

UNIVERSIDAD POLITÉCNICA DE MADRID

Escuela Técnica Superior de Ingenieros Industriales



**METHODOLOGICAL
DEVELOPMENTS FOR
SUSTAINABILITY ASSESSMENT
OF ENERGY TECHNOLOGIES**

DOCTORAL THESIS

Ana R. Gamarra Rodríguez
Máster en Ingeniería Ambiental

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DEPARTAMENTO DE INGENIERÍA QUÍMICA, INDUSTRIAL Y DEL
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Por lo que está por venir.

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ABSTRACT

During the last centuries, human activities have intensified their influence over the environment triggering environmental, social and economic problems. Among these, climate change is bringing unequivocal consequences for the lives of people at the global scale. The damages on ecosystems, human health, biodiversity and impacts on social and economic well-being of people have been demonstrated. Faced with the challenge of confronting this situation, a new paradigm of sustainable development is emerging.

The theoretical umbrella of this thesis is the sustainability framework. After presenting the concepts and main foundations of sustainability, the introductory section frames the nexus between energy transition and use of limited resources. Among the wide range of policies fostering a more sustainable model of development, those related to energy agree on the need to achieve an energy transition towards a decarbonised energy system with renewable energies playing a pivotal role. The assessment of this energy transition requires methodologies that support decision-making processes based on quantifiable criteria. Not exempt of limitations, existing methodologies for sustainability assessment are able to evaluate the impacts on the three pillars of sustainability – environmental, economic and social –. This section also highlights the importance of taking into account new challenges posed by the large-scale development of renewable energies such as new resources' dependence issues and the supply risks along the value chain.

The **goal of this thesis** is to propose methodological developments to improve the current methodologies for sustainability assessment and apply them in the field of energy technologies. Therefore, two lines of research were identified, which have been developed in parallel. Due to the methodological nature of this research, the state of the art early alludes to methodological contents, presenting the main foundations, limitations, advantages and recent progresses of the methods and tools for sustainability assessment. Among those, the Extended Multiregional Input-Output Analysis (EMRIO) and the Life Cycle Sustainability Analysis (LCSA) stand out as the most widely used methodologies.

Research Line I was focused on expanding the existing sustainability assessment framework based on EMRIO to identify and quantify the risks along the supply chain. EMRIO methodology enables tracing back the direct and indirect contribution of each country or region to the production of goods and services, and therefore, offers valuable data for the geopolitical analysis of the value chain. This analysis was conducted in three steps. In the **first step**, two main geopolitical aspects were explored: dependence and level of governance. Various metrics of

diversity and various indicators of governance were used to characterize the value chain in a comparative case study of two power generation technologies: a Natural Gas (NG) power plant and a Concentrated Solar Power (CSP) plant with thermal storage. Results showed that the CSP plant supply chain included a more diversified portfolio of countries and with better governance levels than in the case of the NG plant supply chain. This means, a priori, that the supply risks of investing in CSP plants will be lower, as well as the endogenous geopolitical risks. However, a sensitivity analysis for the solar plant components considering different suppliers reveals that the CSP power plant value chain could also entail similar or even higher levels of governance risk than NG power plants when some components are supplied from China. Therefore, the proposed method allows to identify hidden dependencies, and characterize them in terms of dependence and governance. However, limitations to properly reflect the exogenous geopolitical risks and the own limitations of EMRIO should be considered.

In the **second step**, a new combined dependence-governance indicator was proposed as methodological improvement from the previous step. In addition, this analysis was conducted as a part of a comprehensive integrated sustainability assessment based on EMRIO. As case study, the implementation of a 200 MW CSP plant in Spain was evaluated by comparing the sustainability impact of the two main technologies (parabolic trough and central receiver) under three different scenarios of supply (in terms of the origin of components). Another novelty was the application of the indicator of supply risk for the extraction of silver, a key mineral to the deployment of solar technologies. Results revealed that supply risks were lower when Germany supplies the main components. The scenario in which Spain supplies all components did not show significant differences with the scenario in which China supplies some components in terms of value of the indicator of supply risk, although differences in origin were identified. These results suggested greater efficiency in the use of resources by German sectors and greater involvement of European suppliers (with higher levels of governance, with some exceptions).

The **third step** was focused on developing a framework of analysis able to cover the basic dimensions of the energy security characterizing the vulnerability of the energy supply chain: availability, dependence and resilience. Additionally, governance considerations were included in the framework of analysis for each individual component. The aim of the method was to identify and characterize the potential risks and strengths along the supply chain of a set of metals associated to energy investments. Given the relevance of minerals for the energy transition the assessment departed from quantification of the required extraction of ten different metals along the value chain using EMRIO methodology. As case study, two

solar energy technologies were evaluated and compared: CSP with thermal storage and photovoltaics (PV) with batteries. First, different metrics and indicators for the analysis of the supply chain were analysed. Second, a framework of analysis including quantifiable components of the supply chain risks and strengths was proposed. Geographical diversity of suppliers, abundance of reserves, circularity and level of governance were found as the key components able to cover these components. Then, two perspectives for the analysis were presented: (1) the analysis of individual components of the supply risks' criterion; and (2) a combined index that represents the strength of the value chain. The results showed, in general, a better performance of the CSP in the indicators of availability of resources and diversity of suppliers but slightly worse scores in the resilience and governance criterion. The analysis based on the index reflects an overall better performance of CSP. As for the metals, platinum, silver and tin play the main role in the analysed risks.

