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A Methodological Proposal for the Metals' Supply Chain Risk Analysis of Investments Applied to Solar Energy Technologies in Europe

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Abstract

This paper focuses on assessing the potential risks and strengths along the supply chain of a set of ten popular and precious metals associated with two solar energy technologies: concentrated solar power with thermal storage and photovoltaics with batteries. The Extended Multi-Regional Input–Output methodology is used to quantify the required extraction of the metals along the value chain. First, various metrics and indicators are explored to analyze the supply chain. Second, a framework of analysis is proposed to cover the main components of supply chain risks and strengths. Then, we compare the results from two perspectives: analysis of individual supply risk components and a combined index representing the strength of the value chain. The results show, in general, a better performance of the concentrated solar power supply chain in terms of resource availability and supplier diversity, but slightly worse scores in the resilience and governance components. The index reflects better overall performance for concentrated solar power. Among metals, platinum, silver, and tin play the leading role in the analyzed risks. The European deployment of renewables should be accompanied by measures to secure supply, such as cooperation agreements, and also foster the recovery of secondary materials, thereby maximizing intra-European resilience.

Keywords: supply chain risks; raw material supply; renewable energy; multi-regional input-output

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1. Introduction

The Green Deal Industrial plan, aimed at making Europe the hub of clean tech and industrial innovation on the path to net zero, has been in the spotlight at the World Economic Forum Annual Meeting 2023 in Davos [1]. Stress was put under the aim to "*improve the refining, processing and recycling of raw materials here in Europe*" as well as "*to facilitate open and fair trade [. . .] there will be a need for strong and resilient supply chains*". It is a fact that the supply of raw materials can pose a threat to the urgent need for a rapid European energy transition towards carbon neutrality, given the increasing global demand in the present and foreseeable future [2]. Many decarbonization strategies will rely on the availability of several raw materials, many of which are classified as critical due to their economic importance and supply risk criteria [3,4]. Electricity network deployment requires a substantial amount of copper and aluminum. Lithium, nickel, cobalt, manganese, and graphite are crucial to battery performance, longevity, and energy density. Rare earth elements are essential for permanent magnets that are vital for wind turbines and electric vehicle motors [4]. Despite other goods and services that can be produced by substituting some primary and intermediate inputs, these materials are fixed both in country endowments and in the production process.

The crisis over certain minerals needed for the deployment of renewables is even more relevant, given Europe's need to reduce its dependence on fossil fuels, a need exacerbated by the Russia–Ukraine conflict. Raw materials are strategically crucial for the European economy in social and socioeconomic terms [5,6], but also for energy system security [7]. However, the concentration of these resources in a few countries (mainly in non-EU countries) makes them prone to supply disruptions, as seen in recent world history (the COVID-19 pandemic crisis [8] or the semiconductors crisis [9,10]), as well as the current US trade war [11–13]. Furthermore, the low rates of recycling and substitution of scarce materials in Europe are a weakness.

The assessment of energy security has been widely studied in the field of the social sciences. Azzuni et al. [14] identified 66 different definitions of the concept and its associated dimensions. Some of these include extensive lists of dimensions and components, proposing complex and lengthy sets of indicators [15–21]. Otherwise, the definition provided by ref. [22] does not consist of a set of dimensions, and they purely define energy security as "low vulnerability of the vital energy systems". From the field of physical and sustainability assessment, several metrics and indicators have been proposed to address the material supply risks along the value chain. Regarding the availability and demand of minerals, most studies are based on Material Flow Analysis (MFA) and Life Cycle Analysis (LCA) methods. These methods provide highly detailed figures of the involved flows but have some disadvantages. Among these are time-consuming data collection, the need to establish system boundaries (with the associated limitations such as the cut-off and a certain level of truncation), and the poor regionalization of the resource production existing in the LCA databases. On the contrary, the Extended Multi-Regional Input–Output (EMRIO) method [23] is especially suitable for the analysis of the supply chain as it allows identifying those countries involved and can focus on several key aspects, such as the amount of materials traded in a region, the quantification of governance levels in the supply chain, and the dependence on imports [24–26]. In environmental analysis, this model has been used to quantify the material requirements involved in the deployment of energy policies as part of sustainability impact assessment [27,28] and for the accounting of the abiotic depletion potential (ADP) involved in the value chain [29–31]. In addition, hybrid approaches, such as LCA-EMRIO, have also been used for the specific analysis of certain minerals [27,32].

Beyond the quantification of flows, the ref. [33] proposed two mechanisms that would result in a situation of material scarcity: physical constraints, the amount and quality of a resource that is physically determined, and ultimately, the limiting of resource availability; and institutional inefficiency, the failures of markets, firms, and governments that can result in transitory resource unavailability (circularity and governance aspects would be included here). Novel indicators have been proposed in this sense. From the perspective of material flow vulnerability, Adibi et al. (2017) [34] identified four groups of indicators in the literature. The Global Resources Index (GRI), which combines ADP, recycling, and governance metrics, is one example. However, GRI is unable to reflect the unequal and heterogeneous geographical distribution of resources and, therefore, does not include the dependence dimension in the index (such as concentration or diversity). On the contrary, the approach followed by the supply risk factor (SR), based on LCA inventories and material metabolism indicators [35], incorporates dependence by including a metric of supply concentration. This last one was recently applied to the analysis of photovoltaics (PV) and wind power production [36], reflecting weakness and risks associated with both power technologies.

In summary, the review of the state of the art in risk analysis of the supply chain from the sustainability assessment approaches revealed that, while such methodologies and tools offer significant insights, they have key limitations:

- MFA and LCA: Although detailed in tracing direct material flows, these approaches are time-intensive, bound by narrow or arbitrary system boundaries, and suffer from truncation errors and weak regionalization—thus failing to capture indirect flows and granular, country-level supply dependencies across global chains.
- Available supply risk indices: Tools like GRI and SR capture only some aspects (resource availability, recycling, governance, or supply concentration), never the whole spectrum (including circularity, regional diversity, and governance) within one cohesive methodological framework.
- Diversity and Governance Gaps: Prior frameworks rarely synthesize governance quality of supplier countries or the entropy (diversity) of supplier distribution with resource availability and circularity, leading to incomplete or regionalized policies that do not directly support European energy security policy, especially amid geopolitical interdependencies and critical mineral bottlenecks.

Then, the research gap addressed in the manuscript lies in the disconnect between what sustainability assessments currently quantify—resource and energy flows, or selected risk components—and what is needed: a robust, globally comprehensive, and operational tool for comparing multi-dimensional supply chain risks across alternative technological strategies and the origins of the supply. The proposal contributes to the field of sustainability assessment, as it enables the incorporation of supply risk assessment to maximize the potential for supporting decision-making processes for renewable technology deployment alternatives.

First, we present the individual indicators and metrics in Section 2 as part of the methodological argumentation. In addition, we propose a comparative analysis by individual component, as well as an indicator that combines all the criteria and provides a single quantitative value for the supply chain of each metal evaluated. Secondly, in Section 3, the results of the individual indicators, the comparative analysis by individual component, and the combined indicator are presented. In Section 4, the results, as well as the main advantages, limitations, and aspects for improvement, are presented and discussed. Finally, conclusions are presented on the methodological aspects and the results of the case studies.

2. Materials and Methods

2.1. Theoretical Approach

Aligned with the definition, provided by Cherp and Jewell (2014) [22], of energy security, the review of the sets of dimensions proposed in the literature [14–16,18,37] has resulted in the development of a framework by discarding the non-vital and non-overlapping ones. We built a framework with three main orthogonal dimensions at the core of the energy security concept to be applied to the supply chain: availability of resources, dependence on the supply origin, and resilience of the supply chain.

The hypothesis is that at the confluence of the lowest values of dependence and the highest values of availability and resilience, vulnerability and, therefore, risk would tend to zero. Figure 1 depicts this hypothesis. A more extensive discussion on the three-dimensional framework can be found in the Supplementary Material.

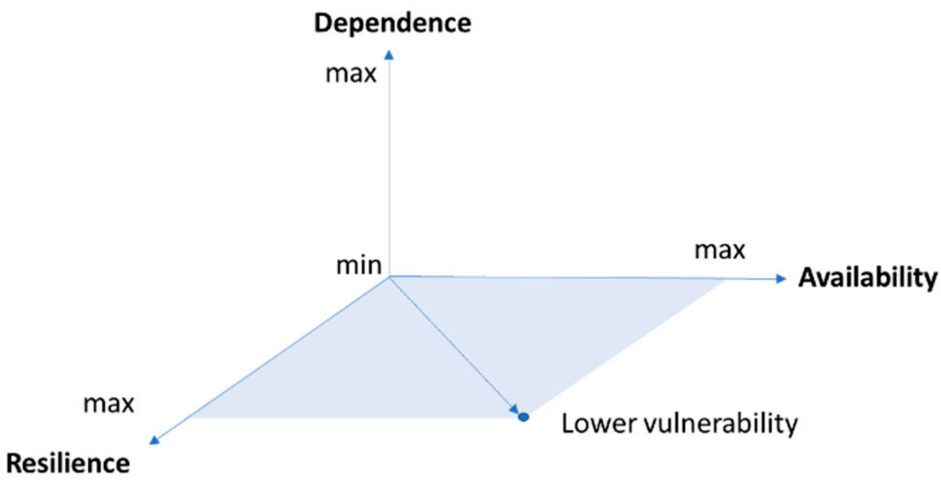

Figure 1. Three orthogonal dimensions of energy security to minimize vulnerability of the energy system supply chain. Own elaboration.

Considering the framework proposed, we seek answers to three questions: (1) How can the assessment of risk and strengths along the supply chain of a set of metals and metalloids (hereafter referred to as metals) for renewable energy deployment be addressed? (2) How can the supply chain risk/strengths of energy investments be measured across the three dimensions of energy security; and (3) can the proposed method be combined with existing EMRIO sustainability assessment methods? To this end, we propose a methodological framework that covers the three dimensions by measuring four components (availability, resilience, dependence, and governance), which can be applied to EMRIO results and are exemplified in the case study of solar technology deployment in Spain, specifically regarding concentrated solar power (CSP) and photovoltaics.

2.2. Model Proposal

Using the output of EMRIO analysis, several factors and metrics are applied in order to propose a methodological framework able to cover the three dimensions of the security of the supply chain mentioned in the Section 1 (availability, dependence, and resilience). The complete framework is depicted in Figure 2.

At the top of the Figure, the matrix algebra calculations of the Multi-Regional Input–Output (MRIO) provide the total (direct and indirect) economic effects (X) associated with any investment. The model is extended (EMRIO) by using specific satellite accounts (m, extension vector) that consist of country and sector coefficients for the domestic extraction of each material per sector's economic output. Thus, the total domestic extraction of a set of metals per country and sector worldwide required along the value chain for the deployment of each solar technology assessed is obtained.

2.2.1. Extended Multi-Regional Input–Output Analysis

As mentioned before, the EMRIO analysis offers a suitable framework to address the analysis of risks, including the three orthogonal dimensions. EMRIO analysis allows quantifying simultaneously economic, socioeconomic, social, and environmental impacts and was successfully applied in material footprint assessments of global value chains [38] and future low-carbon economy scenarios [39]. The use of proper data sources allows for expanding the system boundaries globally to include a wide range of direct and indirect impacts, and enables tracking the specific origin of supply. Based on investment, operation, and maintenance (O&M) cost data for an investment in any location worldwide, the methodology allows quantification of the material extraction of selected metals and minerals in each country and sector along the value chain.

