators included in these dimensions (see the schematic representation provided by Figure 5. Having the MSR dimension a single indicator, its weight is equal to w_{MSR} = 1/3, on the other hand, being the ESR and the IR dimensions composed by three indicators each one, the weights associated with them are w_{ESR} = 1/9 and w_{IR} = 1/9 respectively. This decision is applied to emphasize the effects that the MSR variation produces on the ES, which is evaluated through the ESI represented by Equation (16), in which the complement to one of the MSR and EI is considered because their reduction produce positive effects on the resulting ES.

$$ESI = w_{MSR} \cdot (1 - MSR) + w_{ESR} \cdot (RES + DEV + SS) + w_{IR}\big((1 - EI) + CF + CC\big) \tag{16}$$

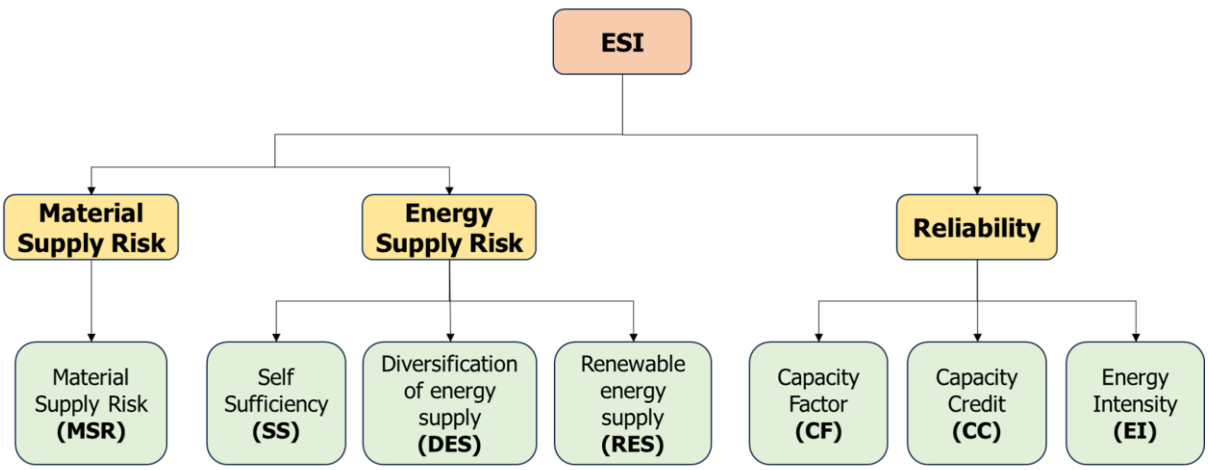

Figure 5. Schematic representation of the ESI structure and of the association of each indicator to its security dimension.

Chapter 3

The case study

3.1 The TEMOA-Italy model

An ESOM framework typically relies on the definition of different interconnected sectors of a specific energy system 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 (possibly) a 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 analysis performed in this work is based on the results produced by TEMOA-Italy model [32], based on the TEMOA modeling framework [90]. The TEMOA version adopted here introduces the possibility of modeling the single materials supply. It is possible to define the material intensity ($Material_{ritv}^{Intensity}$) for a technology (*t*) and material (*i*), referring to the values reported in Section 2.1. Consequentially this model version affords to evaluate the specific material consumption ($Material_{riv}^{Consumption}$), in a certain region (*r*) and vintage (*v*) of the whole system. It is calculated as the sum of the product among the material intensity and the new capacity installed ($Capacity_{rtv}^{New}$), referring to the consumption from the several technologies consuming that specific material ($N_{t,i}$), as represented in Equation (17).

$$Material_{riv}^{Consumption}(t) = \sum_{t}^{N_{t,i}} Material_{ritv}^{Intensity}\left(\frac{t}{Cap}\right) \cdot Capacity_{rtv}^{New}(Cap) \tag{17}$$

In the model framework the material supply ($Material_{riv}^{Supply}$) and consumption must be always balanced. This constraint is imposed through the Equation (18).

$$Material_{riv}^{Consumption}(t) = Material_{riv}^{Supply}(t) \tag{18}$$

These features enable the definition of upper limits on the materials supply through Equation (19). The cumulative material consumption is evaluated as the sum of the consumptions over the entire time horizon, which represents the material demand of the system. The aggregated consumption must be lower than the maximum reserve imposed ($MaxResource_{rt}$), which represents the available material supply over the entire period (*t*). This version allows to better investigate the various effects due to a material supply disruption, studying different alternative scenarios.

$$\sum_{v} Material_{riv}^{Supply}(t) \leq MaxResource_{rt}(t) \tag{19}$$

TEMOA-Italy model is focused on the representation of the Italian energy system, which is accurately described in [91] and it is based on a technology-rich database, providing an extensive techno-economic characterization of the different energy sectors. In Figure 6 the TEMOA-Italy energy system is schematically represented. The supply-side of the system encompasses the upstream sector (see [92] for more details), previously analyzed in Section 2.2 and the power and heat production sector (see [89] and [93] for more details). The model includes an exhaustive description of the hydrogen sector, as reported in [94] and [95]. It is extensively discussed in [96] and [97] the possibility of introducing with TEMOA-Italy a carbon, capture, utilization and storage (CCUS) module and the potential of power and hydrogen storage. 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.

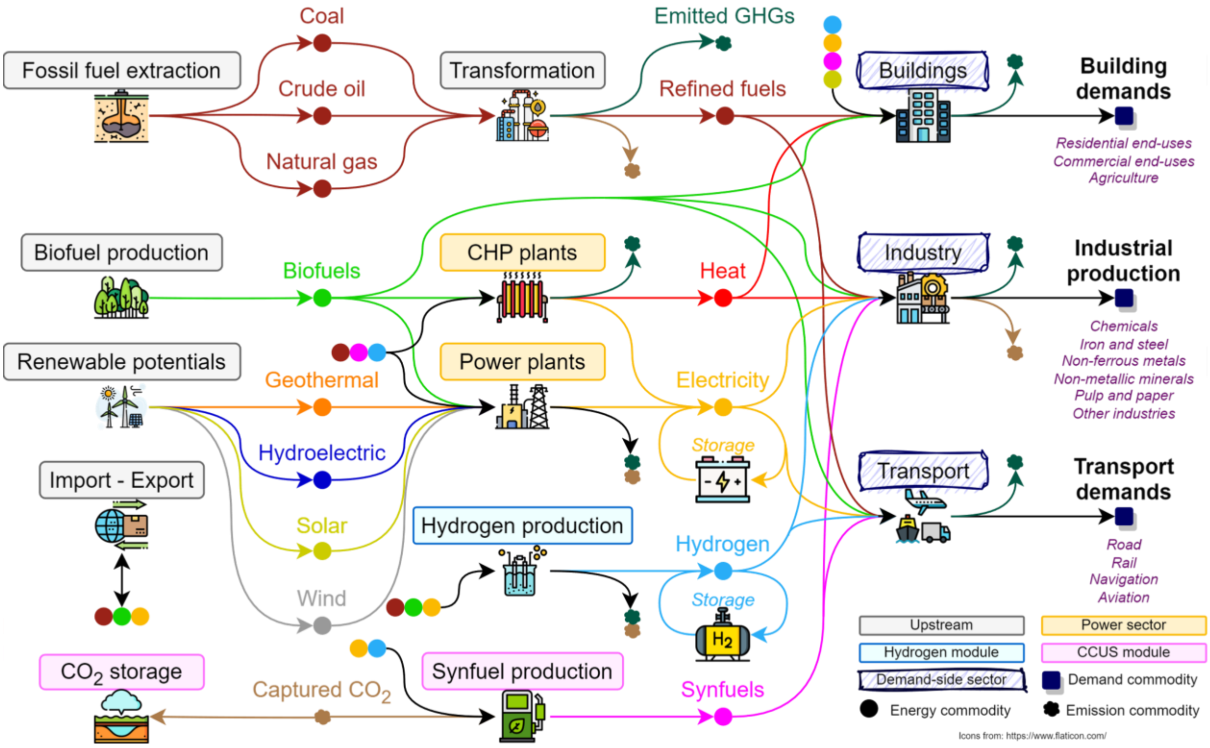

Figure 6. Schematic representation of the whole TEMOA-Italy energy system [89].

The power and the transport sectors are those most interested by this study, which integrate the technology material intensity and, as a consequence, are subject to constraints on material supply. The structure of the power sector is represented in Figure 7, where it is possible to visualize the wide disposal of input commodities. Fossil fuels, biofuels, renewables and hydrogen are the supply sources to the power plants, cogeneration heat and power plants and pure heat plants, producing intermediate commodities such as electricity and heat.

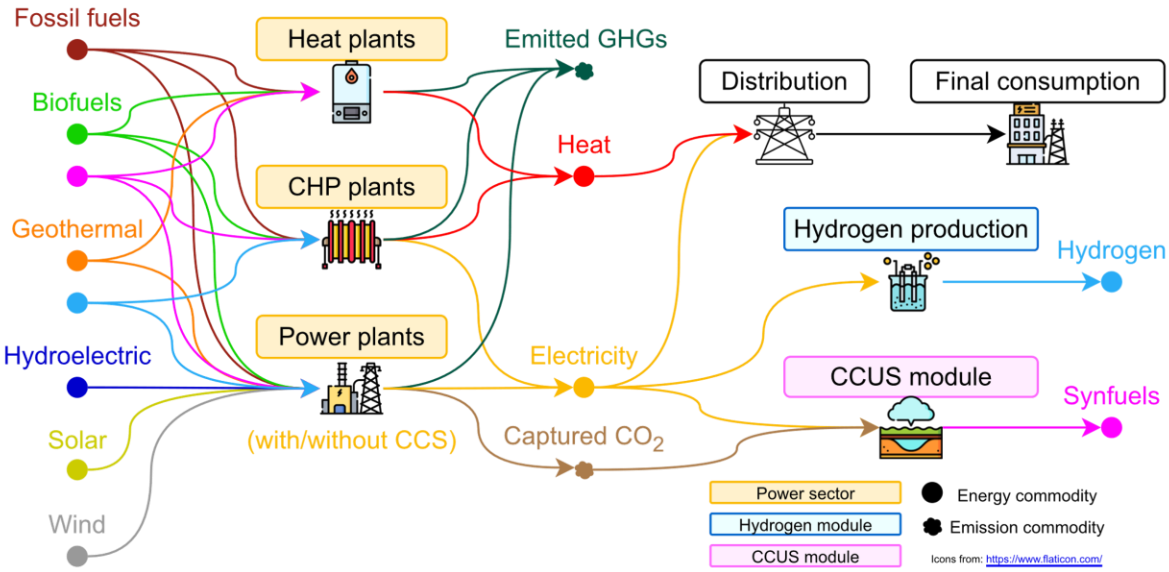

Figure 7. Schematic representation of the TEMOA-Italy power sector [89].

TEMOA-Italy encompasses a wide techno-economic characterization for the power sector technologies, which is deeply analyzed in [89]. An extract is reported in Table 10, where the average values of technical and economic parameters, such as efficiency and technology lifetime and costs are represented.

Table 10. Techno-economic average parameters defining groups of new technologies composing the TEMOA-Italy power sector.

Resource	**Efficiency (%)**	**Lifetime**	**Investment Cost**		**Fixed O&M Cost**		**Variable O&M Cost**	
Natural Gas	35 ÷ 55	30	703 ÷ 1330	M$/GW	21 ÷ 38	M$/GW	0.34 ÷ 1.39	M$/PJ
Coal	40 ÷ 48	15 ~ 30	2240 ÷ 3758	M$/GW	69 ÷ 88	M$/GW	0.64 ÷ 2.22	M$/PJ
Oil Products	40 ÷ 44	30	2240 ÷ 3075	M$/GW	74	M$/GW	2.22	M$/PJ
Biofuels	25 ÷ 40	9 ~ 15	900 ÷ 4416	M$/GW	40 ÷ 151	M$/GW	1.61	M$/PJ
Hydroelectric		30	2250 ÷ 4500	M€/GW	33 ÷ 78	M€/GW		
Geothermal	10	15	3200 ÷ 6000	M€/GW	60 ÷ 86	M€/GW		
Solar		30	620 ÷ 8000	M$/GW	10 ÷ 48	M$/GW		
Wind		20	765 ÷ 5000	M$/GW	33 ÷ 111	M$/GW		
Hydrogen	45 ÷ 47	15	1000 ÷ 3000	M€/GW	56 ÷ 61	M€/GW	8.33 ÷ 29.17	M€/PJ

The transport sector encompasses a broad definition of technologies and commodities, as it is observed in Figure 8. Its structure is based on two main transport categories, namely road and non-road transports. The latter includes rail, aviation and navigation sectors. Each of these categories encompasses different sub-sectors that must satisfy the associated final service demands, projected according to [98]. In the road transport sector two wheelers, cars, and buses for passengers' transport are considered. Light commercial vehicles, medium and heavy trucks represent freight transport. In the same way, rail transport is divided into passenger and freight, while aviation and navigation are classified into domestic and international trips, providing an exhaustive representation of the whole transport sector.