In light of the limitations of EMRIO and LCA, the **Research Line II** focused on proposing methodological improvements of EMRIO-LCA hybridization. To this end, a new stepwise tiered hybrid approach combining Life Cycle assessment and EMRIO was developed, called Identification and Subtraction Method (ISM). Focusing only on environmental assessment, the proposed method was tested by evaluating seven environmental indicators and comparing the results obtained with different methodological approaches: EMRIO, LCA and two hybrid approaches. One more time, the case study of CSP was used. The results showed that, in general, LCA and EMRIO provided the lowest and highest impact values, respectively. The highest differences between the results obtained by the different methods are in the assessment of local impacts and resource depletion, while the methods tend to agree more on the quantification of global and regional impacts. The ISM method achieves the goal of extending the boundaries of LCA by including indirect impacts, avoiding double counting and retaining the technological detail and representativeness of LCA. The main advantage is the ability to establish the impact coming from the LCA system boundaries with high accuracy. However, some truncation error still remains as it cannot include the partial contributions of EMRIO sectors. The proposed ISM method is easy for LCA practitioners to perform, consumes little time once the LCA and EMRIO models are built, and does not require the alteration of the multiregional input-output table like other hybrid methods do. However, both the EMRIO and LCA analyses could imply a large need for detailed data and some limitations on the characterization of substances were found.

Conclusions highlight the relevant contribution to the sustainability assessments of energy investments of the research conducted in Research Line I. In fact, the inclusion of the analysis of risks from the point of view of geopolitical and energy security insights into an integrated

sustainability assessment covering the three pillars conforms a very powerful tool. The research developed provides a tool that covers the three main dimensions of energy security along the value chain - dependence, availability and resilience by the four-component framework and offers a complete characterization of the supply chain. Case study application of this method has led to the conclusion that the European deployment of renewables should be accompanied by measures to secure supply, such as cooperation agreements, and should also encourage the recovery of secondary material by maximising European resilience. As for the contribution of Research Line II, the proposed hybrid ISM method succeeds in improving the quantification of impacts by maximising the completeness of the assessment while minimising the double counting problems of the classical tiered method and the complexity of other hybrid methods. The logical **next step** is to combine the methodological advances developed in Research Lines I and II. That is to assess the risks (or strengths) along the supply chain of a renewable technology, using the method developed in Research Line I, based on the quantification results of metals or minerals provided by the ISM method developed in Research Line II. As for each of the followed research lines individually, many other developments can be undertaken. From the point of view of supply risks analysis, current policy for energy transition put the stress on the assessment of risks of Critical Raw Materials (CRM), not still properly quantified by EMRIO tables. Thus, developments in this regard could be addressed. Related to criteria and components of supply risks, the use of tools for spatial-analysis could address exogenous geopolitical aspects and other indicators related to bilateral relationships among countries. Among the future research following the proposed ISM method, testing the method in other case studies for further validation could be of interest. Secondly, this method could be applied considering other relevant impacts (e.g. land use) not only environmental but also socioeconomic or social impacts.

RESUMEN

Durante los últimos siglos, las actividades humanas han intensificado su influencia sobre el medio ambiente desencadenando problemas medioambientales, sociales y económicos. Entre ellos, el cambio climático está trayendo consecuencias inequívocas para la vida de las personas a escala mundial. Se han demostrado daños en los ecosistemas, la salud humana, la biodiversidad, así como impactos en el bienestar social y económico de las personas. Ante el reto de hacer frente a esta situación, ha surgido un nuevo paradigma de desarrollo sostenible.

El marco teórico de esta tesis gira en torno a la sostenibilidad. Tras presentar los conceptos y fundamentos principales de la sostenibilidad, la sección introductoria enmarca el nexo con la transición energética y el uso de recursos limitados. Entre el amplio abanico de políticas que promueven un modelo de desarrollo más sostenible, las relacionadas con la energía coinciden en la necesidad de lograr una transición energética hacia un sistema energético descarbonizado en el que las energías renovables jueguen un papel fundamental. La evaluación de esta transición energética, requiere de metodologías que apoyen los procesos de toma de decisiones en base a criterios cuantificables. No exentas de limitaciones, las metodologías existentes para la evaluación de la sostenibilidad son capaces de evaluar los impactos sobre los tres pilares de la sostenibilidad -medioambiental, económico y social-. Esta sección también destaca la importancia de tener en cuenta los nuevos retos que plantea el desarrollo a gran escala de las energías renovables, como los problemas de dependencia de nuevos recursos y los riesgos de suministro a lo largo de su cadena de valor.