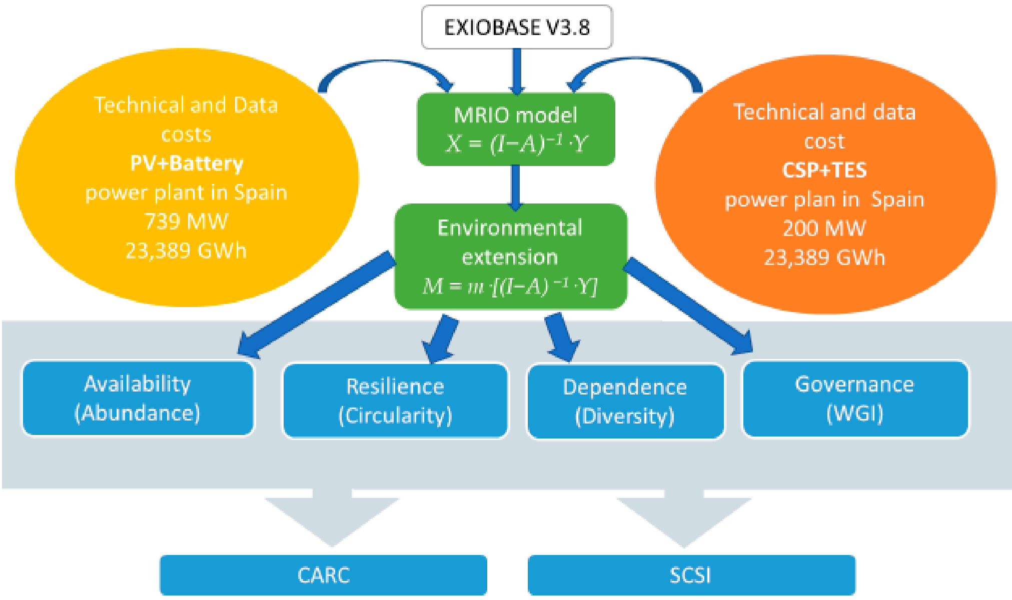

Figure 2. Methodological scheme. MRIO: multi-regional input–output; X: output; Y: costs vector; A: MRIOT; M: amount of domestic extraction used (mass) of each raw material (metal in our case); m: environmental vector of domestic extraction (mass) of each raw material (amount of metal in our case per economic output); WGI: worldwide governance indicators. CARC: comparative analysis of individual risks component; SCSI: supply chain strength index; PV: photovoltaics; CSP: concentrated solar power; TES: thermal energy storage.

The advantage of using the Environmental EMRIO (EEMRIO) is that it (1) can capture direct and indirect extraction of materials while MFA and LCA fail in doing this, (2) the system boundaries are planetary, while in LCA and MFA, the system boundaries are defined by the researcher, and (3) the regionalization in EEMRIO comes from traced global economic flows, allowing the mapping of the supply chain.

As the main data source for the EMRIO assessment, the Multi-Regional Input–Output Table (MRIOT) Exiobase v3.8. [40] corresponds to 2018, the year it was used. The corresponding technical coefficients matrix is noted as A in Figure 2, which is known as the Leontief inverse $(I\text{-}A)^{-1}$, being the core of the EMRIO model. Unlike other methodologies, such as LCA, that require a large amount of data and trace the origin of each raw material, MRIO allows the supply chain to be traced based on the inter-linkages between sectors and regions of the economy, only using a detailed vector of costs.

2.2.2. Availability

In the field of environmental assessment, one of the most used and recommended indicators to quantify the relative contribution of a product system to the depletion of mineral resources is the abiotic depletion potential (ADP) of ultimate reserves [41], expressed as kg of antimony (Sb) equivalent (e.g., kg Sb eq.) per kg of the specific material, calculated by the method proposed by Van Oers (2002) [42]. Other methods found in the LCA literature are LIME2-midpoint [43] and EDIP [44]. In this work, the most recent values of ADP ultimate reserves are used [45]. The characterization model is a function that combines natural reserves (stocks/deposits in the environment) of the abiotic resources and their rates of extraction (see Equation (1)). The characterization factor is the ADP. This factor is derived for each extraction of elements as a relative measure, with the depletion of the element antimony (Sb) as a reference:

$$ADP_m = \frac{DR_m/R_m^2}{DR_{ref}/R_{ref}^2} \quad (1)$$

where ADP_m: abiotic depletion potential of resource m (kg antimony equivalents/kg of resource m (m = Al, Cu, Au, Fe, Pb, Ni, Pt, Ag, Sn, Zn); R_m: ultimate reserve of the metal m (kg); DR_m: extraction rate of resource m (kg/yr); R_{ref}: ultimate reserve of the Sb (kg), and DR_{ref}: extraction rate of the Sb (kg/yr). This indicator represents the relative scarcity of the materials, the opposite of the availability of a specific resource in global terms. Then, the inverse of the ADP (noted as $1/ADP_m$) can be seen as an indicator of the use of abundant resources for comparative purposes and thus provides an indicator of the availability of resources.

2.2.3. Resilience

The resilience of the supply chain to provide each resource can be increased by circular economy (CE) practices, as they reduce the dependence of located resources and contribute to the diversification of the supply of raw materials (e.g., stocks in non-producer countries). The CE is argued to be a way of organizing industrial systems that support resilience through decoupling economic growth from new material consumption [46]. Cherrafi et al. (2022) [47] uses the example of the global pandemic's disruption of the flow and pricing of raw materials and finished products to illustrate how the CE can increase the resilience of the supply chain. By increasing stocks and availability, it can help buffer price volatility and reduce foreign dependence.

As for the measurement of circularity, Corona et al. (2019) [48] and Walzberg et al. (2021) [49] reviewed the methodological developments regarding circularity metrics for products and services to identify the foundations of circularity metrics and applications used to date. The authors evaluated the validity of current circularity metrics based on predefined requirements and a CE definition anchored in the sustainability concept. They concluded that none of the assessed metrics fully address the CE concept, and that there is a need to combine different approaches to overcome the limitations on data availability and provide a holistic assessment. Considering these reviews and recognizing the limitations of the simplicity of some metrics, we include an indicator of circularity of the materials obtained from European Commission reported data [50] and known as end-of-life recycling input rates in Europe ($EOLRIR_m$). It reflects the use of secondary raw materials. As the analyzed case studies are power plants to be deployed in Spain, the European rate is helpful for the assessment. Investments in other regions would need appropriate rates. The proposed rate is used to monitor progress toward a CE in the thematic area of "secondary raw materials" within the CE strategies of the European Commission. The indicator measures, for a given raw material, the proportion of its input into the production system that comes from the recycling of "old scrap" (or "end-of-life scrap"), i.e., scrap and waste derived from the treatment of products at their end-of-life (EOL) stage. As a limitation, little data are available at the European and international level on the amount of secondary raw materials produced. Available data sources for the calculation of the $EOLRIR_m$ are as follows: Material System Analysis data for the EU, currently carried out for a limited number of materials; and international reports, industry data, and scientific publications. Appendix A (Table A1) shows the values of $EOLRIR_m$.

Thus, contribution to the European secondary materials system can be expressed as the ratio (intra-European recycling) of the share of each metal by the total amount of metals extracted considering the set of assessed metals (e.g., kg Fe/ kg total metals extracted), multiplied by the $EOLRIR_m$. That would be a way to measure which portion of each metal used in the deployment of each technology would be potentially recycled, considering the rates of secondary reprocessing in Europe (i.e., kg Fe as consequence of the investment and potentially recycled in Europe/kg total metals extracted), according to Equation (2):

$$ERPR_m = \left({}^{M_m}\!/_{M_t} \right) \cdot EOLRIR_m \tag{2}$$

$$ERPR = \sum_{m}^{n} ERPR_m \tag{3}$$

where $ERPR_m$ is the intra-European recycling potential rate of the metal m extracted as a consequence of the investment, and ${}^{M_m}\!/_{M_t}$ is the share of the mass of each of the extracted metals m (of the sample of n number of metals) with respect to the total mass of metals (quantified) required by each solar power plant deployment. The total $(ERPR)$ is the sum of $ERPR_m$ (Equation (3)).

2.2.4. Dependence

Dependence is included in the methodological framework by measuring the diversity of supply in terms of the variety of origins and the distribution throughout the world (i.e., from how many origins and how much from each of them). We apply a diversity metric known as entropy (E). The entropy metric was used as an indicator of diversity in several disciplines, from physics to ecology, and more recently in economics in publications of the European Central Bank [51], scientific literature [26,52], and environmental studies [53]. The more diverse (higher value of E_m) the value chain, the less dependence on a few suppliers, and therefore, the lower the supply risk of the supply chain of the metal assessed. The entropy is calculated according to Equation (4):

$$E_m = -\sum_{C=1}^{N} S_{m,c} \cdot log S_{m,c} \tag{4}$$

where $S_{m,c}$ is the share of contribution of each country or region c of the sample to the demand requirement of each considered metal m. One of the advantages of using this metric is that it can be compared with a maximum value, E_{mmax}, which is the maximum value of diversity for a sample (given by the number of exporter countries or regions of metal m in the MRIOT). The ratio E_m/E_{mmax} of each material represents the level of diversity of the origin with respect to the maximum reachable entropy for this sample of countries. In addition, the diversity of the chain of the cumulative supply of all the metals assessed is calculated (E_t), and also the ratio with respect to the total entropy (E_t/E_{tmax}).

2.2.5. Governance

Considering the three orthogonal dimensions of security of supply presented before, we introduce the governance aspects into the analysis to nuance the dependence analysis apart from the pure level of diversity. Not only is the number and share of suppliers relevant in the dependence relationship between exporters and importers, but also, geopolitical risks can also be of concern. To assess the quality of different supply origins in terms of endogenous geopolitical risk, a combined metric is proposed that utilizes governance-level criteria for each region or country. Governance can be defined as the set of practices, behaviors, customs, and institutions by which people and government interact to build their societal functioning. We use here the six composite Worldwide Governance Indicators [54,55]. The six criteria are as follows: Voice and Accountability (VA), Political Stability and Violence Absence (PSVA), Government Effectiveness (GE), Regulatory Quality (RQ), Rule of Law (RL), and Control of Corruption (CC). Some of these criteria, as well as the data sources, have already been used in the formulation of previous indicators of the risk of supply of materials to incorporate the endogenous geopolitical risks associated with their origin [34,36] and the risk along the value chain of total goods and services [26,27].

By applying Equation (5), the governance index of the total extraction of each material for each of the six governance criteria is obtained (G_{WGIim}). Thus, we add a component that measures the level of governance along the value chain by weighting the contribution of each metal using a factor that depends on the level of governance in the origin. Then, the lowest risks are obtained when the highest levels of governance are in place:

$$G_{WGIm,i} = -\sum_{C=1}^{N} M_{m,c} \cdot WGI_{i,c} \quad (5)$$

where $WGI_{i,c}$ is the governance value of each indicator for the six indicators analyzed (i = VA, PSVA, GE, RQ, RL, and CC) in the country or region c, and $M_{m,c}$ is the Mg of each metal per GWh produced, resulting in a value of governance-weighted demand of metals/GWh, which allows the comparison among technologies.