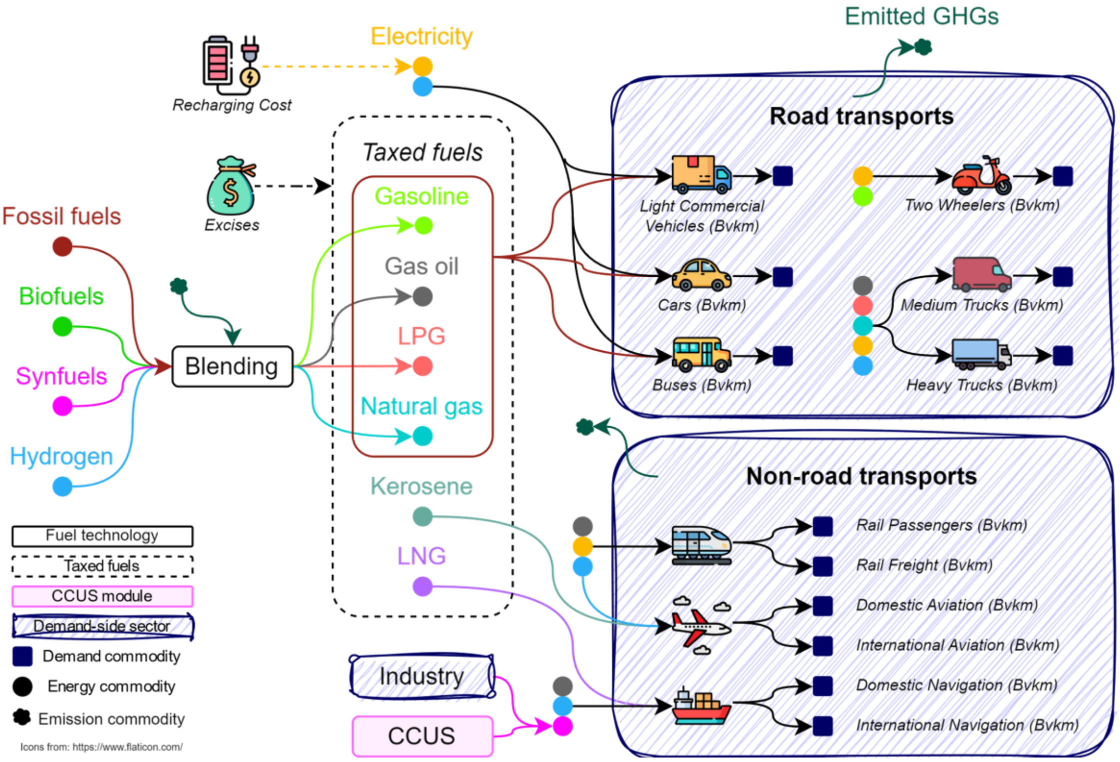

Figure 8. Schematic representation of the TEMOA-Italy transport sector.

Table 11 presents the techno-economic parameters of the cars sub-sector, reporting the lifetime, the efficiency, and the costs of vehicles. As discussed in Section 2.1, the cars sub-sector is the only one within the transport sector interested by the material intensity of the technologies.

Table 11. Techno-economic parameters for new technologies belonging to the cars sub-sector in TEMOA-Italy.

Cars New Technologies	**Lifetime**	**Efficiency (Bvkm/PJ)**		**Investment Cost (M€/Bvkm)**		**Fixed O&M Cost (M€/Bvkm)**
		2020	**2050**	**2020**	**2050**	
Diesel	12	0.43	0.50	1730		63
Gasoline	12	0.36	0.42	1500		63
LPG	12	0.34		1530		64
Natural Gas	12	0.36		1620		64
Battery Electric	10	1.18	1.37	2540	1970	51
Full Hybrid	12	0.51	0.69	1830	1730	62
Hydrogen Fuel Cell	10	0.64	0.94	3770	2920	70

The TEMOA-Italy model version adopted for this work, in addition to the technologies material intensity definition, encompasses a further storage technology, the vanadium-redox-flow batteries (VRFBs), which introduce an alternative to the classic lithium-ion batteries (LIBs) already present in the model. The techno-economic parameters applied are derived from [97], [98], which provide an extensive analysis on the technology costs evolution. These values were also double-checked with the results obtained by [99]. The values reported in Table 12 referred to both centralized and distributed batteries, which are defined assuming a storage capacity of 6h.

Table 12. Techno-economic characterization of the VRFBs in TEMOA-Italy.

VRFBs	Lifetime	Efficiency (%)	Investment Cost (M$/GW)			Fixed O&M Cost (M$/GW)		
			2020	**2030**	**2050**	**2020**	**2030**	**2050**
Centralized	15	0.70	2711	2166	1624	7.7	6.3	4.9
Distributed	15	0.70	2897	2315	1736	8.2	6.7	5.1

3.2 Scenarios definition

The various scenarios investigated in this study are characterized by constraints on the GHGs emissions and on the material supply to the system, which are derived from geopolitical considerations about climate change mitigation and possible risks of material supply chain disruptions. Results obtained by [100], that quantitatively evaluate the potential effects of geopolitical tensions could have on renewable energy investments, show how geopolitical risks negatively affect both short- and long-term investments in the energy system. Further considerations about the risks of material supply chain disruption are analyzed in the IEA clean energy transition risk assessment [101], which provides a set of considerations on the possible risks of mineral supply shortages.

Figure 9 presents the complete set of scenarios analyzed and the associated constraints applied to the model.

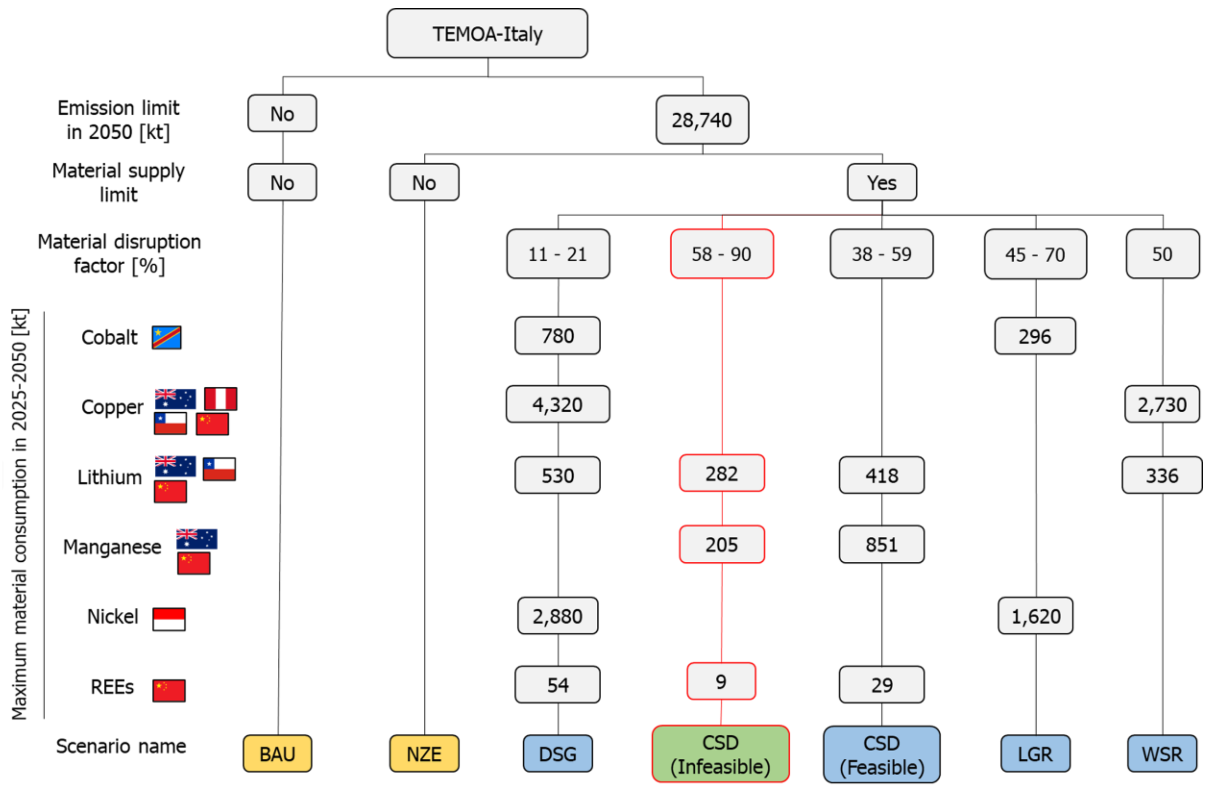

Figure 9. Schematic representation of the studied scenarios and their features.

The reference scenarios defined for this analysis are the business as usual (BAU), which is free from any policy constraint and produces the optimal evolution of the system according to the minimum cost criterion, and the net zero emission (NZE). The latter scenario is limited only to the emission levels and provides the optimal economic solution to reach the decarbonization target. Taking advantage of the model features enabling the system's material consumption evaluation, the material demand in the NZE scenario can be evaluated. Assuming this material consumption as the reference demand required to reach the decarbonization of the energy system, it is possible to analyze the disruption of material supply by applying a disruption factor to the demand derived from the NZE scenario.

The factors applied to the NZE demand are based on geo-political analyses considering the main material exporting countries. In particular, Chinese Supply Disruption (CSD) considers a reduction in the supply of the main materials involved in the Chinese market. The Low Governance Regions (LGR) scenario analyzes the effects of governance instabilities, focusing on Indonesia and Republic Democratic of Congo (RDC) regions. Also, the possible effect due to climate changes is accounted in this analysis, considering the Water Stress Regions (WSR) scenario, which is referring to materials and regions particularly vulnerable to climate changes. Finally, the Demand-Supply Gap (DSG) scenario does not refer to specific regions, but it considers assumptions on the global material production and consumption.

3.2.1 Reference scenarios

The BAU scenario is modeled without the application of external restriction that can influence the model optimization process, considering only technical constraints that guarantee the model calibration.

Instead, the NZE scenario differs from the BAU only for the introduction of external constraints on the total emissions of the system. The considered reduction is extensively analyzed in [96], which relies on the outcomes of the European Commission Fit for 55 package [102] for the 2030 emission reduction target. On the contrary, the constraint imposed to reach the carbon neutrality in 2050 is derived from the long-term Italian strategy on GHG emission reduction[103]. For the objective of this work the restrictions are imposed only on the CO2 emissions of the system and considering a progressive linear reduction. The targets were set to194 Mt in 2030 and a to 29 Mt in 2050.

3.2.2 Material disruption scenarios

As it is represented in Figure 9 all the scenarios involving a restriction on the material supply include the achievement of decarbonization of the energy system, considering the same emission targets introduced in the NZE scenario. Additionally, they account for the possible effects that a variation in the geopolitical conditions can induce on the material supply chains. As reported in Section 3.1, the constraints on material supply are imposed on the future cumulative value of materials consumption, that in this study refers to the period from 2025 to 2050.

The DSG scenario analyzes the eventuality in which a strong demand growth of renewable sources is not adequately supported by an equivalent acceleration in the mining industry investments. This assumption is based on the considerations done by IEA [104], reporting the perspective evolution of the global material demand under different conditions. Moreover, the results observed in a McKinsey's analysis [105] provide a range of material supply-demand unbalance. The range relies on the results obtained by the investigation of three different scenarios which analyzed net-zero transition and the associated deployment of lower-carbon technologies. Each scenario encompasses two distinct cases, which considers different assumption on the evolution of minerals production (mining and refining). Besides it is noticed that natural resources of minerals required for the sustainable energy transition are sufficient to meet the growing demand [106], possible bottlenecks on the material supply could occur if the demand growth outpaces the industry expectation [105].

For the purposes of this analysis, to define the supply-demand gaps, the results provided by [105] are taken as reference. The supply-demand balance range assigned to the "achieved commitments" scenario is considered, which assumes net-zero emission targets are reached by leading countries through purposeful policies. This scenario refers to the base case conditions, encompassing operating mines and projects under construction, in addition to projects for which a feasibility study has been conducted or is currently ongoing. All the announced projects for which any prefeasibility study has not been done yet are excluded. The supply-demand balance proposed in [105] are referred to the period up to 2030. In that period a higher disparity is expected with respect to 2030-2050, where an improved adequacy in the material supply and better technology adaptation [104], [50] allow to reduce the demand-supply gap. Accounting for these aspects and considering that the constraints are imposed on the cumulated amount of material consumption (from 2025 to 2050), the lowest values of the supply-demand balance assigned to the achievement commitment scenario and the base case are taken as reference. These disruption factors are reported in Table 13 and affect the supply of cobalt, copper, lithium, nickel and REEs (i.e., dysprosium, terbium, neodymium and praseodymium).