El **objetivo de esta tesis** es proponer desarrollos metodológicos para mejorar las actuales metodologías de evaluación de la sostenibilidad y aplicarlos en el campo de las tecnologías energéticas. Por ello, se identificaron dos líneas de investigación, que se han desarrollado en paralelo. Debido a la naturaleza metodológica de esta investigación, en el estado del arte se alude a los contenidos metodológicos existentes, presentando los principales fundamentos, limitaciones, ventajas y avances recientes de los métodos y herramientas para la evaluación de la sostenibilidad. Entre ellos, destacan el Análisis Input-Output Multirregional Ampliado (EMRIO por sus siglas en inglés) y el Análisis de la Sostenibilidad del Ciclo de Vida (LCSA por sus siglas en inglés) como las metodologías más utilizadas.

La **Línea de Investigación I** se centró en ampliar el marco existente de evaluación de la sostenibilidad basado en EMRIO para identificar y cuantificar los riesgos a lo largo de la cadena de suministro. La metodología EMRIO permite rastrear la contribución directa e indirecta de cada país o región a la producción de bienes y servicios y, por tanto, ofrece datos valiosos para

el análisis geopolítico de la cadena de valor. Este análisis se ha realizado en tres etapas. En el **primer paso**, se exploraron dos aspectos geopolíticos principales: la dependencia y el nivel de gobernanza. Se utilizaron varias métricas de diversidad y varios indicadores de gobernanza para caracterizar la cadena de valor en un estudio de caso comparativo de dos tecnologías de generación de energía: una central eléctrica de gas natural (NG por sus siglas en inglés) y una central de energía solar concentrada (CSP por sus siglas en inglés) con almacenamiento térmico. Los resultados mostraron que la cadena de suministro de la central de CSP incluía una composición de países más diversificada y con mejores niveles de gobernanza que en el caso de la cadena de suministro de la central de GN. Esto significa, a priori, que los riesgos de suministro de la inversión en centrales CSP serán menores, así como los riesgos geopolíticos endógenos. Sin embargo, un análisis de sensibilidad para los componentes de las centrales solares considerando diferentes proveedores revela que la cadena de valor de las centrales de CSP también podría conllevar niveles de riesgo de gobernanza similares o incluso superiores a los de las centrales de GN cuando algunos componentes se suministran desde China. Por tanto, el método propuesto permite identificar dependencias ocultas y caracterizarlas en términos de dependencia y gobernanza. Sin embargo, deben tenerse en cuenta las limitaciones para reflejar adecuadamente los riesgos geopolíticos exógenos, así como las propias limitaciones de EMRIO.

En el **segundo paso**, se propone un nuevo indicador combinado de dependencia-gobernanza como mejora metodológica del paso anterior. Además, este análisis se llevó a cabo como parte de una evaluación global integrada de la sostenibilidad basada en EMRIO. Como caso de estudio, se evaluó el despliegue de una central de CSP de 200 MW en España comparando el impacto en la sostenibilidad de las dos tecnologías principales (cilindro-parabólica y de receptor central) bajo tres escenarios diferentes de suministro (en cuanto al origen de los componentes). Otra novedad fue la aplicación del indicador de riesgo de suministro para la extracción de plata, un mineral clave para el despliegue de las tecnologías solares. Los resultados revelaron que los riesgos de suministro eran menores cuando Alemania suministra los principales componentes. El escenario en el que España suministra todos los componentes no mostró diferencias significativas con el escenario en el que China suministra algunos componentes en cuanto al valor del indicador de riesgo de suministro, aunque sí se identificaron diferencias en el origen. Estos resultados sugieren que existe una mayor eficiencia en el uso de los recursos por parte de los sectores alemanes. Así mismo, se identificó una mayor contribución de los proveedores europeos (con mayores niveles de gobernanza, con algunas excepciones).

El **tercer paso** se centró en desarrollar un marco de análisis capaz de cubrir las dimensiones básicas de la seguridad energética que caracterizan la vulnerabilidad de la cadena de suministro energético: disponibilidad, dependencia y resiliencia. Además, se incluyeron consideraciones de gobernanza en el marco de análisis para cada componente individual. El objetivo del método era identificar y caracterizar los posibles riesgos y puntos fuertes a lo largo de la cadena de suministro de un conjunto de metales asociados a las inversiones energéticas. Dada la relevancia de los minerales para la transición energética, la evaluación partió de la cuantificación de la extracción necesaria de diez metales a lo largo de la cadena de valor utilizando la metodología EMRIO. Como estudio de caso se evaluaron dos tecnologías de energía solar: CSP con almacenamiento térmico y fotovoltaica (PV por sus siglas en inglés) con baterías. En primer lugar, se analizaron diferentes métricas e indicadores para el análisis de la cadena de suministro. En segundo lugar, se propuso un marco de análisis que incluía componentes cuantificables de los riesgos y puntos fuertes de la cadena de suministro. La diversidad geográfica de los proveedores, la abundancia de reservas, la circularidad y el nivel de gobernanza fueron seleccionados como los componentes clave capaces de cubrir todas las dimensiones. A continuación, se presentaron dos perspectivas para el análisis: (1) el análisis de los componentes individuales de los riesgos de suministro; y (2) un índice combinado que representa la fortaleza de la cadena de valor. Los resultados mostraron, en general, un mejor rendimiento de la CSP en los indicadores de disponibilidad de recursos y diversidad de proveedores, pero puntuaciones ligeramente peores en el criterio de resiliencia y gobernanza. El análisis basado en el índice refleja un mejor rendimiento general de CSP. En cuanto a los metales, el platino, la plata y el estaño desempeñan el papel principal en los riesgos analizados.