2.2.6. Comparative Analysis of Individual Risk Components (CARC)

The comparative analysis of individual criteria provides a global picture of the value chain risks associated with each investment. Table 1 shows the criteria and indicators. The formulation of these indicators facilitates the interpretation of the results, as the general rule is that "the higher the value of all of them, the better performance of this indicator, and the lower the associated risk".

Table 1. Component of the supply chain risk and indicator included in the comparative analysis.

Component of the Supply Chain Risk Analysis	Measure by	Indicator
Availability	Abundance	$1/ADP_m$
Resilience	Circularity	$ERPR_m$
Dependence	Diversity of supply	E_m/E_{mmax}
Governance Level	World Governance Indicators (WGI) criteria	G_{WGIim}

2.2.7. Analysis Combined: Supply Chain Strength Indicator (SCSI)

Due to the existing economic structures and resource provision, different economies have adopted different methods to assess supply risks [56] and have used combined indices focused on different aspects [57]. For example, the European Commission (EC) assesses supply risks using a measure that combines supply concentration, import reliance, governance performance, a trade-adjusted parameter, and a substitution index [35,36]. The Geopolrisk tool (Available at: https://geopolrisk.org/, accessed on 8 November 2022) employs a distinct approach in a combined index that utilizes LCA [58] to assign a value to the geopolitical supply risk. The tool is based on the development of characterization factors for the midpoint indicator 'Supply Risk Potential' that combine the concentration of the supply, imports, and prices.

Other examples include those focused on resource-criticality measurement, such as the one developed for the Chinese context by Yan et al. [59] that analyzed three types of supply risks—sustainability risk, reliance risk, and tolerance risk—to identify the critical metals for China. Another example is the one proposed by the U.S. Department of Energy: a weighted index for evaluating supply risk focused on criticality that includes (1) availability of metals, (2) political, social, and regulatory factors, (3) producer diversity, (4) competing technology demand, and (5) co-dependency with other markets. Later, the U.S. framework was further developed by Graedel (2015) [60], where medium-term risks and long-term risks are differentiated. However, the particular assessment of criticality often limits the analysis to a specific mineral for specific uses (such as rare earth elements for electric vehicles and renewable energy), whose trade flows are not being characterized at a global scale and are based on MFA and LCA, with the main disadvantage of excluding indirect demands. On the contrary, the supply risk using the EMRIO method offers a complete consideration of the supply chain perspective [61].

The Supply Chain Strength Indicator (SCSI) proposed here incorporates the four elements of Availability–Resilience–Dependence–Governance (A-R-D-G), combined to measure the three orthogonal dimensions of energy supply security traditionally discussed in the literature: dependence, availability, and resilience. Additionally, governance is introduced as an additional component to each dimension, qualifying the geopolitical risks associated with the supply chain. SCSI is calculated using Equation (8). The first term measures dependence by a governance-weighted diversity indicator by considering the contributions of each country to the required metal extraction multiplied by the governance indicator ($WGI_{i,c}$), as previously presented in [27].

The second term measures availability. To allow the regional analysis of the use of abundant resources of each metal, we do not use the ADP_m indicator but the ratio between ultimate reserves and production for each metal, obtaining a non-dimensional ratio Reserves-Production (RP_m) of abundance for each metal (Equation (6)). The result is expressed as the number of years of physical availability of the resource until total depletion:

$$RP_m = \frac{R_m}{DR_m} \tag{6}$$

The ultimate reserves include the estimation of the crustal reserves subject to a level of uncertainty related to the extent to which they are available and accessible (due to environmental, physical, and technological constraints, among others). To overcome this limitation, the U.S. Geological Survey [62] uses a definition of reserve that allows for quantifying the part of the ultimate reserve that could be economically extracted or produced at the time of determination. Therefore, provided that the location of the reserve is known, the abundance of each metal in each country or region can be estimated (eRP_{mc}). We have used data presented in the statistics of the US Geological Survey (USGS) [62] and the works carried out by other authors [63–65]. The production by metal and country is also obtained from the 2020 USGS [62] and Reichl and Schatz (2022) [64]. The result can be expressed in the form of a ratio between the current economic reserves of the metal m in the country c and the global economic reserve (Equation (7)), and it is named the economic reserve-production ratio ($eRPR_{mc}$):

$$eRPR_{m,c} = \frac{eR_{m,c}}{DR_{m,c}} \Bigg/ \frac{eR_{mglobal}}{DR_{mglobal}} \tag{7}$$

Then, the second term of the SCSI consists of the economic reserve-production ratio ($eRPR_{m,c}$) of each metal and country involved in the supply chain, weighted by the governance indicator and the diversity of the country supplier.

The third term measures resilience by considering the end-of-life recycling input rates in Europe (EOLRIR) that, in turn, measure the amount of each metal that comes from other countries and will be recycled in Europe, feeding the European stock for this metal. This is then weighted by the governance indicator for Europe (WGI_{iEUR} , which is the average of the governance level for each governance criterion of European countries). The diversity of suppliers is also considered in this term:

$$SCSI_{m,i} = \left[-\sum_{C=1}^{N} S_{m,c} \cdot WGI_{i,c} \cdot logS_{m,c}\right] + \left[-\sum_{C=1}^{N} eRPR_{m,c} \cdot S_{m,c} \cdot WGI_{i,c} \cdot logeRPR_{m,c}\right] + \left[-\sum_{C=1}^{N} S_{m,c} \cdot EOLRIRm \cdot WGI_{i,EUR} \cdot logS_{m,c}\right] \tag{8}$$

$$SCSI_{t,i} = \sum_{C=1}^{N} SCSI_{m,i} \quad (9)$$

The result of the addition of the three terms is a non-dimensional indicator for each metal, the total ($SCSI_{ti}$) per, and the governance criterion ($SCSI_{m,i}$) obtaining a number that brings together the four components (Availability–Resilience–Dependence–Governance) and can be negative or positive. A positive value indicates a higher contribution from countries with positive governance scores and lower risks. The size of the value depends on the governance scores and the diversity of the supply, as well as the reserve availability (economic reserve production ratio for each metal and country), and the supply weighted by circularity. Therefore, the higher (and positive) the value of the index, the lower the risks, and then, the higher the strength of the supply chain. On the contrary, the higher the absolute value of a negative indicator, the higher the risk, and then, the lower the strength of the supply chain.

2.3. Case Studies

The methodological approach presented before was tested in two case studies of solar energy investments in Spain: a CSP plant with energy storage and a PV installation with batteries. The case studies were designed in the development of the EU H2020 MUSTEC (https://mustec.eu/, accessed on 31 October 2020) project. To make the case studies of CSP and PV power plants comparable in terms of dispatchability and flexibility, a storage system capable of providing the same level of electricity production over the lifespan of each plant was considered for each plant. The CSP plant's storage system can provide 11 h of storage, thanks to a Thermal Energy Storage (TES) system. A battery system capable of providing the same amount of energy was considered for the PV case study.

The data costs of a parabolic trough CSP plant and a PV power plant were obtained from ref. [28]. The authors used the latest cost assumptions found in the recent literature on investment and O&M costs [66]. They also used the System Advisor Model (SAM) (https://sam.nrel.gov/concentrating-solar-power.html, accessed on 20 October 2019) to disaggregate these costs into the different components and cost categories. The study considers a plausible scenario of Spanish–German cooperation where the plant is located in Spain, but some components are manufactured in Germany. Cost data for the PV scenario were obtained from the National Renewable Energy Laboratory—NREL [67,68], and combined with photovoltaics O&M cost data disaggregation from [69]. The vector of costs (Y in Figure 2) is built based on the regionalized cost data for each alternative of the solar power plant assessed. Detailed data on the origin and sector allocation of components and services can be found in [70].

3. Results

As PV and CSP have different supply chain profiles, the disparate direct and indirect impacts along their value chains, which are necessitated by deployment, can be traced using the EMRIO method, on which the entire research is grounded. The results from the extension of the model, the EEMRIO assessment, show the different amounts of total (direct and indirect) domestic extraction of the selected metals stimulated for the various investments associated with PV and CSP, disaggregated by origin and sector. Consequently, the results for PV and CSP differ with regard to supplier diversity and governance.

3.1. Availability: Abundance

Table 2 shows the results of ADP and its inverse, as this is the indicator for use of abundant resources. Overall, the CSP plant deployment shows higher values for this indicator in all the metals. This implies that it would be less intense in the extraction of scarce materials. The assessment is performed by energy produced (MWh) to allow a fair comparison.

Table 2. Abiotic depletion potential (ADP) and abundance (1/ADP) of each metal by solar technology.

	ADP (kg Sb eq./MWh)		**1/ADP (MWh/kg Sb eq.)**	
	PV	**CSP**	**PV**	**CSP**
Al	2.30×10^{-8}	3.80×10^{-12}	4.30×10^{7}	2.60×10^{11}
Cu	2.40×10^{-4}	3.20×10^{-5}	4.20×10^{3}	3.20×10^{4}
Au	2.80×10	4.10×10^{-1}	3.60×10^{-1}	2.40×10
Fe	1.30×10^{-8}	9.80×10^{-10}	7.60×10^{7}	1.00×10^{9}
Pb	5.00×10^{-6}	8.10×10^{-7}	2.00×10^{5}	1.20×10^{6}
Ni	5.50×10^{-7}	8.90×10^{-8}	1.80×10^{6}	1.10×10^{7}
Pt	3.30×10^{-2}	1.60×10^{-2}	3.10×10^{1}	6.40×10^{1}
Ag	1.20×10^{-2}	2.00×10^{-3}	8.50×10^{1}	4.90×10^{2}
Sn	3.10×10^{-5}	7.60×10^{-6}	3.20×10^{4}	1.30×10^{5}
Zn	2.60×10^{-6}	5.90×10^{-7}	3.80×10^{5}	1.70×10^{6}
Total	2.80×10	4.30×10^{-1}	3.50×10^{-1}	2.30×10

The regional and sectoral analysis of the contribution revealed that the *mining of iron* in China and the *mining of copper ores and concentrates* in the region of the rest of Latin America (WWL (the region WWL clusters the Latin América and Caribbean, excluding Mexico and Brazil (countries individually included in the regionalization of the MRIOT used—Exiobase v3.8)) together account for more than 56% of the materials required in the case of the PV power plant. In the case of CSP, more than eight regions would be involved in the value chain to reach this share (Latin America, China, Australia, Brazil, Asia and Pacific, Russia, India, and Poland) and three sectors (the sector of *mining of iron*, the sector of *mining of copper ores and concentrates*, and the sector of *mining of lead, zinc, and tin ores and concentrates*). Figure A1 in Appendix B illustrates the regional share of the cumulative amount of metals.

As for the ADP, our results show a total ADP indicator that is 6.6 times higher in the PV system than in the CSP system, similarly to the values found by Mahmud (2018) [71], where the impacts to resource use by the solar-PV system with batteries are ten times as high as the ones for the solar-thermal system by unit of electricity. PV is revealed as more intense than CSP in the extraction of scarce materials, with the difference being especially relevant for gold, silver, and platinum. The last one, metal and the belonging group (PGM), is included in the latest list of Critical Raw Materials (CRMs) developed by the European Commission [72]. These are CRMs with the highest supply risk and economic importance. Moreover, a subset of materials relevant to green transition, digital transition, defense, and space applications is collectively known as strategic raw materials (SRMs). Copper and nickel are among the SRMs [73].