As it is noticed by [106], the global critical mineral reserves are more distributed than current mineral production, enabling the opportunities for diversifying the supply and reducing the risk of monopoly of mineral production, which could threaten the geopolitical dynamics and resource security. Considering the geopolitical analysis conducted by [6] and more recently investigated in [101], it is noticed that China is covering always more a predominant role in the clean energy market. In this regard, Figure 10 reports both mining and processing minerals distribution at global level, moving from a relatively distributed condition in mining to a Chinese quasi-monopoly for processing.

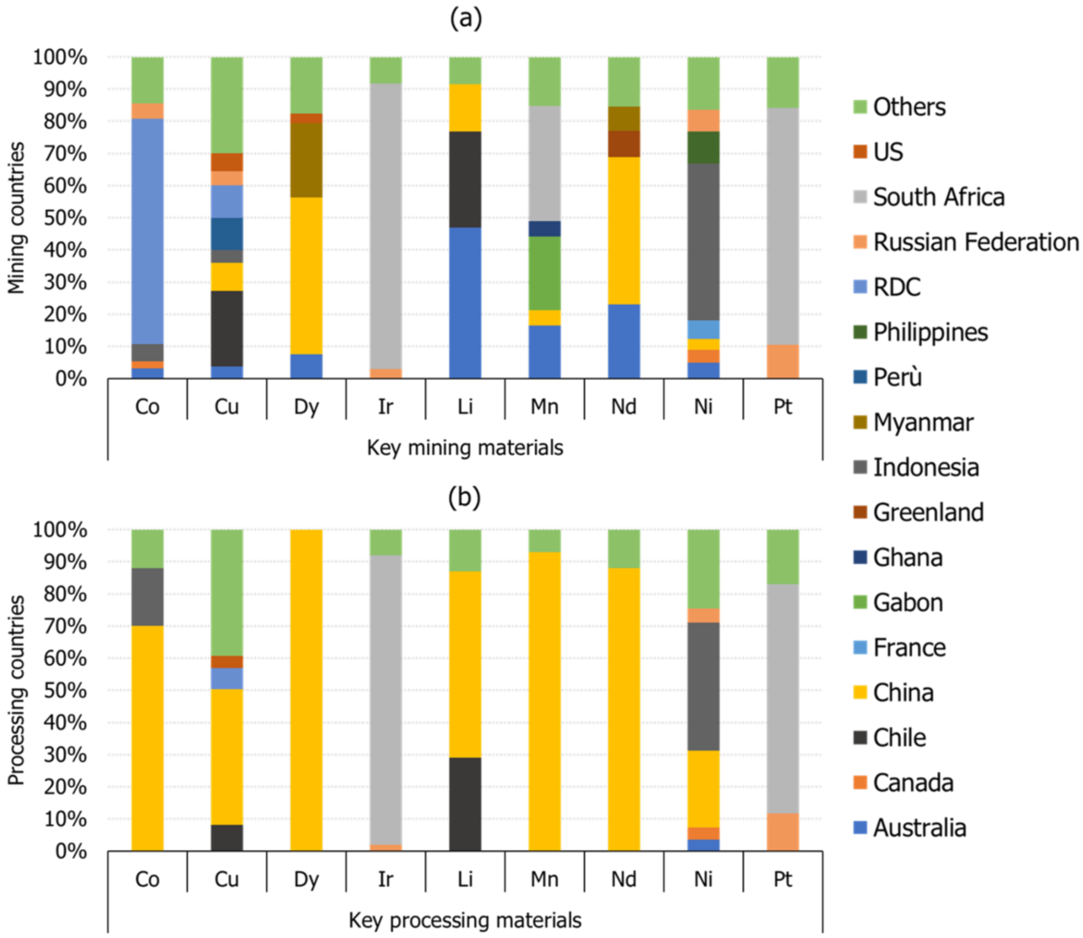

Figure 10. Minerals mining and processing distribution for the main producing countries.

The current mineral industrial conditions may pose strong uncertainties in the future market perspectives for scenarios facing a decarbonization of the energy system, in which an increase in renewable technologies demand is expected, for EVs and LIBs. The higher request of clean energy technologies, which strongly rely on materials such as lithium and REEs, can further boost a concentration of the market toward China, resulting in a dramatic market uncertainty and price peak volatility, as occurred in 2010-2011 with the rare earth crisis [106]. The growing critical materials demand can also lead to export restrictions, representing an important possibility for the developing countries that account for relevant mineral reserves, as Chile, bringing to a nationalization of the mineral industry.

All these factors are considered in the CSD scenario, which investigates the implications of a complete supply disruption from China. It includes dysprosium, lithium, manganese and neodymium. As shown in Figure 9, the complete supply interruption of these minerals from China leads to an infeasible scenario. This result means that the model is not able to reach the decarbonization of the energy system with such restrictions, representing a further bottleneck for the energy transition and threatening the ES of the system under analysis. Hence, the maximum acceptable material disruption factor that allows the system decarbonization is investigated. An equal reduction of the constraints on material supply allows the model to reach the decarbonization targets considering at maximum 65% of supply disruption from China. The resulting disruption factors are reported in Table 13.

A critical aspect that must be considered in the analysis of critical materials scenarios is the political instability. Indeed, today most of the minerals are extracted in countries categorized as either extremely unstable or unstable in the Worldwide Governance Indicators [106], which measure the quality of governance of a region. Further investigations are conducted by IEA [6], in which it is noticed that nickel and cobalt production are in regions with a significant governance instability. Today, Indonesia represents the largest supplier of nickel, covering almost the 50% of production and keeping its predominance also in the next decades [101]. Being it considered as an unstable region; its governance uncertainty can lead to possible disruption in the nickel production with dramatic consequences on its global supply. Similarly to the Indonesian situation, the Republic Democratic of Congo (RDC) covers a predominant role in cobalt mining and processing. The 70% of its global production is in such region, which presents an extremely unstable governance condition. Based on these considerations, the LGR scenario investigates the possibility of a complete disruption of nickel and cobalt from such regions with high political instability.

The last scenario modeled in this study accounts for the effects that climate change could induce on mineral production. As reported in [104], the water needed in mining and processing of critical minerals is often very high. Lithium and copper are considered particularly vulnerable given their higher water requirement. This aspect is extensively analyzed in [6], in which it is observed that more than 50% of Lithium and copper production is concentrated in areas of high or extremely high-water stress, such as Chile and China. The location of these critical materials can threaten their global production, especially in the situation of extreme climate change-related events, such as droughts, which can dramatically affect the water availability. The WSR scenario encompasses all these aspects, investigating the disruption of copper and lithium, considering a reduction of 50% in the global supply due to the concentration of these minerals in such critical regions. For this scenario it is assumed that water shortages impact only on the material supply and not on other model specifics, such as hydrogen production, that can be considered water intensive [107].

The material disruption scenarios are modeled to investigate the effects that specific shortages on future global material production may have on energy system composition and its ES. In Table 13 the disruption factors applied on the TEMOA-Italy material supply in the different scenarios are reported, assuming that the global disruption is reflected on the model supply with the same percentage.

Table 13. Material supply disruption factor for the 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

Chapter 4

Results

4.1 Energy and technology mixes

The results obtained through TEMOA-Italy are here analyzed for the proposed scenarios. In Figure 11 the TPES both in the BAU and NZE scenarios are represented, showing how the supply from the various energy sources changes in the low emissions scenario. It is characterized by a general reduction in the energy supply, due to an increase in the electrification of the end uses and in the average efficiency of demand-side technologies. Specifically, gas supply is strongly reduced and substituted by a higher penetration of biogas. Instead, the energy mix composition does not significantly vary across the different materials disruption scenarios.

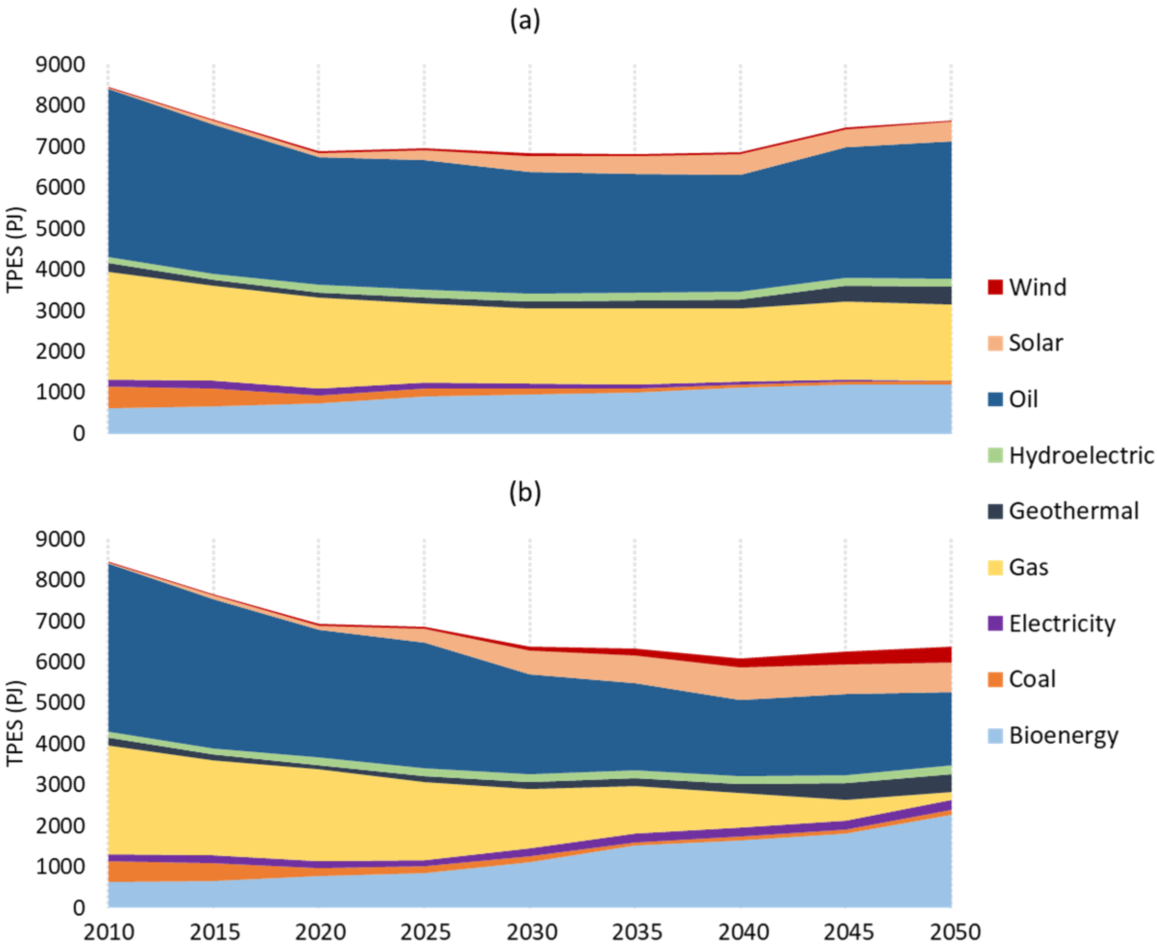

Figure 11. TPES in the BAU (a) and NZE (b) scenarios.

The energy and technology mixes for the various sectors are now analyzed. The power sector encompasses almost the same distribution of energy sources in all the scenarios. Similarly to the aforementioned TPES, the low emission scenarios are characterized by reduction in the gas share thanks to an expansion of renewable sources, such as wind and solar. This result is well represented in Figure 12, showing the power sector capacity (Figure 12a) and electricity production (Figure 12b), including also hydrogen and storage technologies. All the scenarios are the same in 2020 due to calibration. Then, all the low-emissions ones (NZE + materials disruption scenarios) encompass a significant penetration of solar and wind technologies in 2050. The penetration of traditional NGA power plants and hydropower is almost unchanged. Considering the materials supply disruption scenarios the only remarkable variation is noticed in the WSR power sector capacity, which presents an important fraction of hydrogen. Indeed, the deployment of PEMFC emerges as the optimal choice to satisfy the reserve margin constraint in place of the natural gas capacity in this scenario, due to the application of the lowest constraint on the copper consumption (see Figure 9) and the high copper intensity of natural gas power plants (see Table 5). Note that the material intensity of hydrogen production technologies is neglected in this analysis, and this may influence this outcome.