A la luz de las limitaciones de EMRIO y el Análisis de Ciclo de Vida (LCA por sus siglas en inglés), la **Línea de Investigación II** se centró en proponer mejoras metodológicas de la hibridación EMRIO-LCA. Para ello, se desarrolló un nuevo enfoque híbrido escalonado, denominado Método de Identificación y Sustracción (ISM). Centrándose únicamente en la evaluación medioambiental, el método propuesto se puso a prueba mediante la evaluación de siete indicadores medioambientales y comparando los resultados obtenidos con distintos enfoques metodológicos: EMRIO, LCA y dos enfoques híbridos. Una vez más, se utilizó el estudio de caso de la CSP. Los resultados mostraron que, en general, el LCA y el EMRIO proporcionaron los valores de impacto más bajos y más altos, respectivamente. Las mayores diferencias entre los resultados obtenidos por los distintos métodos se dan en la evaluación de los impactos locales y el agotamiento de los recursos, mientras que los métodos tienden a coincidir más en la cuantificación de los impactos globales y regionales. El método ISM consigue el objetivo de

ampliar los límites del LCA incluyendo los impactos indirectos, evitando la doble contabilización y conservando el detalle tecnológico y la representatividad del LCA. La principal ventaja es la capacidad de establecer con gran precisión el impacto procedente de los límites del sistema de LCA, aunque sigue existiendo cierto error de truncamiento, ya que no puede incluir las contribuciones parciales de los sectores EMRIO. El método ISM propuesto es fácil de aplicar para los profesionales del LCA, consume poco tiempo una vez contruidos los modelos LCA y EMRIO, y no requiere la alteración de la tabla input-output multirregional como hacen otros métodos híbridos. Sin embargo, tanto el análisis EMRIO como el LCA podrían implicar una gran necesidad de datos detallados y se encontraron algunas limitaciones en la caracterización de sustancias.

Las **conclusiones** destacan la relevante contribución de la investigación realizada en la Línea de Investigación I a las evaluaciones de sostenibilidad de las inversiones energéticas. De hecho, la inclusión del análisis de riesgos desde el punto de vista geopolítico y de seguridad energética en una evaluación integrada de la sostenibilidad que cubre los tres pilares conforma una herramienta muy potente. La investigación desarrollada proporciona una herramienta que abarca las tres dimensiones principales de la seguridad energética a lo largo de la cadena de valor: dependencia, disponibilidad y resiliencia mediante el marco de cuatro componentes y ofrece una caracterización completa de la cadena de suministro. La aplicación de este método a casos prácticos ha llevado a la conclusión de que el despliegue europeo de energías renovables debe ir acompañado de medidas para garantizar el suministro, como acuerdos de cooperación, y también debe fomentar la recuperación de material secundario maximizando la resiliencia del sector industrial europeo. En cuanto a la contribución de la Línea de Investigación II, el método híbrido ISM propuesto consigue mejorar la cuantificación de los impactos maximizando la exhaustividad de la evaluación y minimizando al mismo tiempo los problemas de doble contabilidad del método clásico por niveles y la complejidad de otros métodos híbridos.

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I. INTRODUCTION

1. THE GLOBAL CHALLENGE FOR A MORE SUSTAINABLE WORLD

During the last centuries, society has been undergoing a continuous energy transition driven by various innovations. The historical transition associated with the post-industrial period during the 20th century, was based on the shift from biomass-based energy sources to fossil products and was driven by the availability of efficient fuels and conversion technologies. However, over time, a greater understanding of the global climate and environmental impacts associated to energy provision, has prompted the current impulse to a new energy transition towards a decarbonised and cleaner energy future. Human influence on climate has unequivocally been the dominant cause of observed warming since the mid-20th century, when global average surface temperature reached 1.1°C above in 2011-2020 as pointed by the recent published Sixth Report of the Intergovernmental Panel on Climate Change (IPCC)(Lee et al. 2023).