3.2. Resilience: Circularity

Related to circularity, the difference between the total ERPR of PV power and CSP plants is small, as shown in Figure 3. PV shows a slightly higher contribution to the European secondary materials through the recycling of raw materials. In both cases, the primary materials reintroduced in the European economy are iron and copper.

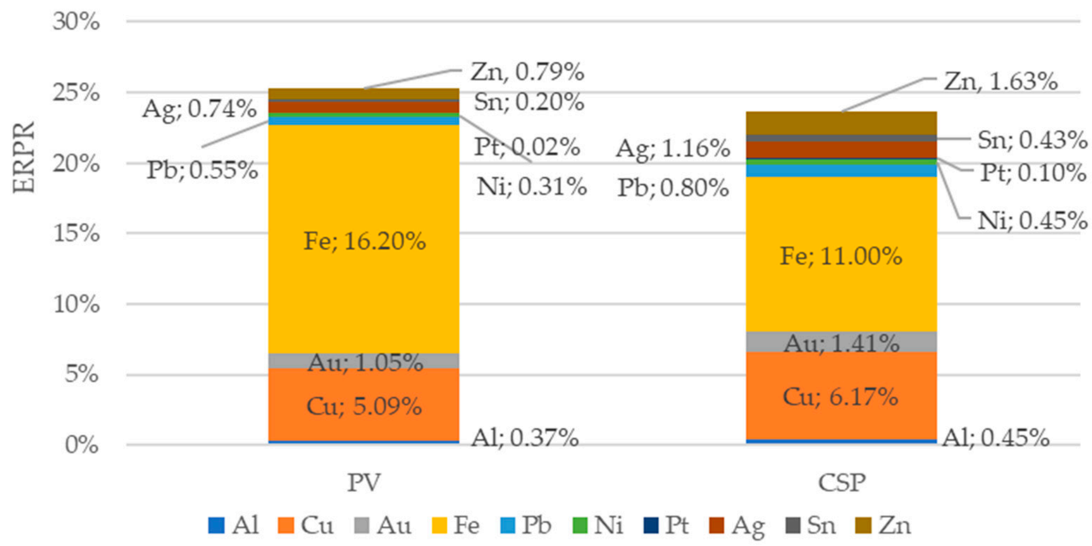

Figure 3. European recycling potential rate of the metals extracted along the supply chain of both solar power plants, per metal (ERPR).

3.3. Dependence: Diversity of the Supply

From the dependence side, the concentration of the origin of raw material supply and components leads to dominant roles for a few suppliers, driving unequal trade relationships and increasing dependence on them. On the contrary, the higher the number of suppliers along the value chain and the more distributed their contributions, the lower the dependence and supply risk. The share of material extracted in each region or country associated with the supply chain of each solar power plant assessed is graphically depicted in Figure A1 of Appendix B.

The values of E_m/E_{mmax} (Figure 4) show that the CSP supply chain is more diverse than the PV supply chain for all the metals assessed, except for platinum and tin, for which, while the CSP value of E_m/E_{mmax} is 18% and 46%, PV achieves 30% and 53%, respectively. There are no significant differences between the investment and O&M stages. Only the value chain of Zn would present a change in the trend, being slightly more diverse in PV than in CSP for the O&M stage.

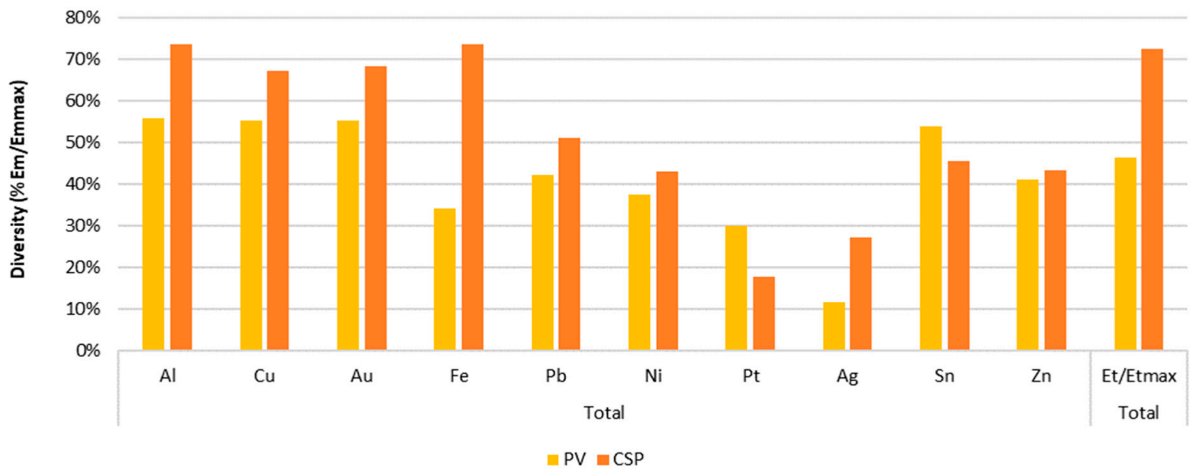

Figure 4. Diversity indicator (E_m) of the supply chain associated with each solar power plant deployment, per metal.

Recent works have applied a similar approach to analyzing this aspect of dependence using EMRIO, considering the total economic trade of goods and services demanded by CSP and natural gas power plant deployment [26].

3.4. Governance: Six-Composite Indicator

Figure 5 shows the results of the governance-weighted number of extracted metals ($G_{WGIm,\ i}$) per unit of electricity produced (top graph) and per unit of installed capacity (bottom graph).

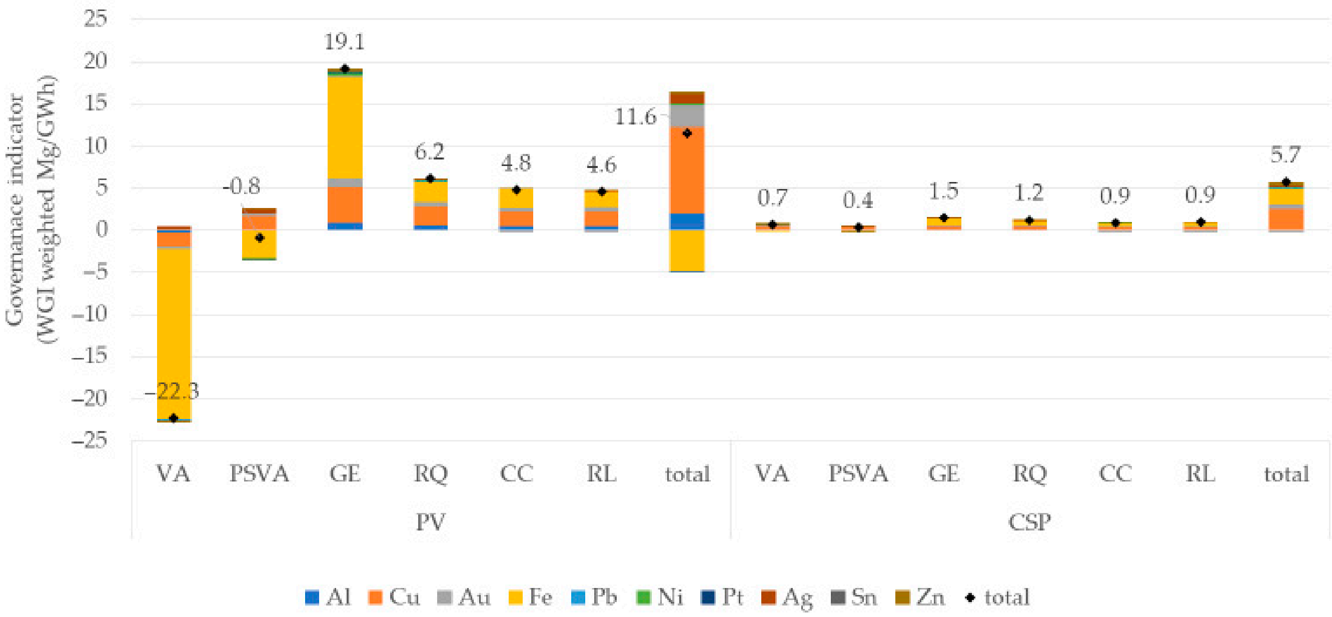

Figure 5. Governance indicator G_{WGIi} of the supply chain in each scenario (PV on the right, and CSP on the left) by metal (colors), per governance indicator, and per electricity produced. VA: Voice and Accountability; PSVA: Political Stability and Violence Absence; GE: Government Effectiveness; RQ: Regulatory Quality; RL: Rule of Law; and CC: Control of Corruption.

Per unit of electricity production, PV scores better in all indicators, except in Voice and Accountability (VA) and Political Stability and Absence of Violence (PSAV). It is worth noting that the CSP value chain presents all indicators on the positive side of the axis. In contrast, some of the PV value chain indicators have negative values for governance. Iron (yellow in Figure 5) and copper (orange in Figure 5) are the most essential metals in the analysis of governance. A cumulative total value is included in the Figure to show the final balance. The PV value chain achieves a higher score in total value due to its significant positive contribution to Government Effectiveness (GE) in the case of iron and copper, followed by positive scores in Regulatory Quality (RQ), Control of Corruption (CC), and Rule of Law (RL). A very high negative score is due to iron in VA, and in PSAV, mainly associated with the Chinese origin. The contribution from Australia plays a role in the positive side of both graphs. Figure A2 of Appendix B shows the detailed contribution of the different suppliers (countries or regions).

Note that the greater the amount of material, the greater the absolute value of the indicator (positive or negative). For example, even including the governance weighting, the results show that the PV alternative requires a much higher extraction in origin of metals per electricity produced.

For the comparative analysis in the case of the governance indicator, in order to remove the negative numbers in the G_{WGIi} results, the absolute value of the lowest value of all the results of this index ($G^*_{WGI\_Fe}= -156$ for PV, see Figure 5) have been added to all of them, obtaining G^*_{WGIi}, which only have positive values in order to apply the ratio PV/CSP without distortion.

3.5. Comparative Analysis of Individual Risk Components: CARC

Once the individual measurement component of the risk has been analyzed using the set of indicators, the comparative analysis can be conducted. The ratio PV/CSP is used for the comparison. This ratio reveals in which indicator and metal the PV supply chain outperforms the CSP supply chain (values over 1 in the graph) and in which indicators and metals the CSP value chain performs better (values below 1 in the graph).

The comparison of the performance of the supply chain associated with each solar power plant deployment is shown in Figure 6. Results show that the PV supply chain would be much more vulnerable than the CSP supply chain, considering the physical availability of all the metals. In the case of the resilience criterion, the intra-European circularity, the CSP value chain would also perform better than PV in most metals. However, the PV value chain performs much better in one of them (iron), resulting in a total result in favor of the PV value chain. As for the measurement of the dependence, the diversity indicator indicates that the CSP value chain would have a lower risk than the PV value chain, as it would have a more diverse origin for most of the metals assessed, except in the case of Pt and Sn. Finally, the values of governance, aggregated and adjusted to a positive scale, show higher total scores in the PV value chain. The PV value chain obtains better scores for all the metals, except for iron, lead, and tin. Apart from the greatly higher score in iron, CSP would perform slightly better in the value chain of lead, nickel, platinum, and tin. Note that the higher demand for materials by the PV value chain per MWh amplifies the range of positive and negative values of the indicator.