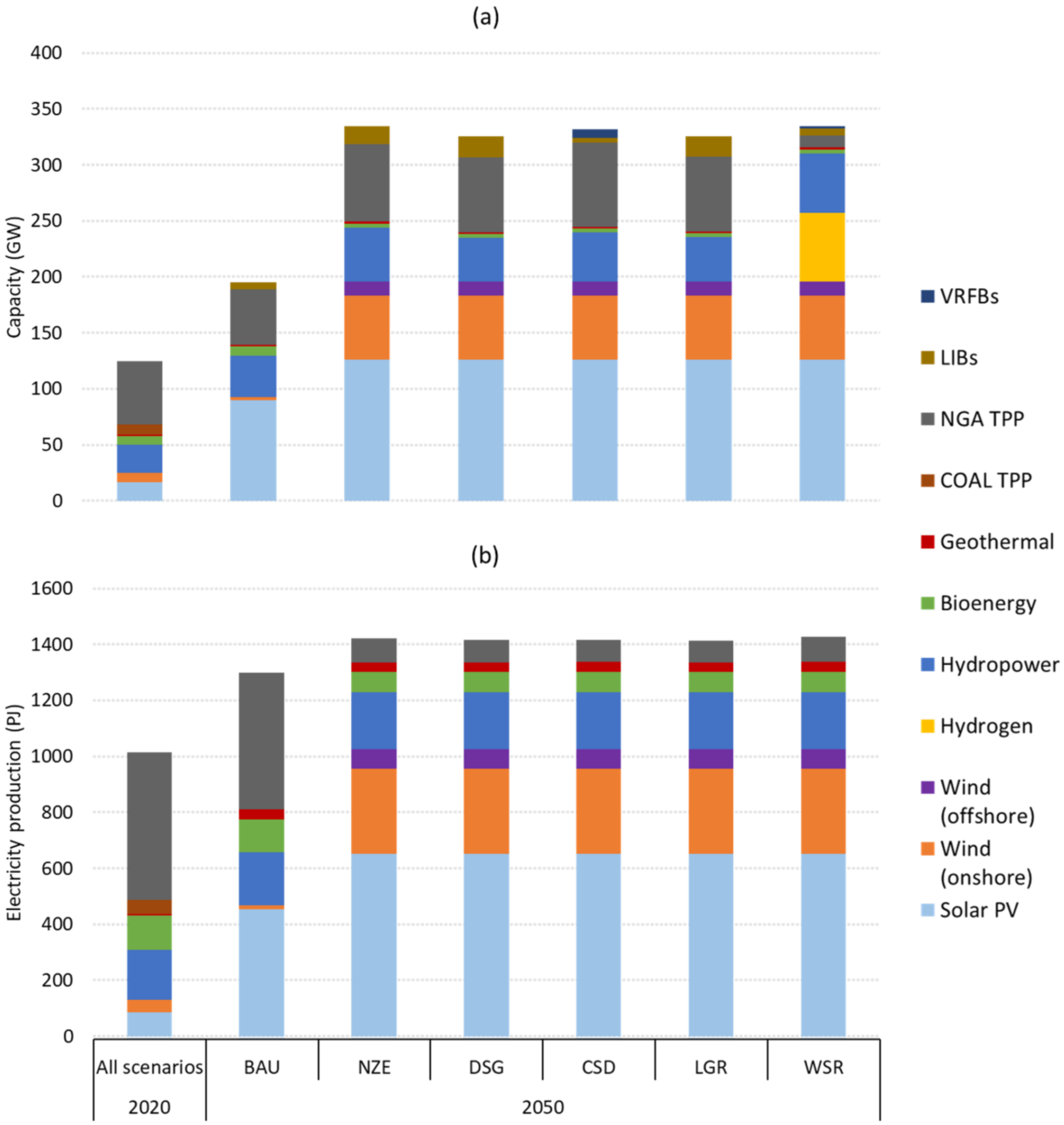

Figure 12. Power sector capacity (a) and electricity production (b) by different technologies and scenarios.

In Figure 13 the storage activity in 2050 for the different scenarios is reported, reaching the peak in the DSG scenario with 19 GW of storage capacity installed. LIBs are the main storage solution. However, the lowest associated penetration is observed in the scenarios characterized by a higher lithium disruption, in which a little VRFB penetration occurs.

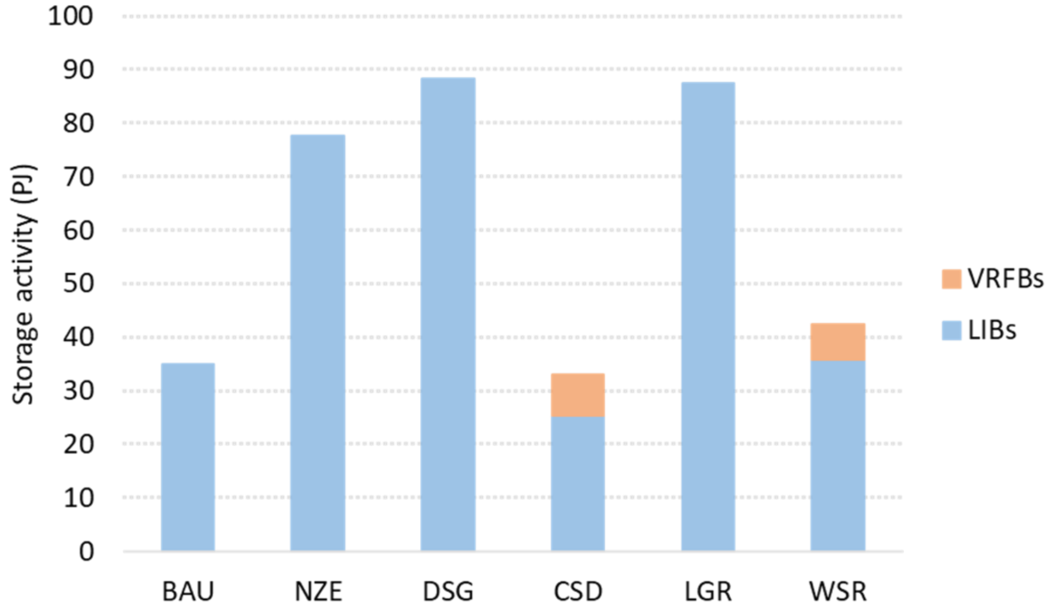

Figure 13. Storage activity in 2050 for different technologies and scenarios.

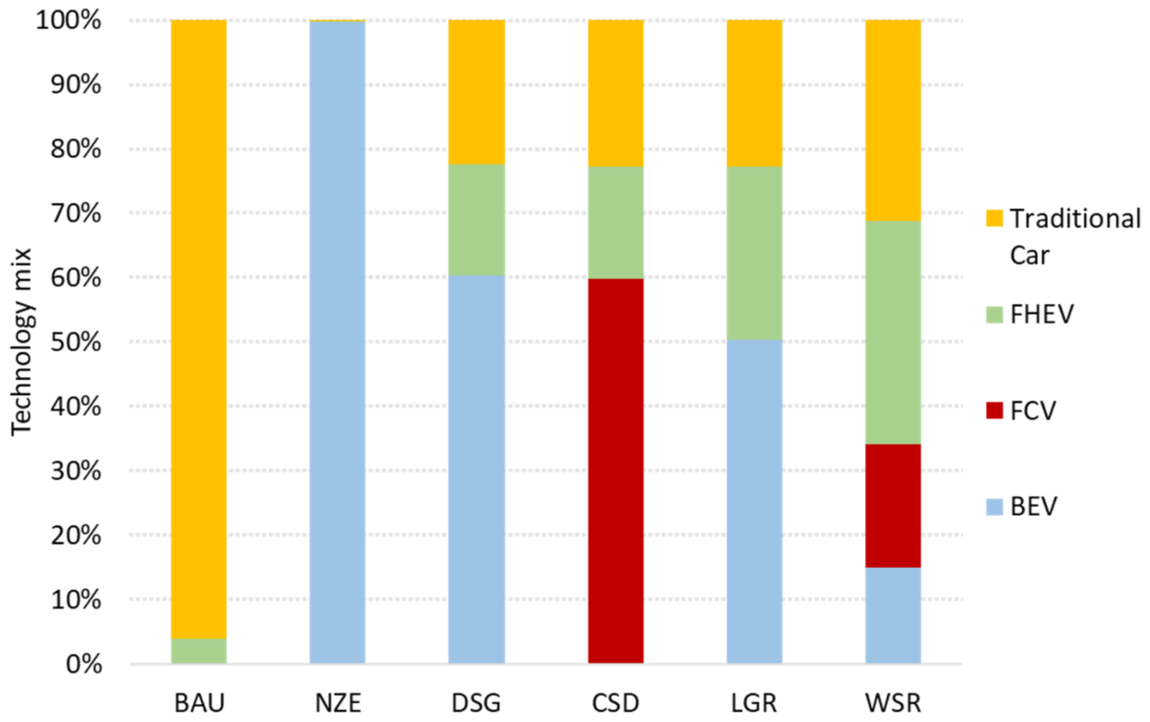

Figure 14. Demand satisfaction by car technologies in the various scenarios in 2050.

The cars transport demand in 2050 accounts for the 65% of the total road vehicles demand, representing the dominant road vehicles sub-sector. Figure 14 shows the cars technological mix in 2050.

The mix strongly changes, moving from a situation of quasi-monopoly of traditional vehicles in BAU and BEVs in NZE, to a more diversified portfolio in the other scenarios. In decarbonization scenarios BEVs are always considered as a suitable alternative to the traditional ones, except in CSD and WSR scenarios. The CSD scenario encompasses important limitations on lithium and manganese supply, which are consumed less in FCVs than in BEVs. In addition, this scenario considers strong shortages of REEs, in particular for dysprosium, that is not much present in FCVs. The combination of such supply disruptions produces a strong reduction in the BEVs penetration, till a complete substitution from FCVs in CSD scenarios.

4.2 Energy security

The time evolution of the complete set of ES indicators is here discussed to provide a comprehensive overview of the ES of the system. The MSR evolution is observed in Figure 15, showing that the low emission scenarios present much higher risks with respect to the BAU scenario. This result is related to the strong penetration of renewable technologies and in particular to the low carbon vehicles, whose installation is higher in the last years of the time horizon (2045-2050). The NZE scenario is characterized by a progressive BEVs penetration, resulting in a higher average value of risk. On the contrary, the materials disruption scenarios present a limited introduction of low carbon vehicles up to 2035. Then, their installation increases, reaching the peak at the end of the time horizon. This result is particularly relevant in the DSG and CSD scenarios, whose MSR peaks exceed the NZE one.

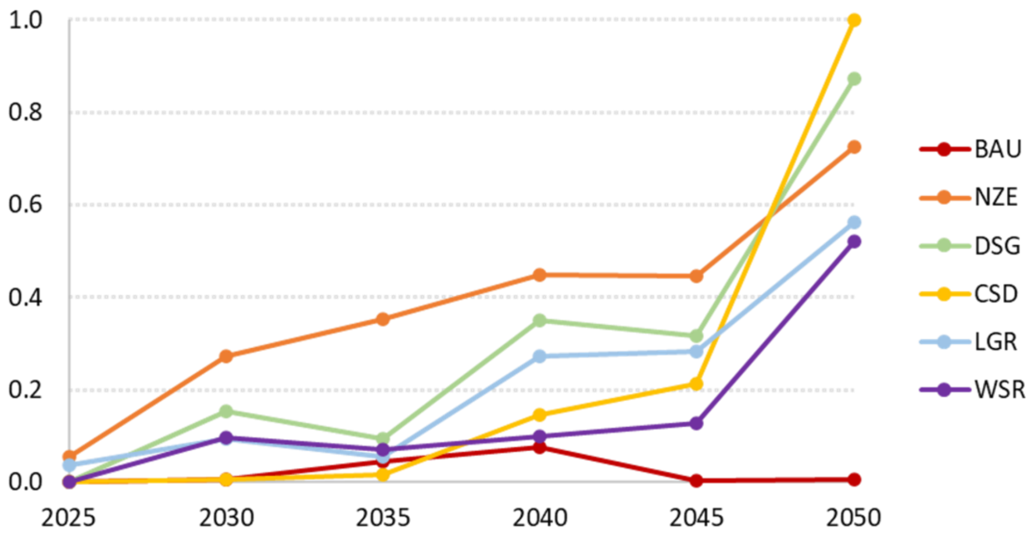

Figure 15. MSR time evolution.

In Figure 16 the trends of RES (Figure 16a) and the SS (Figure 16b) indicators are shown. They are not particularly different in the decarbonized scenarios, but results much higher than the BAU. This result is connected with the TPES mix of the system (see Section 4.1). The low RES and SS values for the BAU scenario are mainly due to the high gas imports. While the low emission scenarios are characterized by similar TPES mixes, resulting in similar RES and SS trends.