The new 21th century transition could certainly help to limit the global warming effect and mitigate the climate change generated mainly as a result of the current energy model (Edenhofer et al. 2014). Besides, fossil-based economic model has encountered many other drawbacks as the finite and exhaustible nature of the energy resources (Eriksson 2013) and the production of other relevant environmental impacts apart from climate change (IRENA 2016; UNECE 2021). Demand for water, food, non-renewable energy resources, land and minerals is rising substantially, making natural resources increasingly scarce and more expensive (European Commission 2019a).

The Planetary Boundaries Framework (PBF) defines a safe operating space for humanity based on the intrinsic biophysical processes that regulate the stability of the Earth system. Figure 1 depicts the PBF (Rockström et al. 2009), with nine dimensions. The framework has attracted considerable interest and discussions within the policy, governance, and business sectors as an approach to inform efforts toward global sustainability. Unfortunately, scientific evidence applying the framework indicates that some of the boundaries in some dimensions have been already exceeded (Steffen et al. 2015; Persson et al. 2022; Wang-Erlandsson et al. 2022) which in turns increases the risk of generating large-scale abrupt or irreversible environmental changes.

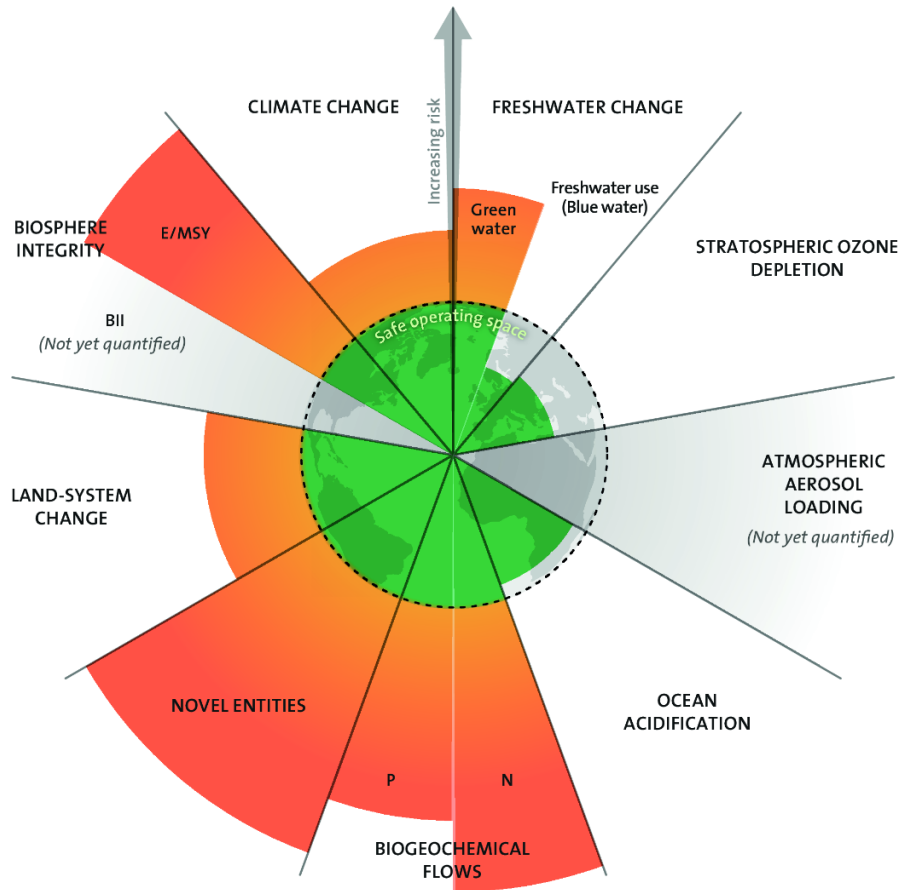


Figure 1. The planetary boundaries framework.

Source: J. Lokrantz/Azote based on the works and updates of the framework (Rockström et al. 2009; Steffen et al. 2015; Persson et al. 2022; Wang-Erlandsson et al. 2022).

Therefore, joint global efforts are needed to ensure a safe operating space within the Earth's planetary boundaries, and support global sustainable development and the well-being of humanity, assuring preventing other negative effects (inequality, dependence and political conflicts, etc.). In this regard, the PBF was proposed to be combined with the boundaries for social essentials to achieve an inclusive sustainable economic development. Known as Doughnut Economics and formulated by Raworth (primarily in 2012 (Raworth 2012), and later (Raworth 2017)), the combined framework allows to give an indication of the current state of human and planetary well-being in relation to the boundaries of sustainable development and can also be used to explore interactions between the boundaries. Figure 2 shows the visual representation of the framework, in which the central region, shaped as a Doughnut located among the environmental ceiling (given by the physical planetary boundaries), and, the social foundations (as basics to assure a just and safe space for humanity), would be the region in which human well-being is maximised.