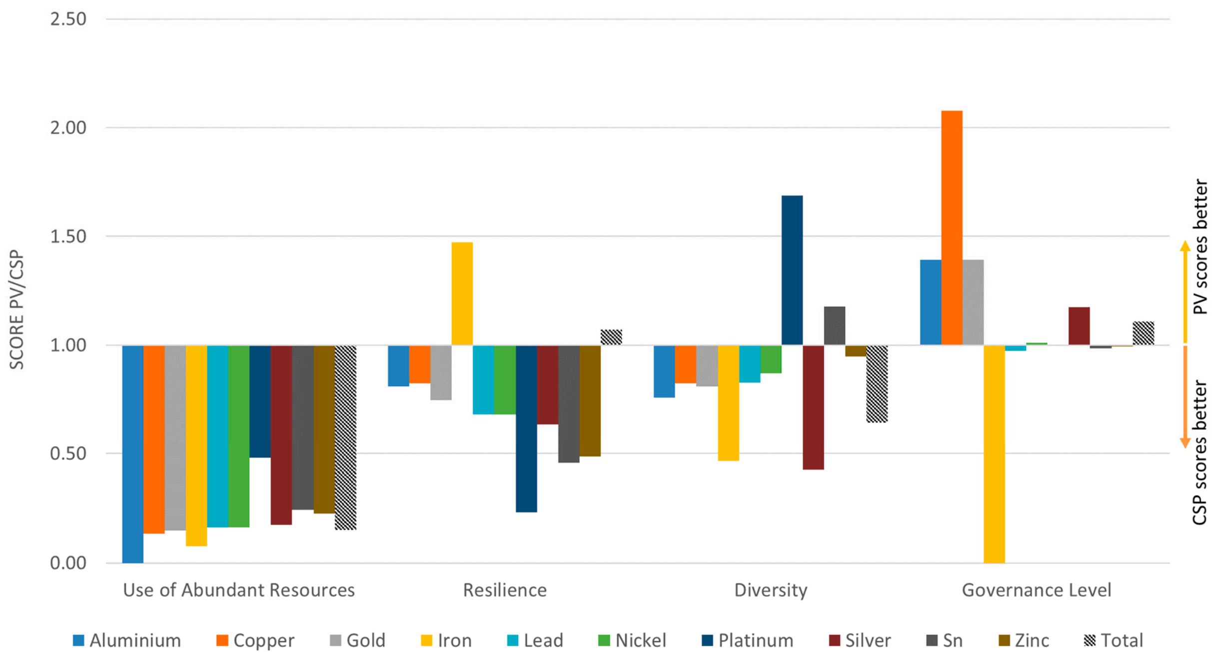

Figure 6. Risk component comparative analysis (CARC) results. Values over 1 mean a better score (lower risk) of PV for the criterion. Values below 1 mean a better score (lower risk) of CSP value chain for the criterion.

From these results, it cannot be concluded that one value chain is better than the other in terms of security, since CSP scores better for availability and diversity, but worse for resilience and governance.

3.6. Supply Chain Strength Index: SCSI

Results of the SCSI of the supply chain of the PV and CSP case studies are shown in Figure 7. At first glance, the PV supply chain makes a lower contribution to the negative side of the graph (Figure 7) for all indicators, except for VA. However, focusing on the total value for all metals, PV performs worse in the SCSI scores for all governance criteria. Results on the contributions per country and metal reveal more detailed differences (see Figure A3 in Appendix B).

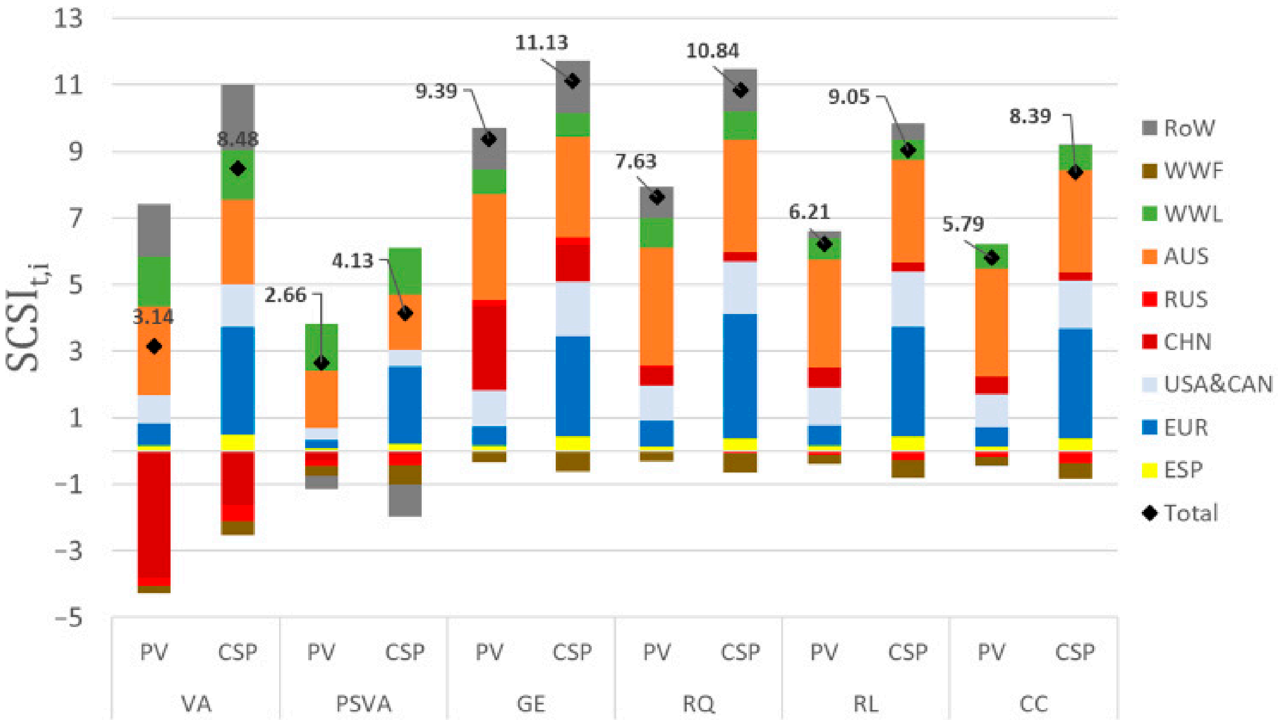

Figure 7. Results of the combined indicator Supply Chain Strength Indicator ($SCSI_{t,i}$) for each technology. RoW: Rest of the world; WWF: African region; WWL: Latin American region; AUS: Australia; RUS: Russia; CHN: China; USA&CAN: United States of America and Canada; EUR: Rest of European region; ESP: Spain; VA: Voice and Accountability; PSVA: Political Stability and Violence Absence; GE: Government Effectiveness; RQ: Regulatory Quality; RL: Rule of Law; and CC: Control of Corruption.

The indicator reflects a larger diversity of supply origins in the CSP supply chain. In the PV analysis, the contributions from Australia (orange), WWL (green), and China (dark red) clearly dominate the result, followed by North America (noted as USA&CAN), with Canada being the primary contributor, and finally, RoW (gray), with Indonesia being the main contributor. In the CSP value chain, the result is influenced by a broader range of countries. The participation of European countries, such as Poland, Finland, or Sweden, is higher in the CSP value chain; therefore, the contribution of the REU region to strengthening the value chain is relevant. Additionally, the participation of other countries, such as those in the rest of the African region (WWF, brown) and Russia (light red), contributes to the main negatives.

The highest differences can be seen in the total value of SCSI for VA, RQ, RL, and CC, with the value achieved by the CSP supply chain being higher due to its higher diversity and greater contribution from European countries for every governance indicator. In addition, the higher share of iron used by PV from low-governance countries contributes to this result. Although a significant share of the supply originates from China, the Chinese supply does not play a prominent role. However, this does not mean that it was not relevant. What happens is that a significant amount of metal coming from China is upgraded in terms of governance by the inclusion of the circularity component. Consequently, the negative scores are partially compensated. This can be seen in the complementary Figure, Figure A4, in Appendix B.

As for metals, the lead value chain would be the strongest component in both supply chains, due to the combination of high circularity, moderate availability, and a moderate contribution from a diverse range of countries with high governance levels. Platinum, silver, and tin would be the weakest supply chains. Although aluminum and iron are pretty abundant in the crust, and they have a high circularity in Europe, they score low in the SCSI. The reason for this is a less diverse supply chain, as the mining is highly concentrated in countries with poor governance, as can be seen in the PSVA indicator.

4. Discussion

4.1. Solar Technologies Comparison

As for the results of the case studies assessed, the CARC analysis shows that CSP plant deployment shows lower risks of metals availability. Focusing on the intra-European circularity component, CSP would perform better in most metals; however, PV performs much better in one of them (iron), resulting a cumulated overall total result slightly in favor of the PV value chain (1.07 times better PV than CSP), but what that reflects is the more intense use of iron in PV plants (with a high rate of input recycling). Regarding the measurement of dependence, the diversity indicator yields lower risk results for the CSP supply chain, as it has a more diverse value chain in terms of origins for most of the metals assessed, except in the cases of platinum (Pt) and tin (Sn). Finally, the scores for governance in the PV supply chain are relatively better for Cu, moderately better for Al, Au, and Ag, and slightly better for Ni and Pt. In contrast, CSP achieves significantly better governance along the iron supply chain and shows slight improvement in Pb and Sn.

According to the SCSI, the highest differences can be seen in the total (cumulated) SCSI for Rule of Law (RL), Regulatory Quality (RQ), and Control of Corruption (CC). According to Blengini (2017) [35], among the governance criteria with the highest impact on the supply chain risks are RQ and RL, which would allow addressing the regulatory component of the supply risk, and PSVA, which would address the risk associated with more extreme events (e.g., war, conflicts, and insurgency). We also highlight the role of CC, as the supply chain can be threatened by illegal pathways that are frequently connected with corruption.

The results of the case studies highlight the supply risks of some metals widely used in solar technologies. As renewables will likely remain a policy priority in many European countries in the coming years, the European Union will need to emphasize the importance of securing the supply chain. The development of industrial agreements among European countries to boost European supply capacities, as well as with third-world countries to secure its supply, should be a priority. Additionally, in fostering the implementation of CE strategies in the renewables manufacturing industry in Europe, maximizing the recovery of metals is also required.

4.2. Supply Risk Analysis

Comparing the two methodologically proposed analyses, the CARC offers a simpler framework and allows individual analysis per the criteria of risk. The SCSI provides a measure including availability, dependence, and resilience, and allows tracing the countries, regions, and the governance criteria scores that are behind the results. This approach to analysis is useful for regulators and decision makers. For instance, in the deployment of a PV power plant, regulators should take care of the diversity of the supply, design mechanisms of protection, provide additional efforts on matters of corruption in origin, and impel commitments with third-world countries acting as suppliers for RL developments and the promulgation of more exigent standards. However, this SCSI approach presents the disadvantage of the aggregation of the component, which hides the contribution by component (A-R-D-G), and therefore, they cannot be easily disentangled. Other works found in the literature used a similar approach. For example, the valuable developments of the Talens Peiró (2022) [36] renewables supply chain from the European perspective using results from LCA. The authors use the Herfindahl–Hirschman Index (HHI) indicator, which provides a measurement of the concentration of the suppliers (the higher the score, the higher the risk), and then combine this indicator with WGI. In the present work, the use of entropy instead of HHI enables a strength-based perspective, rather than a risk-based one, which facilitates the interpretation of the results. Also, the use of the EMRIO framework instead of LCA allows tracing back the origin of all the metal extraction processes in the global value chain that are directly and indirectly demanded and avoids the truncation errors of the LCA method [74,75]. The limitations of the EMRIO have to be taken into account. As is widely recognized [76,77], the sectoral aggregation can distort the results and cause deviations from the actual demand for metals. Furthermore, the number of metals included in the environmental satellite accounts of domestic extraction used is shorter than those included in the LCA databases, which typically encompass many of the CRM. Comparisons have shown relevant discrepancies in the quantification of materials by these two methodologies [78].