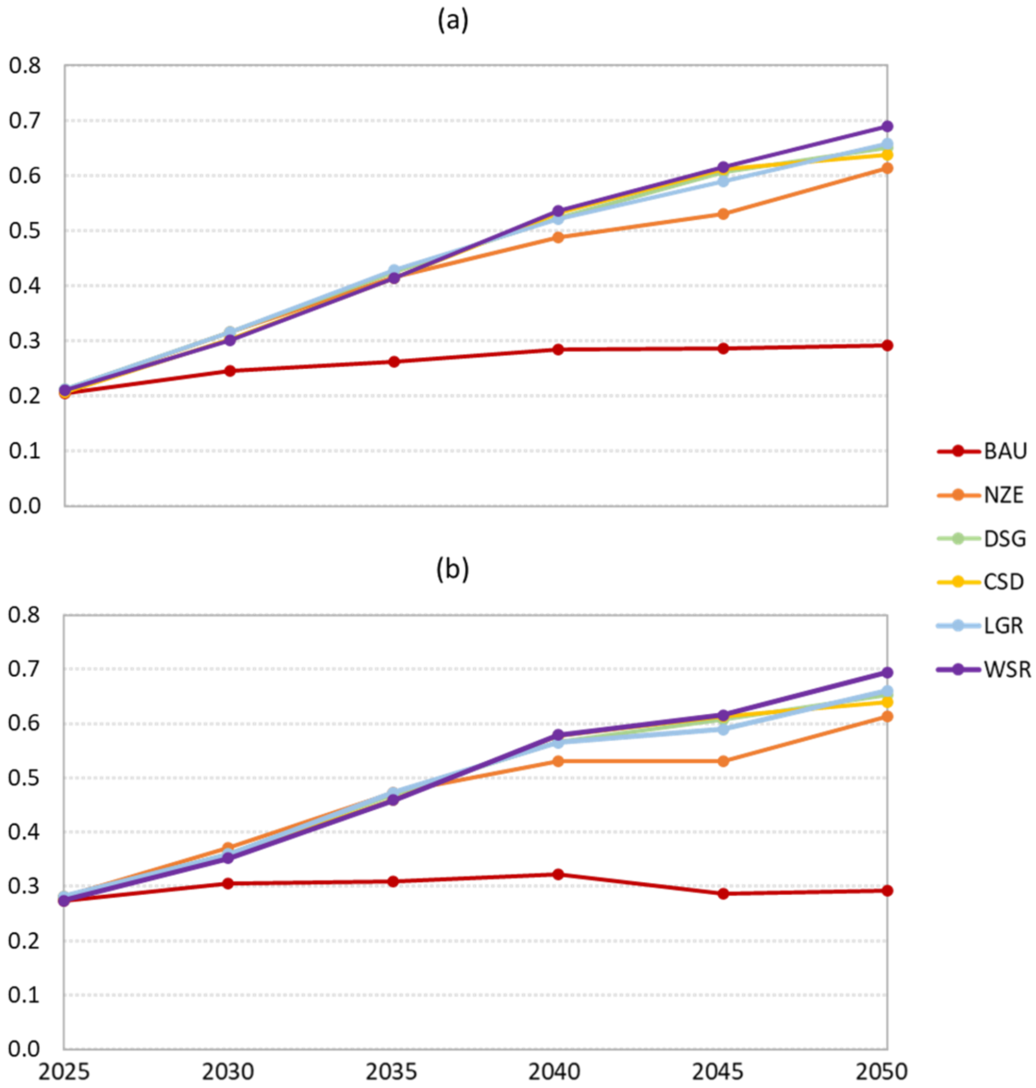

Figure 16. RES (a) and SS (b) time evolution.

A similar considerations can be done for the DES and EI, which are analyzed in Figure 17. In particular, the DES (Figure 17a) presents high values in all the scenarios, where the intensive gas consumption observed in BAU is partially substituted by a strong introduction of bioenergy sources in the decarbonized scenarios. On the other hand, the EI (Figure 17b) of the system is equally reduced in all the low emission scenarios, due to a higher electrification of the end use sectors and with a consequent enhancement in the energy efficiency with respect to the BAU evolution. As for the MSR, the reduction in the EI of the system involves an increase in the final ES.

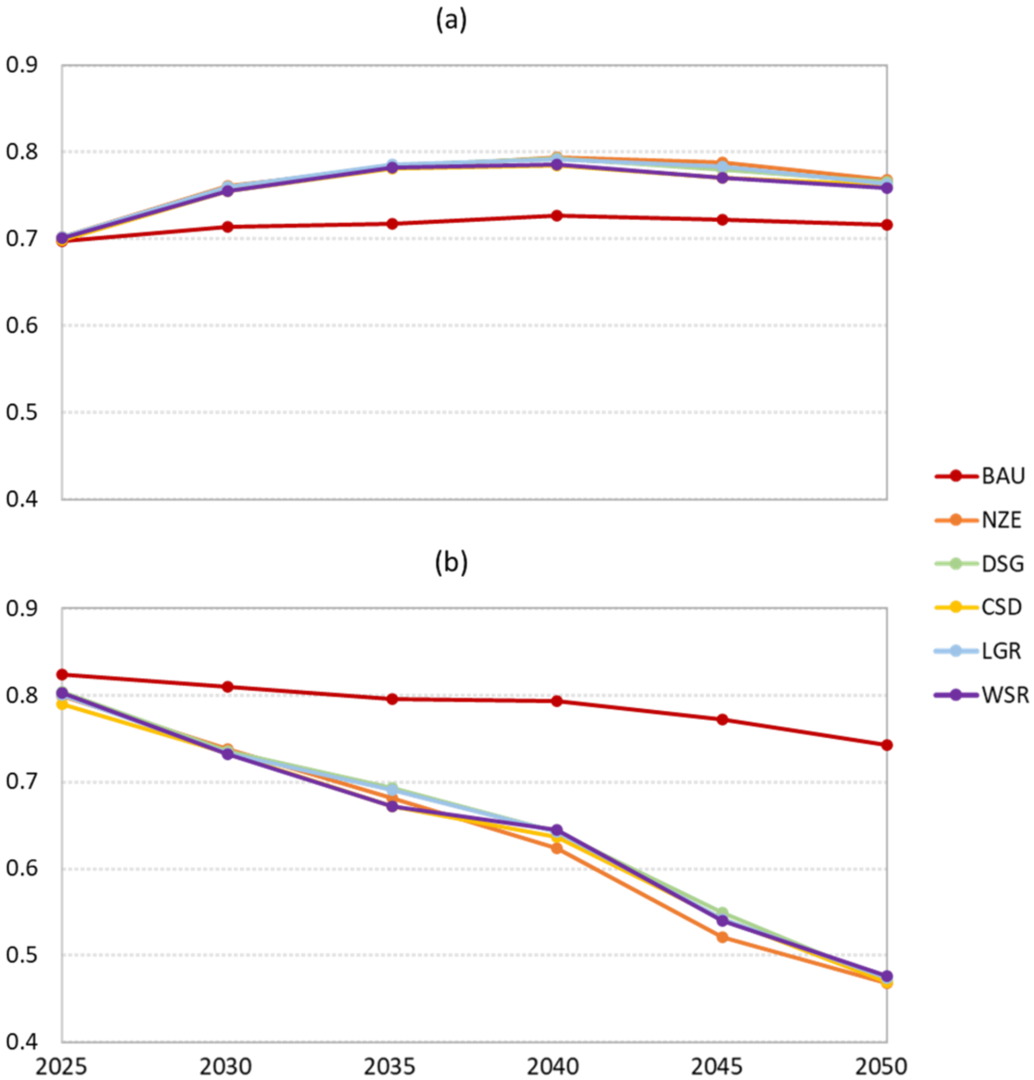

Figure 17. DES (a) and EI (b) time evolution.

The CF and CC of the energy system are reported in Figure 18a and Figure 18b, respectively. Being the technological composition of the power sector (see Section 4.1) almost unchanged in the different decarbonization scenarios, also its CF and CC indicators do not significantly change, since they are directly related to the power sector structure. In addition, it is noticed that the CF reduces over time. This is due to the higher penetration of renewables, presenting a lower CF with respect to the traditional power technologies.

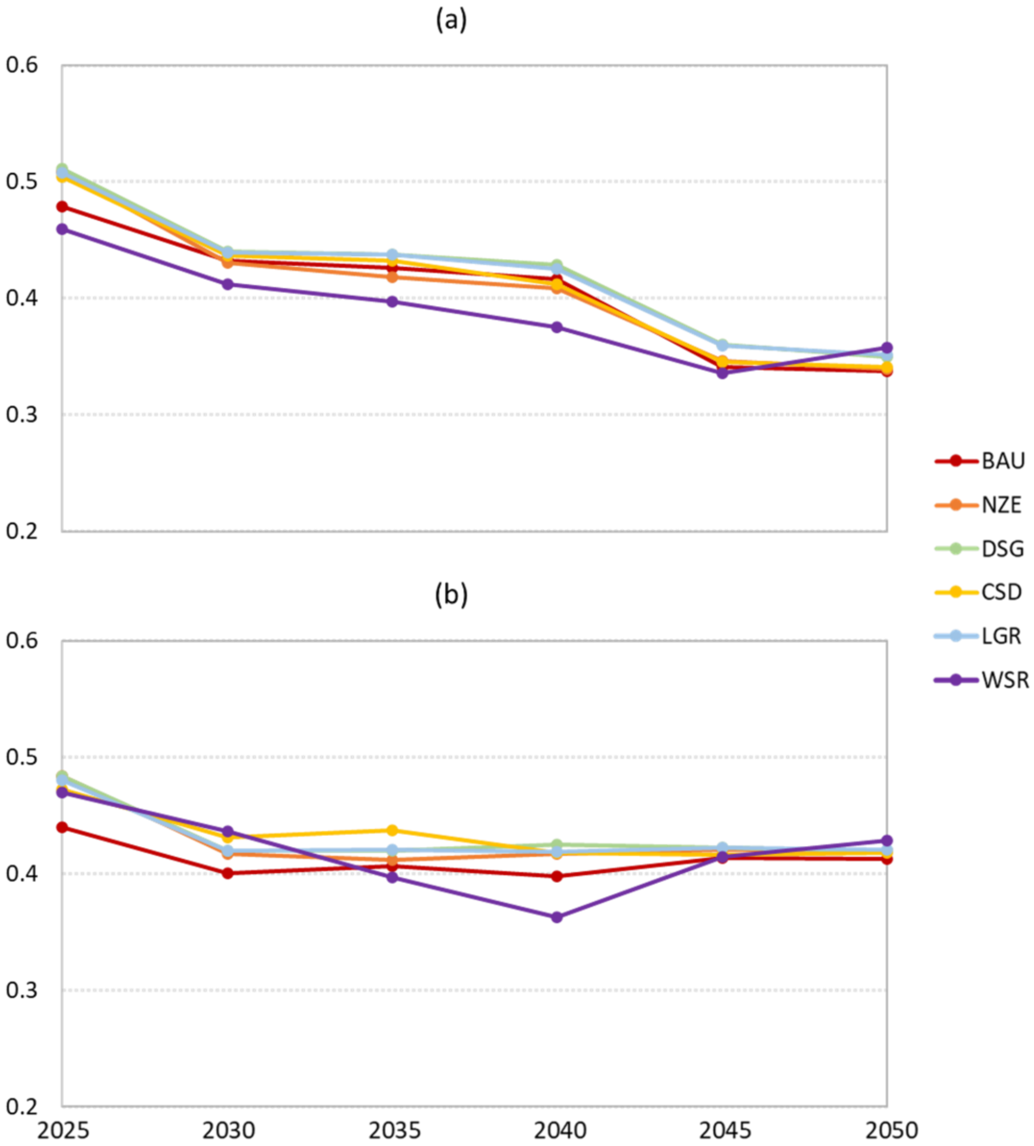

Figure 18. CF (a) and CC (b) time evolution.

Figure 19 shows the time evolution of the ESI, which is evaluated considering the MSR dimension separately from the energy supply risk and reliability dimensions (see Equation (16)). This procedure assigns a higher weight to the MSR. The latter induces stronger effects on the ESI development, especially in the final portion of the period, closer to 2050, when the MSR of the materials supply disruptions scenarios reaches its peak (see Figure 15).

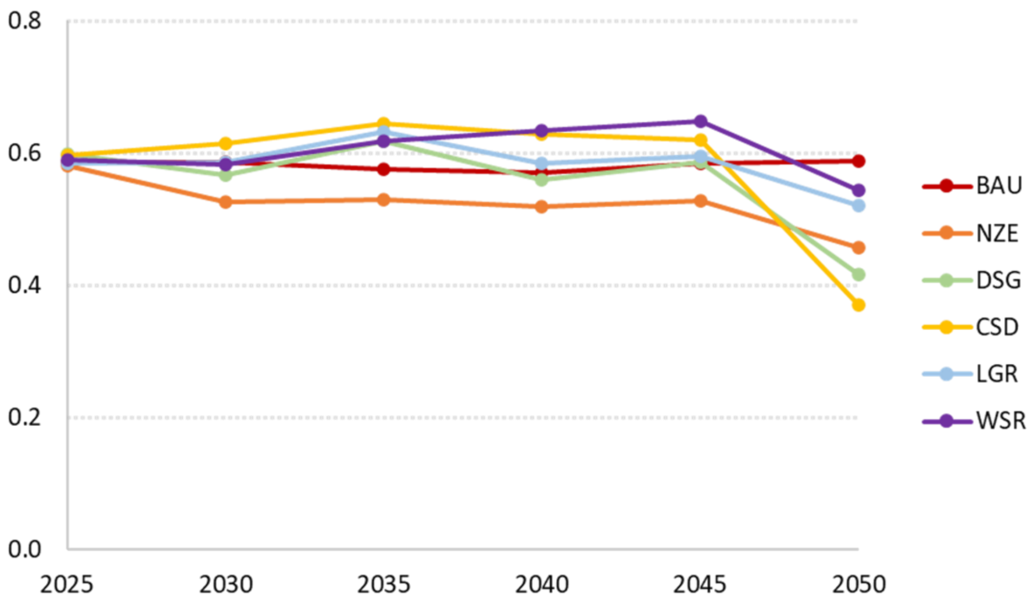

Figure 19. Temporal evolution of the aggregated ESI.