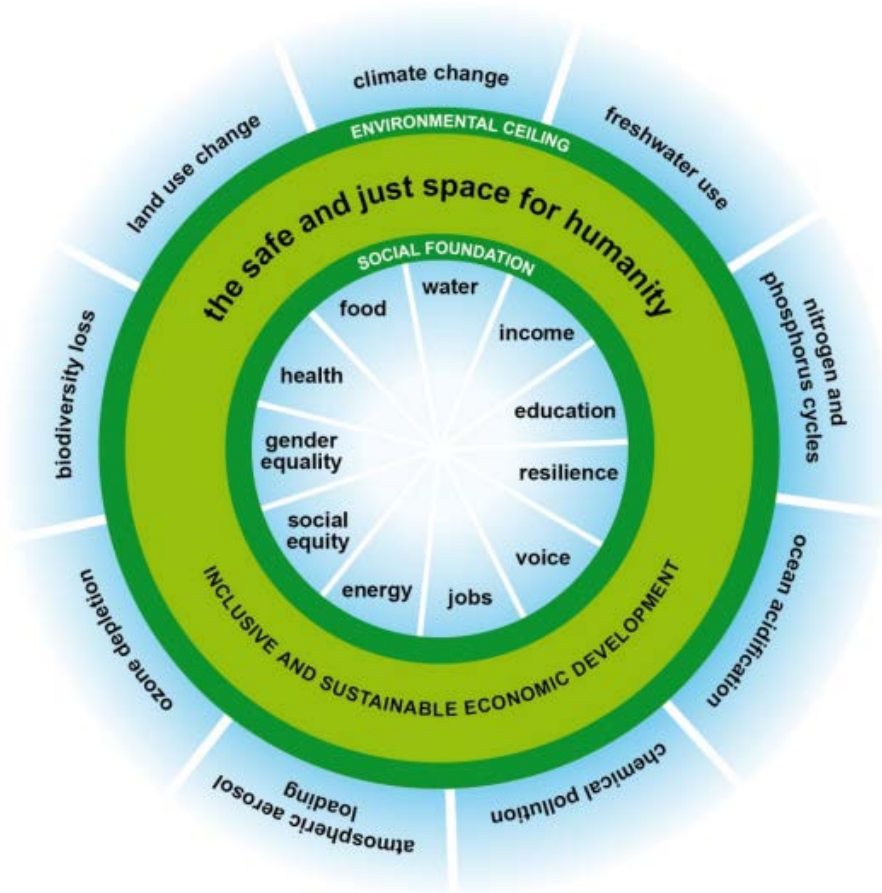


Figure 2. The 11 dimensions of the social foundations.

Source: Figure available in (Raworth, 2012). The 11 dimensions of the social foundation are illustrative and are based on governments' priorities for Rio+20. The nine dimensions of the environmental ceiling are based on the planetary boundaries set out by (Rockström et al. 2009).

At the basement of the urgent action is to foster the change and leave behind the failed economic model of growth, based on fossil fuels and intense use of resources. The success of the global action hangs on the ongoing energy transition, which will depend on the way the deployment of a new energy system is undertaken. According to most of the prospective analysis published (IRENA 2020; IEA 2021a; IPCC 2022), the main foundation is the use of renewable sources, such as wind and solar, as well as an efficient and scalable storage technologies, such as batteries and thermal storage. However, there are also shadows on the pathway to the deployment of these technologies. While progress towards a decarbonisation of the economy is favourable from a climate change point of view, it is important to assess the new energy system from a broader perspective of sustainability. As these technologies reach higher levels of deployment, new trade-offs emerge. For example, the exploitation of new minerals, including scarce and critical ones, is expected to increase (IEA 2021b; Henckens et al. 2016). Other possible drawbacks of renewable energy deployment arise with the land availability (Capellán-Pérez, de Castro, Arto 2017; de Boer et al. 2015) and the increasing competition with

the traditional use of land and its direct and indirect effects on land use displacement (IEA Bioenergy 2014), associated impacts (Panichelli, Gnansounou 2008; Deutz et al. 2018) and the effect in connected markets (e.g. food market (Elobeid et al. 2019; Debnath et al. 2019)).

In this context, policy makers are faced with the challenge of developing policies for transforming existing economic systems into more sustainable ones while providing clean and affordable energy to foster socio-economic development. In front of this challenge, it is essential to focus research efforts on finding suitable tools and methods to guide and support the decision-making on investments, strategies and projects, to commit the transition targets.

2. SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT

The concept of sustainability has been gaining prominence as humanity has intensified the use of resources and the pressure on life-supporting ecosystems. While sustainability responds to a rationale of equilibrium with resources for survival from an anthropocentric perspective, the concept of sustainability as it is used in its current narrative is beginning to take shape in the 21st century, converging among the various disciplines. The current narrative addresses strategic issues at the core of sustainability challenges, suggesting, for instance, which and/or how resources and services should be used and distributed across societal actors (e.g., considerations regarding rural-urban and North-South dynamics) (D'Amato 2021). The new meta-level definitions achieve accommodate most of the central meanings conventionally assigned by sustainability literature, put them in explicit connection with other spheres in which sustainability is used (DesRoches 2023).