As the main advantage of the proposed methodologies (CARC and SCSI), it can be highlighted that they can be easily adapted to any investment made in any region, for smaller or larger scales, as long as detailed cost data is available to provide a representative EMRIO result of the impact along the entire supply chain.

The three-dimensional framework can also be discussed. This three-dimensional framework formulation to assess the risk of supply is an outcome of a review of the literature on energy security conceptualization from the social sciences and the geopolitics fields of research. Similar approaches have been found in the literature, including four or more dimensions (the four A's [15] or the proposal by Cox (2017) [16]). The election of these three dimensions has primarily been based on the premise that the lowest risk would be attained when the supply chain vulnerability is minimized. The approach followed allows a comprehensive examination of vulnerabilities as a combination of risk exposure and resilience in an orthogonal combination. A broader discussion on the three-dimensional framework can be found in the Supplementary Material.

Regarding the indicators used in the assessment, the end-of-life recycling input rate (EOL-RIR) could also be subject to criticism as a circularity indicator. In this research, the EOL-RIR is used to quantify the potential amount of each metal that will be retained and used in Europe as a result of the recycling of materials in the decommissioning of the facility. With this in mind, the values used in this document are specific to the European region and, therefore, cannot be applied to other areas. To apply the framework to other countries or regions, the EOL-RIR should be calculated for the specific region or country. We have not found the metric for Spain. We assume that the EOL-RIR values for the European recycling industry are representative, as there is a common European market where countries exchange secondary raw materials. Regarding the values of EOL-RIR, one's own limitations must be taken into account. Several metals among the assessed (as bulk metals) are largely and efficiently recycled in Europe; however, their EOL-RIR value is still relatively low, mainly because they are embedded in long-life capital goods and may not be available for recycling until the future. Other materials have instead very high values of the EOLRIR because legislative bans have drastically reduced the use and demand. That could limit the application of the assessment to other metals apart from those assessed in the present work. For a large number of materials, including many CRMs, the

EOL-RIR is null or very low because they have been introduced only recently in innovative and complex products (e.g., e-vehicles, renewable energy plants, and electronics), and technologies for their recycling are still not available or have not been reported yet. Still, data on secondary materials produced can refer to more general estimations, including average sectoral and international data. This is why values for the European aggregate are used in the present study. Indeed, for several raw materials (including many CRMs), the EU countries are relying on imports and exports of scraps, which are finally recycled by a limited number of specialized industries not evenly distributed in the European territory.

Regarding availability, the economic reserves have been utilized in the SCSI to offer the possibility of allocating resources to a country or region; however, reserves in the Earth's crust and new reserve discoveries could occur, potentially affecting the results of the SCSI. The use of the ADP could be less sensitive to these events. The results of this methodological framework are not subject to volatility, such as that in prices or the import/export ratio. Still, they are based on the quantification of direct and indirect material extraction to satisfy flows, which are more stable over time. Since the substitution of materials is much more difficult than that of any other input or productive factor, being relatively inelastic, it lends robustness to the analysis compared to others based on prices.

The methods developed in this research can indeed help policymakers in identifying the strongest supply chains and can be used to identify potential reliable trading partners along the supply chain. The method completes the overall sustainability assessment of energy investments, based on environmental and socioeconomic EMRIO, identifying potential hotspots and designing mitigation strategies. For instance, it can be used to evaluate the benefits of the intra-European circularity of different energy investment alternatives and the associated supply risk mitigation. Imposing some requirements on the suppliers of materials in terms of recyclability (e.g., that regulate the mandatory level of recycling rates and minimum thresholds) or promoting certification schemes for the sustainability of extraction activities (e.g., the case of illegal rare earths in China could help in reducing supply risk, as well as other impacts). Putting in place better collection systems, harmonized waste regulations, and a sound investment framework for recycling facilities are vital to position the EU as a leader in this space. The circular economy introduced by the European Commission, specifically for battery recycling, will establish a new legal framework to ensure standards and targets for recycling.

We note that the EMRIO method can be used to assess investments anywhere in the world, provided that cost data is available in sufficient detail. The CARC and SCSI, which are proposed to assess the risks or strengths along the value chain of metals, can be applied to using EEMRIO results, regionalized by country or region. The only additional requirement is a specific statistical metric for circularity, which is needed to characterize the resilience of the country or region where the investment is located. The rest of the metrics, secondary data, or statistics used in the paper can be applied to the assessment of any investment.

4.3. Novelty Contribution, Limitations, Challenges, and Next Steps

The research provides a novel contribution as it addresses the research gap within the context of state-of-the-art risk analysis in sustainability assessment, which is the lack of a holistic, multidimensional methodology to quantify and compare supply chain risks using pre-existing sustainability methods, such as EMRIO, that can trace direct and indirect regional impacts along the value chain. Therefore, the research breaks new ground through the following:

- EMRIO-Based integration: It uses EMRIO analysis, enabling planetary system boundaries, global traceability of material extraction, and quantification of both direct and indirect (embedded) flows not reachable to classical LCA/MFA.
- Multidimensional risk framework: The proposed assessment encapsulates four core components—availability (inverse ADP), circularity (end-of-life recycling input rates), dependence (entropy-based diversity), and governance (using WGI)—reflecting the three orthogonal supply security dimensions crucial in current energy-transition policy thinking.
- Composite and actionable indices: By formulating the Comparative Analysis of Risk Components (CARC) and, more importantly, the Supply Chain Strength Index (SCSI), the manuscript offers a single, policy-relevant metric, enabling robust cross-technology and cross-scenario risk comparisons.
- Empirical validation for policy relevance: The methodology is practically tested with detailed case studies comparing CSP and PV supply chains (with storage) for Spain, offering evidence for decision support, in contrast to largely theoretical or mineral-specific case studies in the recent literature.
- Inclusion of governance and circularity: This is one of the first attempts to holistically quantify how supply risk is mitigated or exacerbated not only by material flows and reserve/production ratios, but also by governance quality and circularity—filling acknowledged gaps in both the LCA and criticality/risk literature.

The approach advances beyond the previous literature by integrating diverse risk dimensions (availability, dependence, resilience, and governance) within a single, coherent Extended Multi-Regional Input–Output (EMRIO) framework, supported by innovative, policy-relevant composite indicators.

The paper answers the three questions raised in the introduction by proposing and demonstrating a supply chain risk assessment methodology for metals critical to renewable energy deployment using Extended Multi-Regional Input–Output (EMRIO) analysis. First, it establishes a quantitative framework measuring risk and strengths via four key components: resource availability (via abiotic depletion potential), resilience (circularity/recycling rates), dependence (supply diversity using entropy metrics), and governance (using six WGI) along the value chain of ten metals for solar energy. Second, it shows how these components collectively cover the three dimensions of energy security—availability, dependence, and resilience—with governance providing a cross-cutting risk assessment. Finally, the study demonstrates that the method seamlessly integrates supply chain risk analysis into EMRIO-based sustainability assessment, enabling a comprehensive evaluation of both environmental and supply risks for energy investments.

The metrics and measurements proposed in the paper are subject to risks such as data limitations, choices regarding system boundaries, and methodological simplifications, all of which can affect the validity of the results. For instance, EMRIO relies on aggregated economic and resource flow data, which can obscure regional and sectoral nuances or overlook indirect supply chain interactions. The use of global recycling rates and governance indicators also introduces uncertainty due to variable data availability and reporting standards. Such factors can lead to under- or over-estimation of both risks and strengths, thereby influencing the accuracy and reliability of conclusions about supply chain security for PV and CSP investments

To overcome the disadvantages and limitations of the proposed methodologies, some challenges have been identified. To address aggregation errors that can lead to significant deviations in estimates of impacts, the research can depart from an EMRIO approach (such as the one used in the present work, regarding the domestic extraction of metals) and adopt other models, such as hybrid LCA. Montana et al. [79] carried out a review on the approaches adopted for the CRM content in energy technologies and how to assess their supply risk. They also agree that it would be fruitful to combine inventories from LCA and MRIO databases to obtain the most effective results of supply risks of CRMs and SRMs to properly consider macroeconomic aspects. The integration of the methodological frameworks proposed here with integrated assessment models would improve the reliability of the scenarios proposed.

Also, future lines of work include applying the frame to other metals and energy technologies. While solar technologies are based on common metals (Fe, Al, Cu, etc.) and precious metals (Ag, etc.) assessed here, batteries and other renewables, such as wind power, have a stronger demand for rare earths and other CRMs. A new data source would be required to calculate the EOL-RIR for CRMs.

The method simplifies some aspects, equating 'governance' with a numerical score and 'dependence' with a statistical measure of diversity. This means that factors such as strategic alignment, regime type, and the active weaponization of economic interdependence (supremacy, and neighbors' influence) are not assessed. Other criteria could be included in the proposed framework. As an example, China started introducing export restrictions on rare earth elements (REEs) in 2006, which resulted in an increase in prices and the United States filing a World Trade Organization (WTO) case in 2012 [4]. The fluctuations and volatility of metal prices, and their affordability, could be a criterion (considering the CARC) or a component (considering the SCSI) to be included in future work as uncertainty analysis of the results.

5. Conclusions

This paper proposes a methodology based on EMRIO assessment to enable the analysis of risk and strengths of the supply chain of metals associated with the deployment of potential renewable investments for the decarbonization of the energy system. Metals reserves and production statistics, diversity metrics, and governance indicators are combined to provide a holistic assessment covering the three main orthogonal dimensions of energy security (availability, dependence, and resilience). The quantification of the four key parameters is used to characterize the vulnerability of the supply chain (availability, circularity, diversity of suppliers, and the level of governance in the origin). To provide a comprehensive final result encompassing all key parameters, two analytical perspectives are employed: a comparative analysis of individual risk components (CARC) and a combined index (SCSI). Two alternative solar technologies' supply chains have been used to test the method and quantify the risk along the ten-metal supply chain.

The results showed that, in general, the CSP plant supply chain entails lower risk than the PV power plant supply chain. The PV supply chain has a lower level of supplier diversification than the CSP supply chain and generally exhibits a lower level of governance in its origin. This implies that the extraction of metal required to deploy each MW from the CSP plant considered would come from a more diverse set of countries and regions, and from countries with better governance levels than for PV. The measurement of the resilience of the deployment is achieved by including a circularity metric. This metric increases the strengths of both value chains, especially the value chain of PV.