In Figure 20 the average levels of ESI over the 2025-2050 period are reported. These resulting values provide a general overview of the ES for the specific scenarios, allowing to recognize the energy system configuration that averagely presents the highest level of ES. Figure 20 also shows the average contribution of the various indicators in the ESI, noticing that the MSR has the largest variability among all the scenarios, while the other indicators are almost constant.

Considering an ESI ideal maximum value of 1, the average ES level in the various scenarios is quite far from such an ideal condition. None of the scenarios present an average value lower than 0.5, considering also the strong reduction in the last portion of the time horizon for the materials supply disruption scenarios. Figure 20 shows that the maximum value reached is equal to 0.6, observing that averagely the ESI variation is not so strong. The NZE scenario provides the lowest level of ES, this is mainly related to the high MSR obtained from the quasi monopoly of BEVs (see Section 4.3). On the other hand, BAU is based on more traditional technologies, relying less on CRMs and resulting in a much higher level of ES with respect to the NZE scenario. In Figure 20 the highest value of ES is reached in the WSR scenario, which analyzes the potential risk of lithium and copper disruptions, providing a more diversified energy system with respect to the other scenarios. In particular, the WSR energy system encompasses both the available storage technologies (LIBs and VRFBs) and a well-diversified transport sector (see Figure 14).

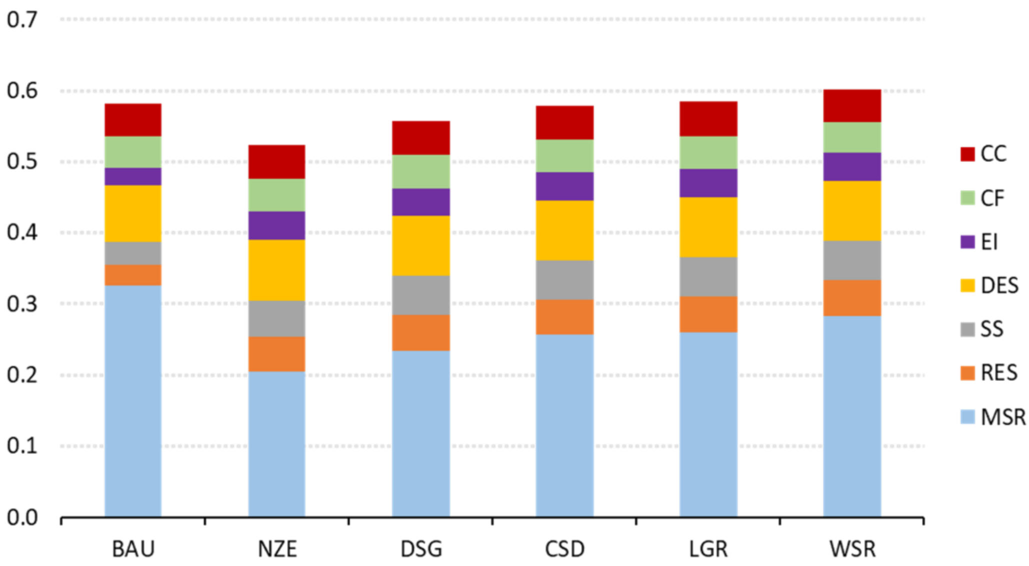

Figure 20. Aggregated ESI and indicators contribution in 2050.

4.3 Material supply risk

As reported in Section 4.2, the MSR is a parameter having relevant implications on the final ES value. In this section a deeper analysis of this indicator is performed.

The different technology mixes observed in Section 4.1 determine the amount of minerals consumption and MSR of the energy systems. In Figure 21a, the cumulated power sector's material consumption, from 2025 to 2050, is shown for the various scenarios. In the evaluation of material consumption and MSR the power sector encompasses also the storage technologies. It is noticed that in the decarbonization scenarios the amount of minerals consumed is much higher than in the BAU scenario, almost the double. For these scenarios the order of magnitude is about some Mt, between 3.4 Mt (WSR) and 4.4 Mt (DSG). In particular, solar PV, wind and storage technologies cover approximately the whole consumption.

The material consumption of transport sector is shown in Figure 21b. It is observed how the low carbon vehicles influence the consumption at system level. In the NZE scenario, which is characterized by a strong penetration of BEVs, the amount of minerals consumed in the period from 2025 to 2050 exceeds the 16 Mt, resulting roughly 6 times the BAU consumptions. The BEV are the vehicle technology presenting the highest material consumption (see Section 2.1), therefore the scenarios which encompass a higher penetration of this technology are also the scenarios which consume more minerals, resulting in a MSR growth. Due to a higher diversification of transport technologies in the materials supply disruption scenarios, a portion of BEVs is substituted with less material intensive technologies such as traditional cars and FHEVs. The traditional cars mainly rely on diesel vehicles, in which the fraction of biodiesel consumed is growing from 7% in 2025 up to 30% in 2050. These technology mixes show a lower material consumption increase due to the decarbonization, positively affecting the MSR of the whole system.

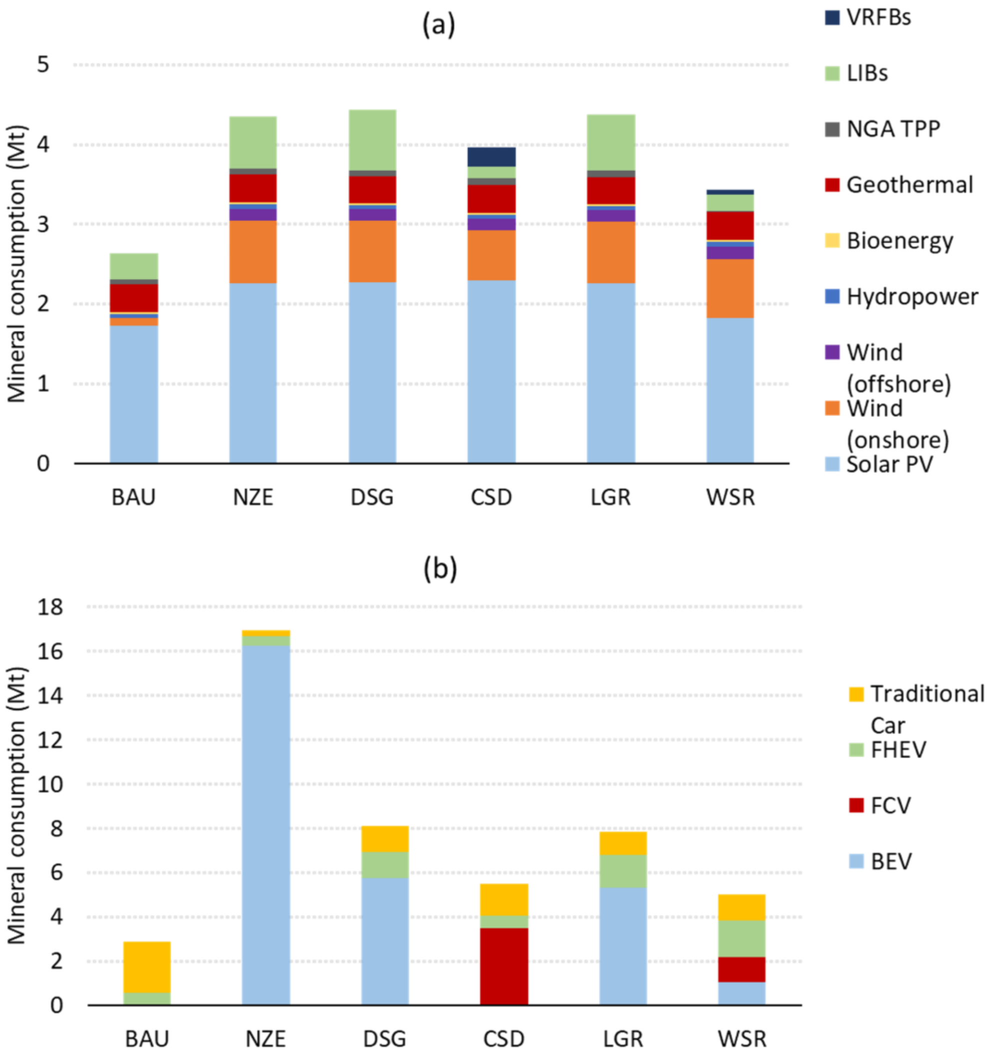

Figure 21. Mineral consumption of power sector (a) and transport sector (b) in the period between 2025 and 2050.

Finally, in Figure 22 the specific minerals cumulative consumption from 2025 to 2050 is represented. It is noticed that the transport sector (Figure 22b) is much more material intensive than the power sector (Figure 22a). Lithium and cobalt consumptions are dozens of times bigger, except for the CSD scenario, for which there is no BEVs penetration. It can be observed that aluminum and copper cover a predominant role in the energy systems mineral demand, representing almost 70% of the total power sector demand. It is observed that manganese and nickel are other major minerals in the power sector. Instead, the transport sector shows a more diversified materials requirement, especially in the decarbonized scenarios. From the analysis conducted it results that the transport sector has an average REEs consumption four times bigger than the power sector, with an average value of 52 kt in the decarbonized scenarios. In the power sector the REEs are mainly involved in electric motors for wind plants. While in the transport sector the REEs consumption is not only due to the electric motors of BEVs and FHEVs, but also the FCVs present an elevated REEs consumption principally related to the fuel cell components.

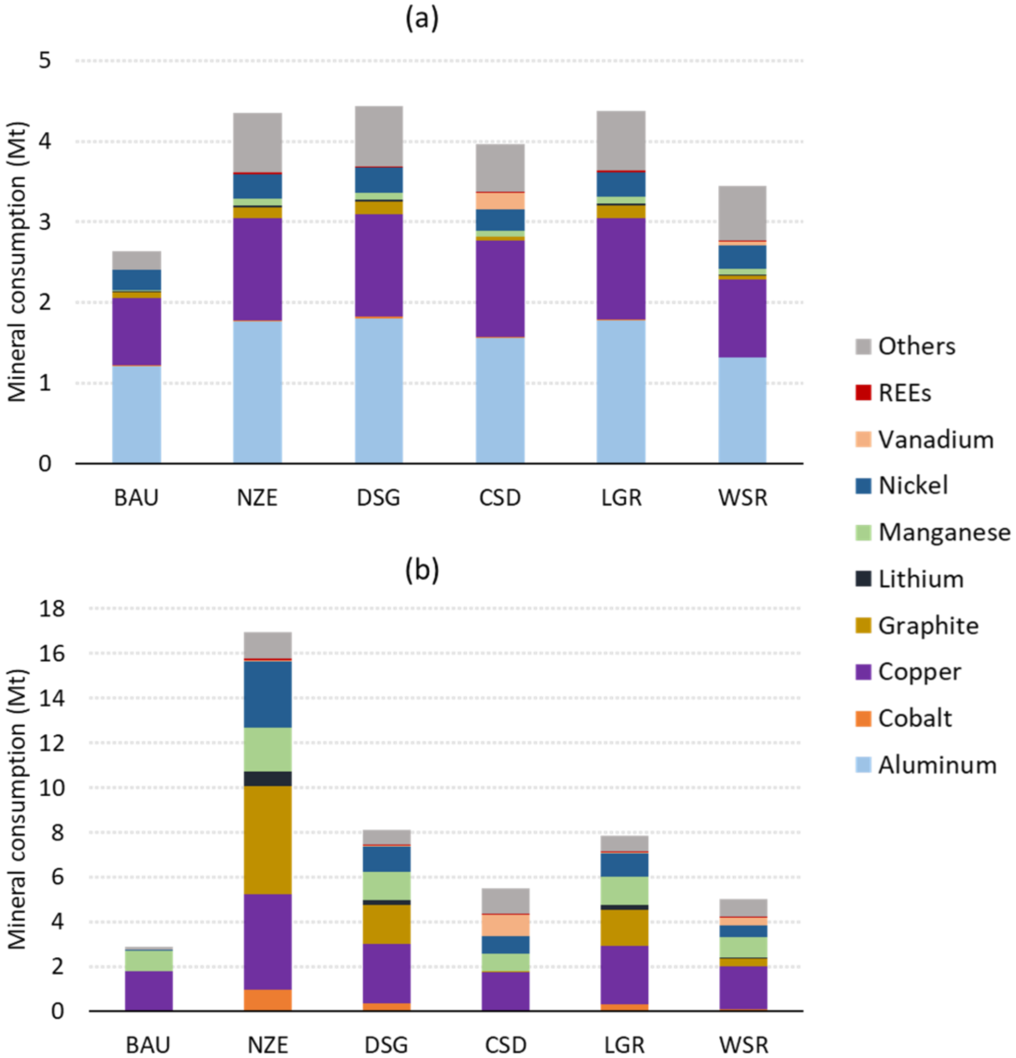

Figure 22. Specific material consumption of power sector (a) and transport sector (b) in the different scenarios, from 2025 to 2050.