Previously, from foresters in the seventeenth and eighteenth centuries, engineers and forestry experts such as von Carlowitz in 1713 (Christof Mauch 2014; Rachel Carson Center for Environment and Society 2015) introduced the concept of "sustainable yield" in response to declining forest resources across Europe due to the high intense use of wood in construction and of energy in the mining and metallurgy sectors (Von Ulrich Grober 1999). In the realm of political economy Smith, Mill, Ricardo and Malthus questioned the limits of economic and population growth in the wake up of the industrial revolution (Zweig 1979), and recognized the inherent trade-offs between wealth generation and social justice. Already in the 19th and early 20th centuries, naturalists and ecologists contributed to reinforcing the divide between anthropocentric conservationists, on the one hand, who prescribed the conservation of natural resources for sustainable consumption, and biocentric conservationists, who advocated the preservation of nature because of its inherent value (Vucetich, Bruskotter, Nelson 2015; Martin, Maris, Simberloff 2016; Callicott, Mumford 1997).

However, the modern concept, along with the language of sustainability in a global sense, did not emerge until the late 20th century, being the 70s and 80s the main decades of conceptualization and theorization (Marien 2016; Purvis, Mao, Robinson 2019). In 1972, the Club of Rome's "The Limits to Growth" called for a *sustainable world system* (Meadows et al. 1972) and the editors of the magazine the Ecologist presented a *sustainable society* supporting in the well-regarded *Blueprint for Survival* (Goldsmith et al. 1972). The World Council of Churches commission on "The Future of Man and Society" finds the notion of a "sustainable society" more acceptable than the language of limits in 1974 (Von Ulrich Grober 1999). Also the

Ecology Party (United Kingdom) published its *Manifesto for a Sustainable Society* (Ecology Party 1975) and a set of books were also published highlighting the concept of sustainability. According to the review of Marien in 2016 (Marien 2016), the first four books including the word “sustainability” in their title were *The Sustainable Society: Ethics and Economic Growth* (Stivers 1976), *Energy for a Just and Sustainable World* by the WCC, *The Sustainable Society: Implications for limited growth* (Pirages 1977) and *Building a Sustainable Society* (Brown 1981).

In a practical sense, the application of the modern concept of sustainability reached its peak when it was linked to "development", when the Brundtland Commission in their report *Our Common Future* (WCED 1987) proposed this concept as the key for the global agenda to fight the global environmental and social troubles caused (and expected to be caused) by the economic model followed until then. In this document, sustainable development was defined as:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" and was presented at the World Conference on Environment and Development (WCED) through the report "Our Common Future" (WCED 1987).

After three decades of formalisation of the concept of sustainable development, discussion on the topic remains largely on international and national agendas (Holden, Linnerud, Banister 2017). In 2012 a review of literature found more than 500 different definitions of sustainability (Stockmann 2012). However, there is consensus that it can be only achieved when there is a balance or trade-off between the three basic dimensions of sustainability: environmental, social and economic. Figure 3 depicts some of the typical representations of the dimensions of sustainability.

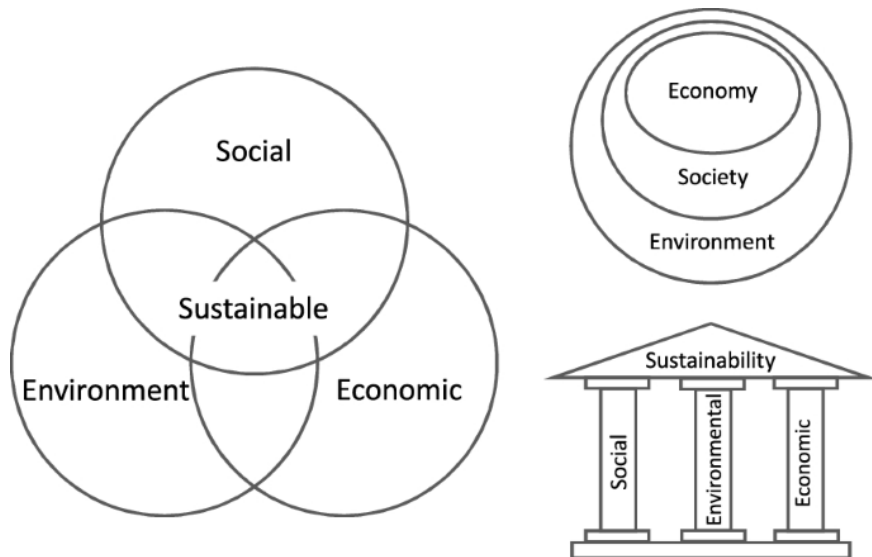


Figure 3. Sustainability pillars.

Left, typical representation of sustainability as three intersecting circles. Right, alternative depictions: literal 'pillars' and a concentric or nested circles approach. Source: (Purvis, Mao, Robinson 2019).