The case studies of the solar technologies evaluated confirm the effectiveness of employing a relatively simple methodology for obtaining valuable information regarding key supply risk and strength factors, allowing robust comparisons to be made between technologies using readily available data. Furthermore, the exercise demonstrates that including metals (or raw materials in general) assessments in EMRIO can help to visualize the relevance of the global supply chain in achieving energy targets and, therefore, to urge the development of new resource management measures directed to secure the supply of key raw materials and/or components for renewable energy technologies. Given Europe's potential role in promoting net-zero industrial strategies and considering its dependence on the foreign extraction of key metals and minerals for this purpose, circularity and recycling policies are essential. Therefore, indicators should include these aspects.

The research advances beyond the previous literature by integrating diverse risk dimensions (availability, dependence, resilience, and governance) within a single, coherent Extended Multi-Regional Input–Output (EMRIO) framework, supported by innovative, policy-relevant composite indicators. Unlike prior research, which was limited by narrow system boundaries, single-indicator focus, or a lack of traceability, this research's contribution is a rigorously formulated, multi-dimensional, and empirically validated framework that applies to case studies enabling sustainability risk analysis of metals supply chains—aligned with the needs of policymakers and investors facing the real-world complexities of clean energy deployment and critical material access.

As a response to the limitations, future lines of work have been identified. Among these, expanding the analysis to assess the supply of CRMs for renewable energy deployment is crucial. Notwithstanding the limitations discussed, the proposed method can support the decision-making process of both public sector policymakers and private sector investors by helping them decide between alternatives and identify geopolitical weaknesses along the value chain. Furthermore, this method may also be used by regulators to test the necessary measures and put them in place to mitigate the identified risks and to foster the potential strengths.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su172310827/s1. The Supplementary Material contains: (1) a table summarising the description and formulation of the components for measuring the supply risks along the value chain, covering the three dimensions framework; and (2) a review of literature and discussion of the three dimensions of energy security to be applied to the supply risks along the value chain.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

$(I\text{-}A)^{-1}$	Leontief inverse
A	Technical coefficients matrix based on the MRIOT
ADP	Abiotic depletion potential
ADP_m	Abiotic depletion potential of the metal m
Ag	Silver
Al	Aluminum
Au	Gold
c	Countries or regions included in the MRIOT
CC	Control of Corruption
CE	Circular economy
CSP	Concentrated solar power
Cu	Copper
DR_m	Annual production or extraction rate of resource *m* (kg/yr)
DR_{ref}	Annual production or extraction rate of the Sb (kg/yr).
$DR_{m,c}$	Extraction rate of resource *m by the* country *c* (kg/yr)
$DR_{m,global}$	Extraction rate of resource *m* globally (kg/yr)
E_m	Entropy of the extraction of the metal *m* along the supply chain
$EOLRIR_m$	End-of-life recycling input rates in Europe of the metal *m*
E_{mmax}	Maximum value of Entropy considering the number of countries or regions c of the extraction of the metal m along the supply chain
EMRIO	Extended Multi-Regional Input–Output
$eRPR_{m,c}$	Reserve-production ratio
$eR_{m,c}$	Reserve of the reference metal m in the country *c* (kg)
$eR_{m,global}$	Reserve of the metal *m* globally (kg)
$ERPR$	Total Intra-European recycling potential rate of the assessed metals extracted as consequence of the investment
$ERPR_m$	Intra-European recycling potential rate of the metal *m* extracted as consequence of the investment
EU	European Union
E_{tmax}	Maximum value of Entropy of the total extraction of the assessed metals along the supply chain
E_t	Sum of Entropy of the extraction of assessed metals along the supply chain
Fe	Iron
$G_{WGIm,i}$	Governance index of the total extraction of each material m per governance criteria i
GE	Government effectiveness
GRI	Global Resources Index
GWh	Gigawatts-hour
kg of Sb eq.	Kilograms of antimony equivalent
HHI	Herfindahl–Hirschman Index
i	Governance criterion (i = VA, PSVA, GE, RQ, RL, CC)
LCA	Life Cycle Analysis
m	Each metal (m = Al, Cu, Au, Fe, Pb, Ni, Pt, Ag, Sn, Zn)
MFA	Material Flow Analysis
M_m	Mass of each of the extracted metal as consequence of the investment using EMRIO
$M_{m,c}$	Mass of each of the extracted metal in the country c as consequence of the investment using EMRIO
MRIO	Multi-Regional Input–Output

M_t	Total of the quantified mass of extracted metal as consequence of the investment using EMRIO
MW	Megawatts
Ni	Nickel
Pb	Lead
PSVA	Political stability and the absence of violence
Pt	Platinum
PV	Photovoltaics
RL	Rule of Law
R_m	Ultimate reserve of the reference mineral *m* (kg)
RQ	Regulatory quality
RP_m	Ratio Reserves-Production of the metal *m*
R_{ref}	Ultimate reserve of the reference mineral Sb (kg)
$SCSI_{m,i}$	Supply Chain Strength Indicator of the supply chain of extraction of the metal m for the indicator i
$SCSI_{t,i}$	Supply Chain Strength Indicator of the supply chain of extraction of the sum of assessed metals for the indicator i
Sb	Antimony
Sn	Tin
SR	Supply Risk
VA	Voice and accountability
WGI	Worldwide Governance Indicators
$WGI_{i,c}$	Governance value of each indicator (i = VA, PSVA, GE, RQ, RL, CC)
WGI_{iEUR}	Average of the values of the governance criteria indicator i of the European countries
Zn	Zinc

Appendix A. Values of ADP, RP and EOLRIR

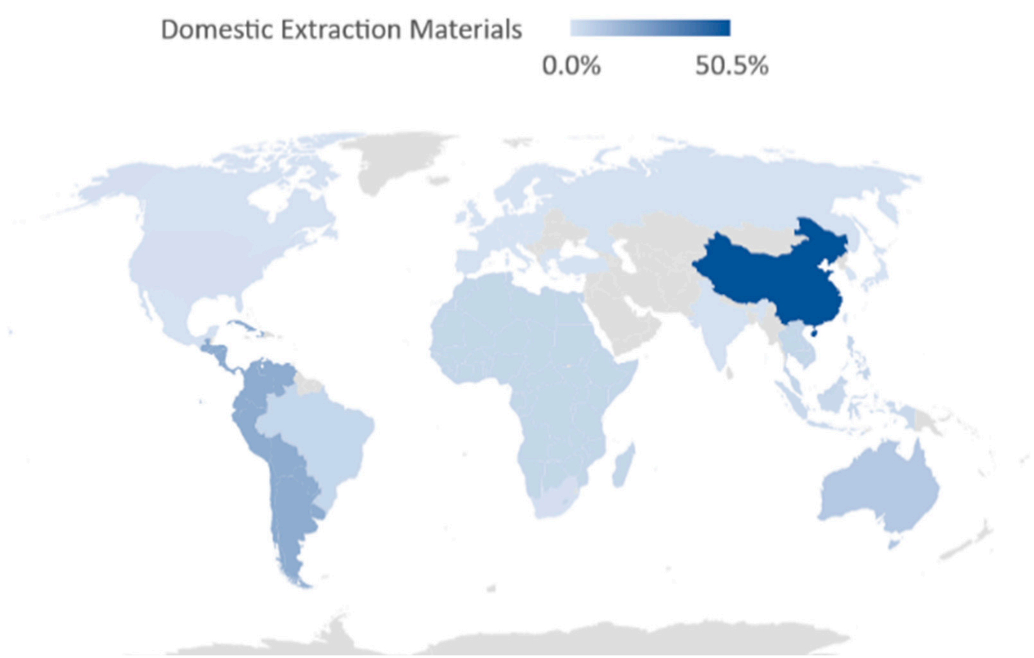
Table A1. ADP characterization factor, RPR and $EOLRIR_m$.

Name	Sym.	ADP	RP	EOLRIR
		kg Sb eq/kg	(kg m R_{2015}/ kg m P_{2015})	%
Aluminum	Al	2.54×10^{-8}	7.68×10^{7}	12.3 [1]
Copper	Cu	2.13×10^{-2}	2.66×10^{5}	16.9 [1]
Gold	Au	1.37×10^{3}	7.73×10^{4}	19 [1]
Iron	Fe	6.92×10^{-7}	5.87×10^{6}	31.5 [1]
Lead	Pb	1.87×10^{-2}	5.01×10^{5}	75 [1]
Nickel	Ni	8.15×10^{-4}	4.16×10^{6}	17 [1]
Platinum	Pt	9.71×10^{2}	3.28×10^{5}	25.3 [1]
Silver	Ag	8.64×10	3.47×10^{5}	20 [2]
Tin	Sr	1.66×10^{-6}	2.98×10^{8}	19 [2]
Zinc	Zn	2.76×10^{-3}	8.61×10^{5}	31 [1]

[1] Source: [50]; [2] Source: [80].

Appendix B. Supporting Figures for the Analysis of Results of Diversity, Governance, and SCSI

(a) PV power plant



(b) CSP plant

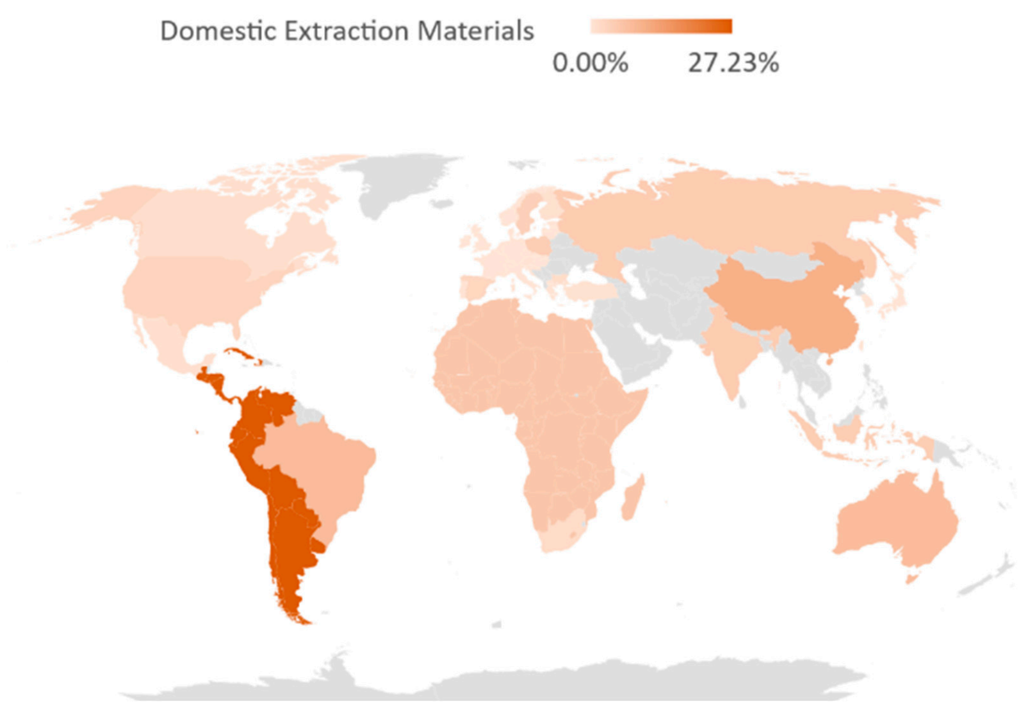
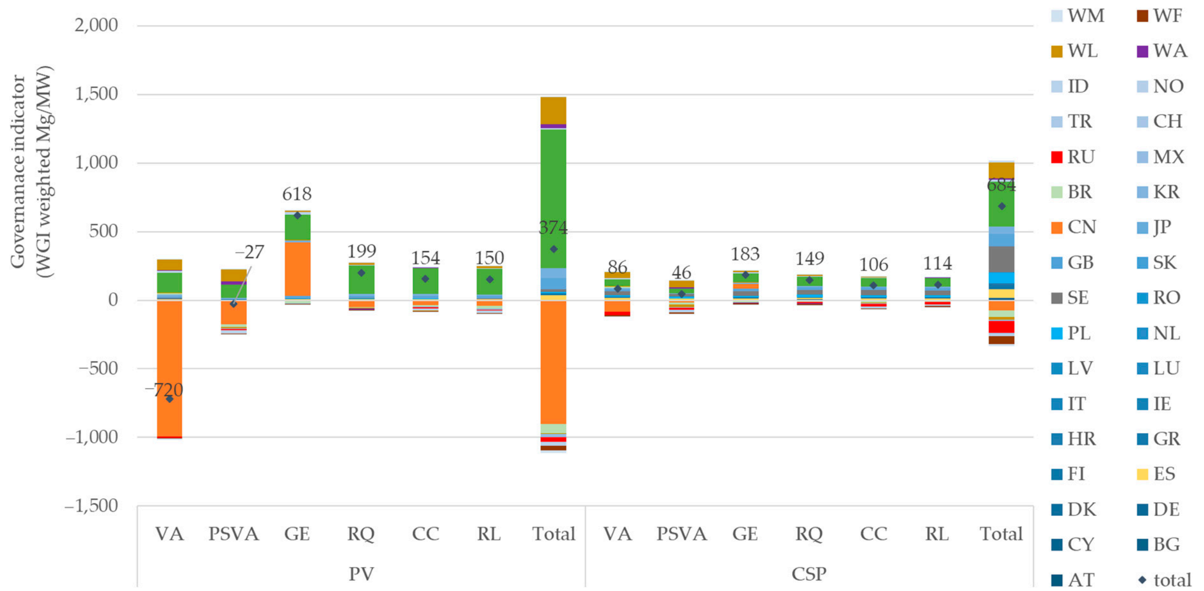