The methodology applied to evaluate the energy systems MSR considers also the effects of the global material consumption (c_i) (see Equation (1)). In particular, the share of global consumption was assumed constant along the entire time horizon. But considering the application of a global material supply disruption factor in the analyzed scenarios, this assumption is not consistent with the model constraints. So, it was decided to apply the percentage values of disruption factors also to the c_i values for the MSR evaluation. An example is shown in Table 14, where the DSG and WSR disruption factors of 21% and 50% respectively, are applied to the global consumptions of copper and lithium. In these scenarios copper and lithium vary their global consumptions accordingly with the factors of disruption scenarios (see Section 3.2).

Table 14. Effects of the materials disruption factors on the global materials consumption.

Material	Global consumption (c_i) $\left(\frac{kt}{y}\right)$		
	NZE	DSG	WSR
Copper	20,547	16,232	10,273
Lithium	57	45	29

Applying the Equation (1), a reduction in global consumption (c_i) results in a further MSR increase. An example of the effect of this assumption is reported in Figure 23 for the CSD and LGR scenarios. Comparing the MSRs in which the disruption factors are applied (CSD' and LGR') with respect to the MSRs that consider always the same share of global consumption (CSD and LGR), an increase in the MSR is observed. In particular, a shortage in the supply of specific materials (see Section 3.2.2) causes a MSR increase in of almost 20%.

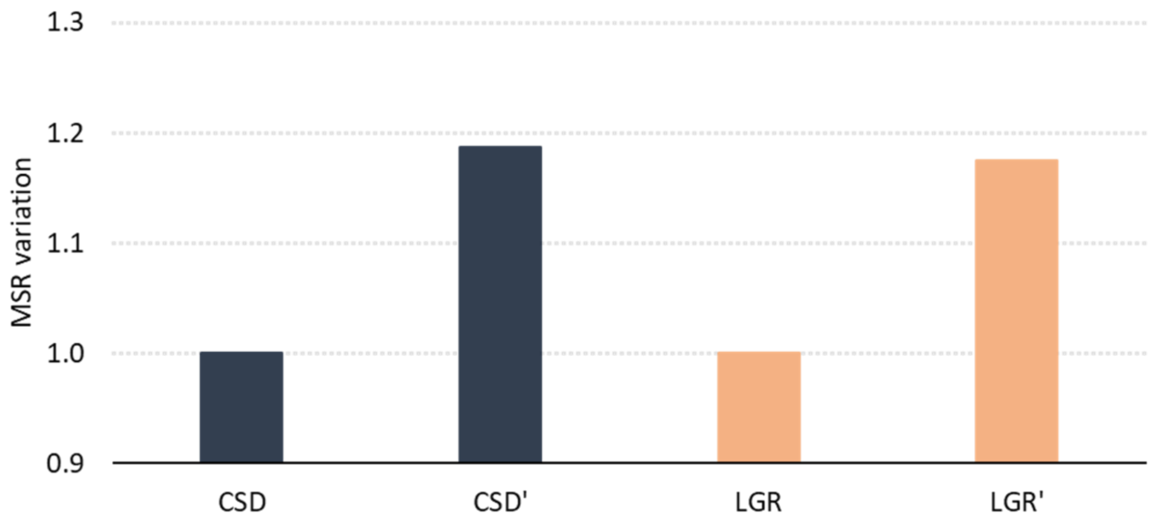

Figure 23. Comparison between the MSR without the application of disruption factors (CSD and LGR) and with their introduction (CSD' and LGR').

Figure 24 shows the values of MSR reached in the different scenarios, considering separately the power sector (Figure 24a) and the transport sector (Figure 24b). The cumulative MSR from 2025 to 2050 is evaluated by normalizing with respect the BAU scenario. This is done to show the MSR growth in the decarbonized scenarios compared to the most conservative condition (BAU). It is noticed that the maximum power sector MSR increment is observed in the CSD scenario, where the VRFBs provide a relevant contribution (see Figure 24a). It is also observed that wind technologies cover always a predominant role in the MSR of the power sector, this is due to the presence of REEs in the electric motors. Instead, in the transport sector the highest MSR refers to the NZE scenario due to the high BEVs penetration (Figure 24b). An important result can be observed comparing the material consumptions and the values of MSR. Figure 22 shows that the aggregated material consumption in CSD scenario is roughly 10 Mt, while in the LGR scenarios it exceeds 12 Mt. On the contrary the LGR's MSR is lower than the CSD's. This result demonstrates that a higher material consumption is not directly connected to a higher level of MSR.

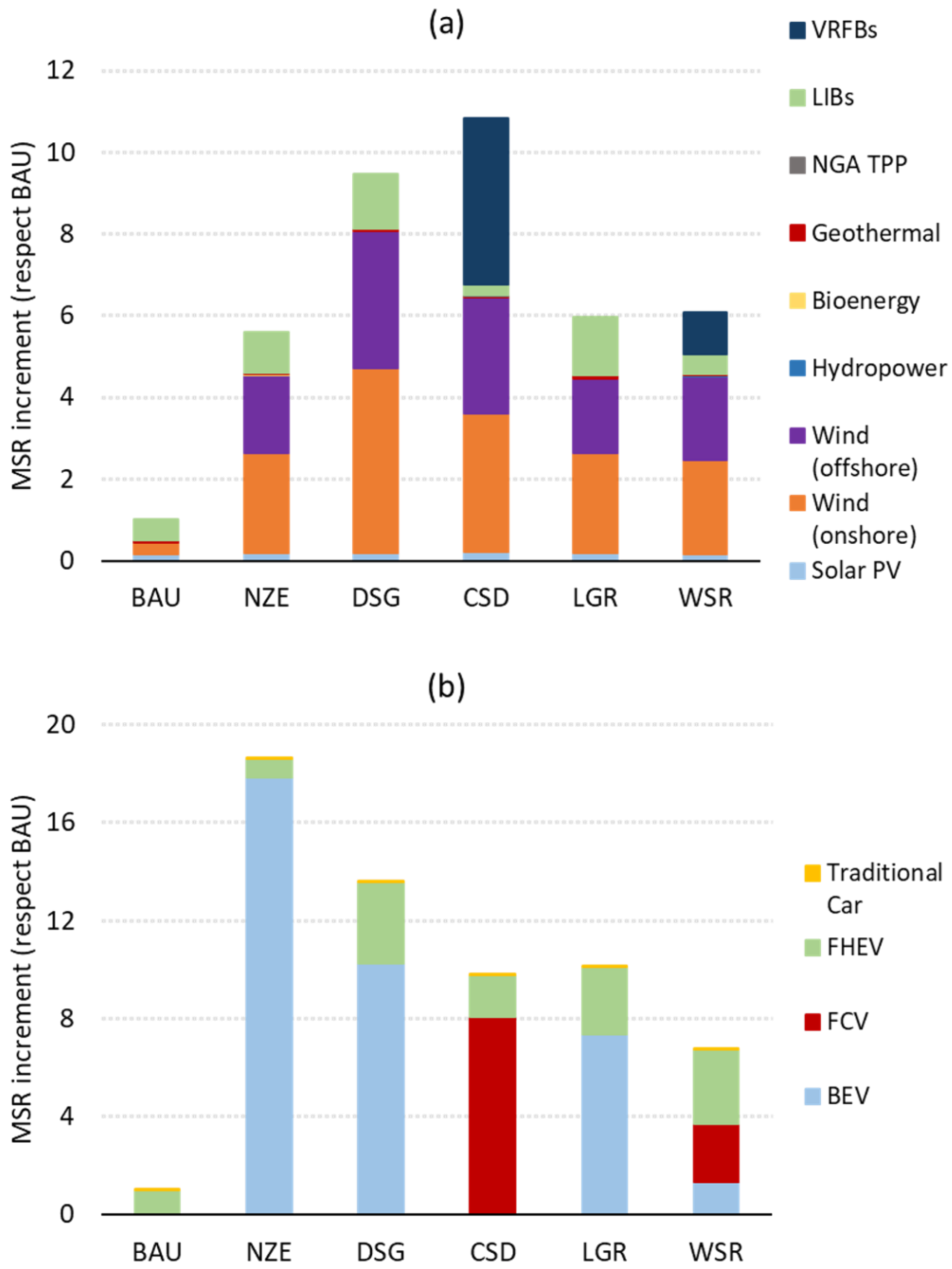

Figure 24. MSR values of power sector (a) and transport sector (b) of the different scenarios compared with respect to the BAU scenario over the time period (2025-2050).

In Figure 25 the comprehensive MSR of the system is represented. It encompasses both power and transport sectors and the values of the different scenarios are normalized with respect to the BAU scenario. Analyzing this indicator, it is possible to notice that the transport sector influences more the final MSR (from 83% to 95%) than the power sector. This result suggests paying particular attention to the mineral demand from transport sector. Except for the NZE scenario, which presents a strong disparity between the transport and power sector materials consumption, the consumption is comparable in the other decarbonized scenarios. This condition means that the transport sector relies on a higher consumption of more critical materials, e.g. cobalt and lithium, that are mainly involved in electric batteries. In particular, the cobalt consumption in the transport sector is averagely thirty times higher than in power sector, for the decarbonized scenarios, consuming almost 353 kt. Instead, the average lithium consumption is 239 kt, that is 16 times higher in the transport sector than in the power sector.

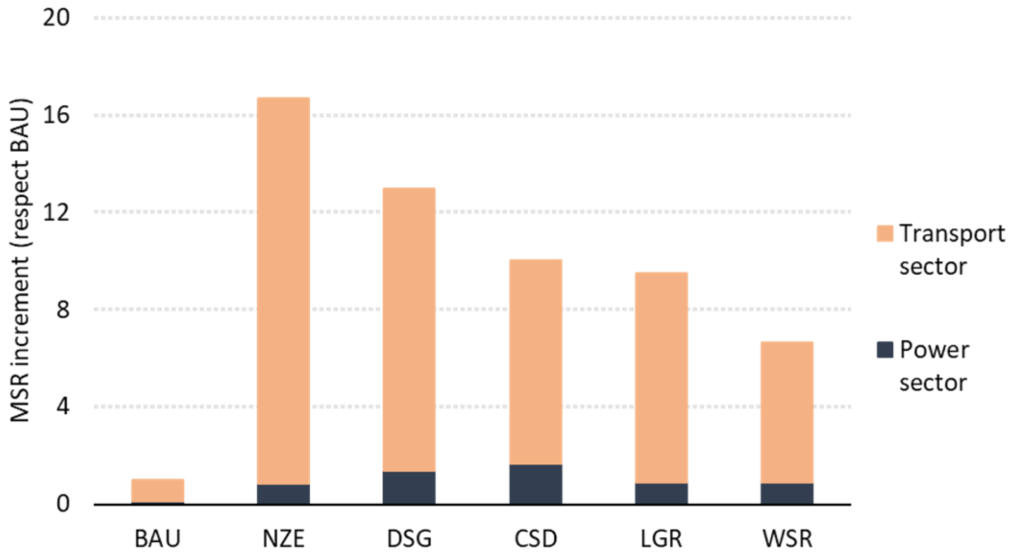

Figure 25. Comprehensive MSR normalized with respect to the BAU scenario over the time period (2025-2050).

Figure 25 also reports how the MSR is significantly changing across the low emission scenarios. This is due to the energy system composition. The minimum MSR occurs in the WSR scenario, which encompasses the highest diversification of transport technologies. This result suggests that to reduce the risk related to the materials supply disruption a diversification of the investments is more effective than the installation of a single technology.

4.4 The cost of energy security

Finally, the ES costs are estimated. The total cost of the energy system and its resulting level of ES (see Figure 20) are analyzed for each scenario. Figure 26 reports the total costs of the energy system expressed in billion euros (B€) and the respective level of ES. As mentioned in Section 3.2.1, the BAU scenario represents the least-cost evolution without emissions constraints of the system and therefore it presents the lowest cost. Instead, the decarbonized scenarios are far from the BAU optimal conditions, resulting in a higher cost of the energy system. And being the energy system in the materials supply disruption scenarios modelled to resound to global geopolitical risks, its composition results more expensive than the NZE system. This means that higher total system costs are associated with higher ES levels. In this regard, Figure 26 also defines the regression line of cost and ES, from which the BAU scenario is excluded. The slope of the line represents the additional cost per security unit earned. The resulting value is about 8.7 B€/% of ES and it represents the growth in costs with respect to the percentage ES increment. In particular, the costs increase approximately of 130 B€ while the ES almost of 15%.