Figure A1. Contribution by origin to the material extraction required by the PV (**a**) and CSP (**b**) power plant deployment (%). Source: Own elaboration using Microsoft Excel with Bing Technology Extension, map data from the Australian Bureau of Statistics, GeoNames, Geospatial Data Edit, Navinfo, OpenStreetMap, Tomtom, and Wikipedia.

(a)



(b)

Figure A2. G_{WGIi} of the supply chain by governance indicator, showing the contribution of the country or region (supplier) of each indicator for each metal in each case (PV, CSP) per installed capacity (MW) (**a**) and electricity produced (GWh) (**b**). List of country or region abbreviations: AT: Austria; BE: Belgium; BG: Bulgaria; CY: Cyprus; CZ: Czech Republic; DE: Germany; DK: Denmark; EE: Estonia; ES: Spain; FI: Finland; FR: France; GR: Greece; HR: Croatia; HU: Hungary; IE: Ireland; IT: Italy; LT: Lithuania; LU: Luxembourg; LV: Latvia; MT: Malta; NL: Netherlands; PL: Poland; PT: Portugal; RO: Romania; SE: Sweden; SI: Slovenia; SK: Slovak Republic; GB: United Kingdom; US: United States; JP: Japan; CN: China; CA: Canada; KR: South Korea; BR: Brazil; IN: India; MX: Mexico; RU: Russian Federation; AU: Australia; CH: Switzerland; TR: Turkey; TW: Taiwan; NO: Norway; ID: Indonesia; ZA: South Africa; WA: Rest of Asia and Pacific; WL: Rest of Latin America; WE: Rest of Europe; WF: Rest of Africa; WM: Rest of Middle East; VA: Voice and Accountability; PSVA: Political Stability and violence absence; GE: Government Effectiveness; RQ: Regulatory Quality; RL: Rule of Law; and CC: Control of Corruption.

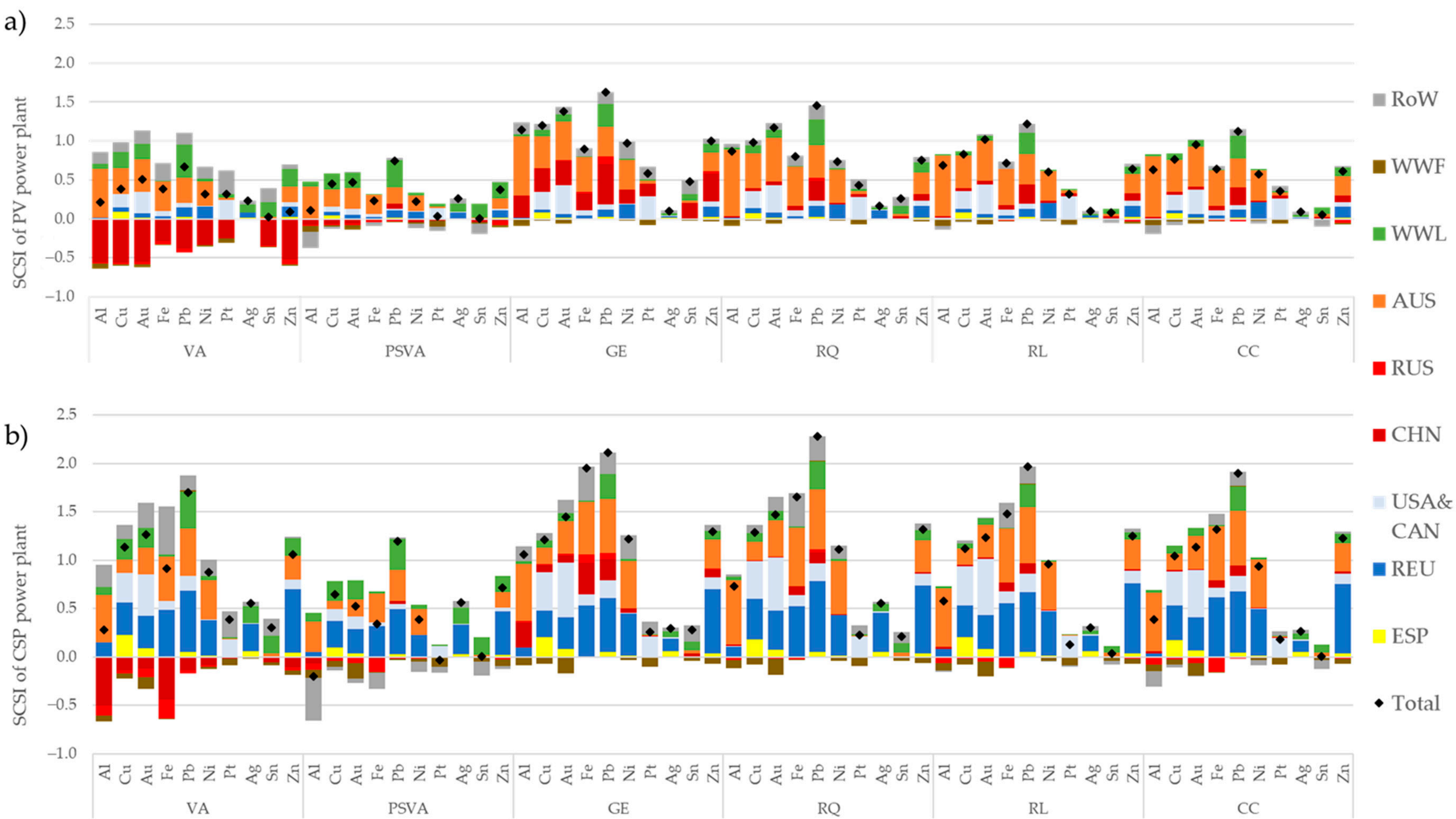


Figure A3. Results of the combined indicator Supply Chain Strength Indicator (SCSI). RoW: Rest of the World; WWF: African Region; WWL: Latin America Region; AUS: Australia; RUS: Russia; CHN: China; USA & CAN: United States of America and Canada; REU: Rest of Europe Region; ESP: Spain. VA: Voice and Accountability; PSVA: Political Stability and violence absence; GE: Government Effectiveness; RQ: Regulatory Quality; RL: Rule of Law; and CC: Control of Corruption. (**a**) Results of the combined indicator Supply Chain Strength Indicator (SCSI) of de PV power plant, per metal and region (**b**) Results of the combined indicator Supply Chain Strength Indicator (SCSI) of de CSP plant, per metal and region.

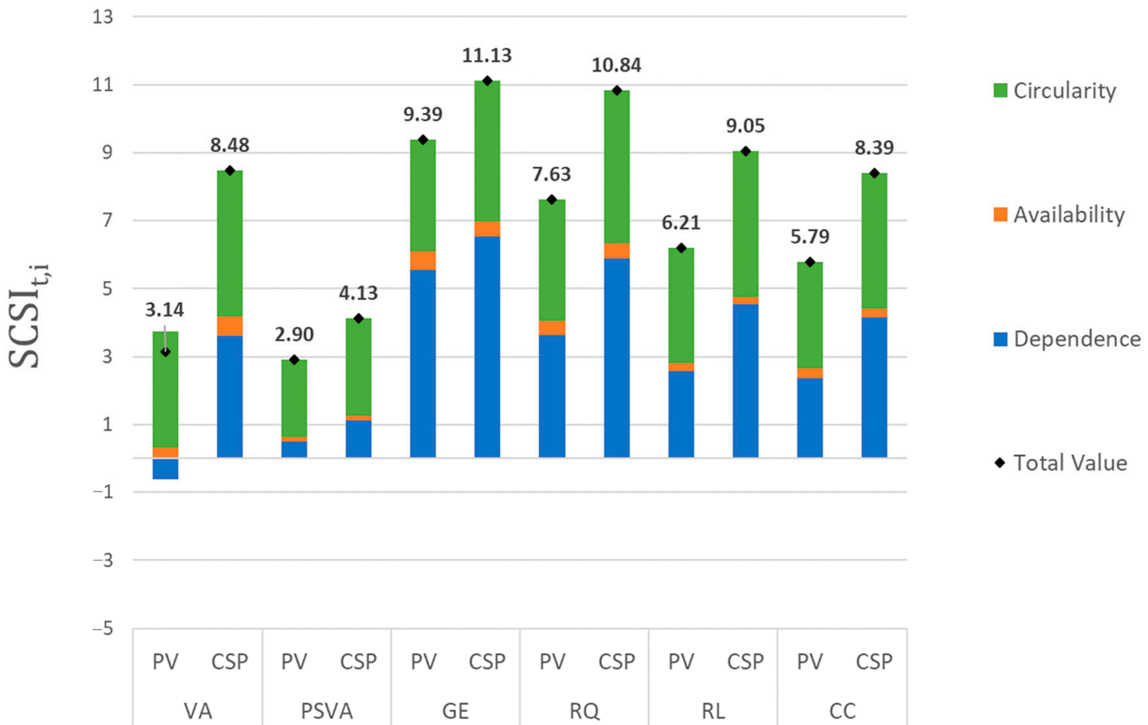


Figure A4. Results of the combined indicator Supply Chain Strength Indicator (SCSI) in term of equation (dependence, availability, and circularity). VA: Voice and Accountability; PSVA: Political Stability and Violence Absence; GE: Government Effectiveness; RQ: Regulatory Quality; RL: Rule of Law; and CC: Control of Corruption.

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