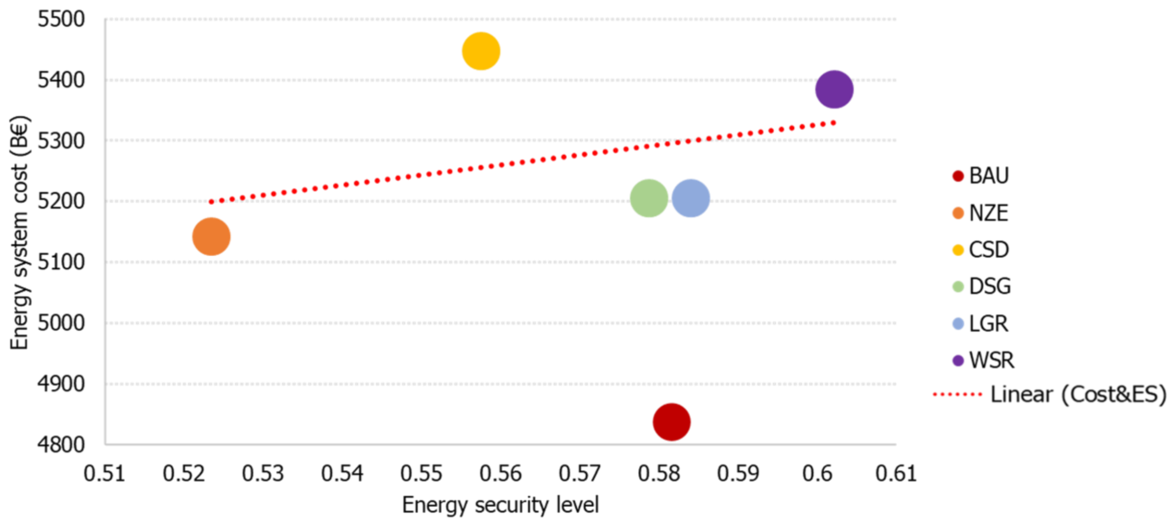

Figure 26. Correlation between the ES and the total costs of the system.

Similarly to ES, the total costs of the energy system compared with the MSR level are reported in Figure 27. The MSR is the main indicator affecting the ES in the different scenarios (see Section 4.2) and its variation is strongly related with technologies investments. The slope of the line shown in Figure 27 represents the cost variation with respect to the MSR variation. Considering the extremes of the regression line, for a MSR reduction of 60% respect to NZE level, the energy system cost increases of 130 B€. The ratio obtained is 2.1 B€/% of reduced MSR, which represents the cost increase associated with the percentage MSR reduction.

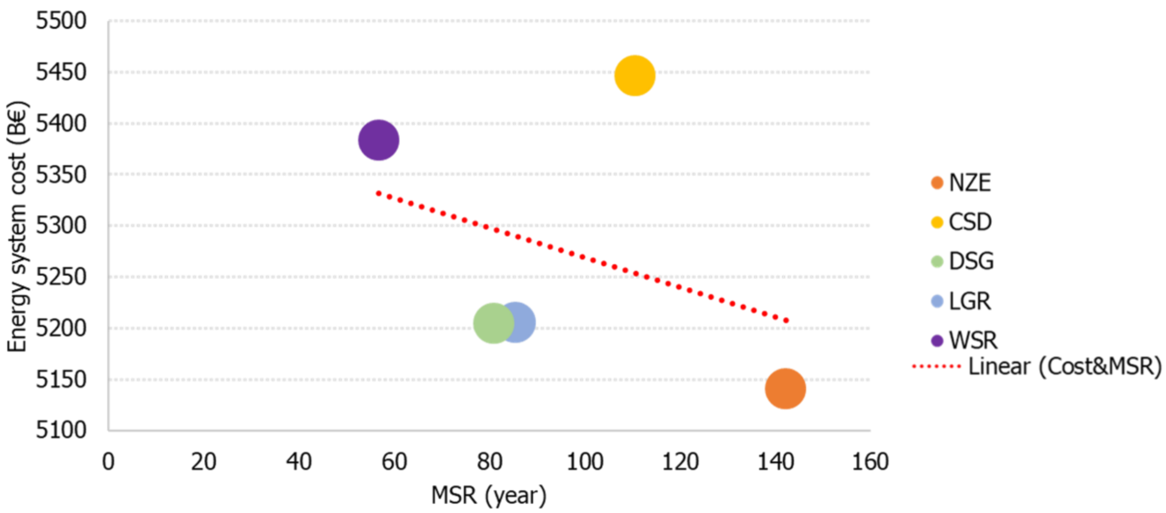

Figure 27. Correlation between the MSR and the total costs of the system.

Chapter 5

Conclusions and Perspectives

This work presents a methodology to quantitatively evaluate the level of ES through the construction of a comprehensive metric and its application to the future energy scenarios generated through the TEMOA-Italy open ESOM. The metric encompasses three dimensions. The material supply risk dimension includes only the MSR indicator. The energy supply risk dimension accounts for the RES, SS and DES indicators. These two dimensions consider the threats that external factors can have on the ES of energy systems. The third dimension represents the internal reliability of the energy system and encompasses the EI, CF and CC indicators, representing the system robustness and the technology availability.

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 concerning many transition technologies and that will gain always more relevance for the definition of energy policies. Accordingly, the scenarios analyzed in this work focused on threats generated by global geopolitical restrictions, paying more attention on regions that cover a main role in the minerals supply chains.

The TEMOA-Italy version adopted in this study allows to impose constraints on the system materials consumption. Such constraints are evaluated on the basis of important geopolitical and environmental aspects. The restrictions applied to the model consider the possibility of materials supply chain disruption, in particular the constraints are applied to minerals covering an essential role in the energy transition. The production of these minerals is concentrated in a few regions worldwide and the constraints are defined to model a related supply disruption.

The results showed that the general composition of the power sector is almost unchanged across the various scenarios. On the contrary, the transport sector, which provides the main contribution to the MSR variation, is more susceptible to materials supply disruption. With the higher penetration of energy transition technologies (e.g. LIBs and BEVs), the level of material consumption dramatically increases. For the BAU scenario the resulting value of materials consumption, in the period from 2025 to 2050, is about 5.5 Mt. While in the NZE scenario the amount is much higher, exceeding the 21 Mt. In the materials supply disruption scenarios, the consumptions are smaller, with an average value of 10.8 Mt, resulting in a lower ESI, too. The BAU energy system encompasses more traditional technologies, resulting in a high level of ES. While in the low emission scenarios, the MSR increment over time strongly affects the ES of the system, as observed in the NZE scenario. The materials supply disruption scenarios encompass the potential risks of mineral shortages in their definitions, leading to different system configurations respect NZE. In these scenarios the main energy system variation is related to energy storage and low carbon vehicles technologies, which rely more on CRMs. The LIBs represent the main solution to store energy, reaching a maximum activity of 88 PJ in 2050 in the DSG scenario. While in scenarios subject to strict lithium supply restrictions, such as CSD and WSR scenarios, the VRFBs became a valuable alternative.

While the minerals consumption of the power sector is roughly the same in all the decarbonized scenarios, in the transport sector there is a significant difference between the NZE scenario and the other low emission scenarios. In the latter a diversified mixes of transport technologies it is observed, where the BEVs do not cover the entire cars transport demand, as in NZE scenario. Other technologies are considered as low carbon solutions, such as FHEVs, that are less material intensive and allow to reach an ES level higher than in the BAU conditions. This means that the energy system is able to respond to external threats, reaching at the same time the decarbonization target.

However, the improved ES does not come for free. The system configurations obtained in the materials supply disruption scenarios present much higher costs than the optimal configuration observed in BAU. Comparing the latter and the WSR scenario, BAU encompasses a final energy system cost of 4,800 B€ and an average level of ES of 0.58. While the cost of the WSR energy system is about 5,400 B€ providing the highest ES level of 0.60. Therefore, the expected final result is that to increase the level of ES of energy systems it is necessary also to increase the final cost.

The methodology adopted to evaluate the MSR is considering only aspects related to the extraction and refining of materials, without including supply risks of technologies components building and assembly, which could significantly impact on the energy security. In particular considering the fraction of components internally produced that can be relevant in the perspective of renewable technology industrial growth. 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 [29]), and the possibility to endogenously evaluate the level of ES in a multi-objective optimization framework.

Data availability

The TEMOA source code used for this thesis is available at [90], while TEMOA-Italy is available at [32].

Acknowledgements

Ed è finalmente giunto quel fatidico momento! Ma prima vorrei condividere una mia riflessione sul percorso che tra poco si concluderà.

In un pomeriggio di quest'ultimi giorni di preparazione per il main event mi sono imbattuto in una considerazione tanto semplice quanto assoluta, "Quando siete felici, fateci caso". Allora mi sono guardato alle spalle e ho iniziato a ripensare a ciò che questo lungo percorso mi ha lasciato. L'università mi ha sicuramente messo davanti a grandi difficoltà, mi ha fatto piangere e disperare. Ma la verità è che mi ha regalato anche inimmaginabili momenti di felicità e di riscatto! Se non fosse stato per lei, non sarei la persona consapevole che sono oggi.

Ma tutte le emozioni che ho provato in questi anni, i momenti vissuti, gli errori e i successi, non sarebbero stati così unici se al mio fianco non avessi avuto qualcuno con cui condividerli! È assolutamente un piacere per me avere la possibilità di ringraziare le persone che mi hanno accompagnato in questi anni.

Ai miei genitori, non posso che dire grazie! Grazie per avermi sempre sostenuto, cercando di togliere dalle mie spalle qualsiasi peso e preoccupazione, per lasciarmi concentrare sul mio percorso. E mio fratello, Iapi. Senza di lui sarebbe stato tutto semplicemente troppo noioso.

Ai miei zii e cugini. Grazie per aver fatto il tifo per me e soprattutto per avermi fatto percepire sempre la vostra vicinanza! Un ringraziamento speciale va alla mia cuggi Guenda, alla quale voglio un modo di bene!

I TORI (Gianfi, Michi, Lazza, Pol, Fafi, Dadi, Lollo e Pise), coloro i quali sono stati il sale delle mie giornate, che con una semplice battuta e risata mi hanno sempre regalato la spensieratezza di cui avevo bisogno!

Tommy (il generale Lomas) e Fede, fratelli di madri diverse! Dire che c'eravate sin dal giorno uno è la verità più assoluta che ci sia. Grazie!

Sara e Denise. Che dire di loro? Uniche ed irripetibili. Sara, prego se continuo ad essere tuo amico, non è facile. Ma la tua sincerità, anche se a volte brutale, è merce rara da trovare nelle persone. Grazie! E Denise, sicuramente la più simpatica della compagnia, non che la mia migliore amica. Grazie per avermi ricordato che nella vita ci vuole sempre un po' di leggerezza!

Giò, una costante fonte di ispirazione ed il Villo, con il quale ho condiviso molte delle difficoltà dei primi anni e probabilmente la persona che ha compreso più di tutti le fatiche di questo percorso. Grazie!

Ringrazio Renzana e Susanna, le mie seconde madri! Grazie per avermi sostenuto in ogni momento e per avermi trasmesso l'importanza dello studio.

I miei compagni di Magistrale. Matte! Dei rinnovabili che si incontrano ad un corso sulla fusione nucleare, in magistrale, assurdo. Però da allora è partita la nostra amicizia e da quel momento abbiamo condiviso moltissimo! Silv, anche lei incontrata al corso sulla fusione! La persona più sincera e colorata che abbia mai messo piede al Poli, la adoro! E infine Walterone, il quale ha riacceso in me la fiamma dell'ambizione dopo un periodo un po' no. Grazie di cuore a tutti.

Ringrazio i miei insegnanti, in particolare il prof. Lorusso e la Matta, coloro i quali mi hanno fatto capire quant'è importante sapersi mettere in gioco. Grazie!

Infine voglio ringraziare la persona che mi ha concesso la possibilità di concludere questo mio percorso nel miglior modo possibile, la professoressa Laura Savoldi. Grazie! E i membri del gruppo

MAHTEP. Soprattutto i due ragazzi che mi hanno guidato in questo lungo lavoro, Gianvito e Matteo! In questi mesi ammetto di averli stressati non poco, ma loro si sono sempre dimostrati disponibili e pronti a supportarmi (e sopportarmi). Mi hanno trasmesso tantissimo, ma più di ogni cosa, mi hanno fatto capire l'importanza di mettersi in discussione, e che si può sempre migliorare se davvero lo si desidera. Grazie infinite!

C'è ancora qualcuno che voglio ringraziare. Avevi detto che ce l'avrei fatta perché ero testardo e come sempre avevi ragione. Grazie!

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