In sum up, environmental sustainability is determined by the capacity of ecosystems to provide resources and services, as well as the value of the environment itself as a maintainer of balance on the planet. Economic sustainability determines the capacity of society to provide goods and services and to maintain well-being and growth. Social sustainability establishes the balance between actors in society, motivating progress towards equitable and fair growth for people. Therefore, far from being independent, these would be the three interdependent orthogonal dimensions of sustainability.

Graphical representation of the interactions between the dimensions of sustainability has been discussed and different models proposed (Figure 3). The relationship between these aspects can be shown graphically by a Venn diagram (three intersecting circles, figure 3 left) composed of three overlapping of each circle. The circles are arranged symmetrically around a central area of confluence denoting the integration of part of each dimension such that sustainability is nominally achieved. Partial integration of the aspects is shown where only two of the three circles overlap or in non-overlapping areas. Despite widespread use, this conceptualization cannot be traced to a single source or explicit theoretical background (Purvis, Mao, Robinson 2019). The diagram of the three intersecting circles does not sufficiently imply the full integration of the environmental, social and economic dimensions and can be interpreted that the diagram ignores the intrinsic and immutable relationships that exist between each of the dimensions (Moir, Carter 2012). Areas of bivalence, where only two of the dimensions overlap, are seen as essentially opposite, while non-overlapping regions are incorrectly perceived as unrelated to sustainability (Lozano 2008). Furthermore, it can facilitate the assumption that the

unrestricted substitution of natural capital by physical and human capital can occur indefinitely, in contradiction with reality. This perspective would follow the precepts of "weak sustainability" (Neumayer 2013; Ekins et al. 2003). On the contrary, the "strong sustainability" recognizes the natural capital as an evolving complex system composed by biotic and abiotic elements that interact determining ecosystems capacity and provide humans with a set of functions and services, far from to be a mere stock of resources substitutable.

In the concentric or nested circles diagram (figure 3 right-upper figure), the outer circle represents the natural environment, the middle one represents society, and the inner one represents economic aspects. That would be interpreted as society is a part of nature, and the economy is a part of society. Some authors (Giddings, Hopwood, O'Brien 2002; Macnaghten, Jacobs 1997) advocate a model in which "economic well-being" is a component of quality of life, which in turn is ultimately constrained by "environmental limits". On the one hand, natural systems in the environment provide the physical support and sustenance for social systems. On the other, social systems are the engine of the human life and purpose for economic systems (Brown, Dillard, Marshall 2006). In other words, the economy is a subset of society, which in turn is a subset of the environment. Many authors consider that this nested model emphasizes that the three systems cannot be separated and are in fact subsystems of each other. Nonetheless, the delimiting of the three aspects by the use of circles does not really reflect the complex inter-connectedness that actually exists among them (Purvis, Mao, Robinson 2019).

Finally, the explicit pillars representation (figure 3 right-down) shows the dimensions contributing in parallel as foundations. In this approach the idea of creating a stable building built over the balanced pillar allows to achieve sustainability. Although this representation keeps the separation among pillars and could create difficulty in the conceptual interpretation of the linkages between all three pillars, the need to sustain among the three pillars a balanced built confers to this model the ability to represent the equilibrium among dimensions (pillars). Other concepts or approaches developed have showed strong parallels to the three pillars sustainability (Purvis, Mao, Robinson 2019). The Triple Bottom-Line (TBL) accounting approach (Elkington 1998) gained popularity at the beginning of the decade of nineties. Coming from the company's traditional financial "bottom line", the TBL is complemented by bottom lines for social and environmental performance. In the companies' sphere, this can be also referred as the Three P's - "people, planet, profit". That aimed to encouraging companies to consider longer-term perspectives in their decision making including in the analysis how the organization affects its employees, the surrounding community and the environment as a whole.

Apart from the three representations many other have been proposed adapted to the specific contexts and cases. Although the general dimensions are common, the specific elements that comprise each dimension are less agreed upon (Schiano, Drake 2021). For instance, Najjar in 2022 (Najjar 2022) theorizes new ground-breaking definition for sustainability; namely the four dimensional spatial sustainability.

The concepts of ecology and economy were understood as opposites for a long time. Therefore, the most pressing social problems - especially poverty in developing countries - did not seem to have a long-term solution. Thus, international discussions increasingly began to look for a model that would complement the general concept of modernization and development, moving towards the model of sustainable development. The sustainable development model (encompassing an environmental, social and economic pillar) is intended to ensure the long-term improvement of economic and social living conditions and, at the same time, the sustainability of natural resources, thus enriching the multidimensional picture of modern society with the addition aspect of sustainability. However, the questions of how to harmonise these three dimensions and what strategies and tools should be used for realising sustainable development are just as controversial as the definition of the guiding principle itself. Even having described the concept, it should be noted that performance in any of the three dimensions is determined by the floor on which the interconnections occur, and how the integration of them is undertaken in the specific context.

The pathway towards climate change mitigation was started in the 1992, in the United Nations Framework Convention on Climate Change (UNFCCC) Rio Earth Summit (UN 1993), with the participation of many nations and the presence of national and supranational organisations. Departing from this frame, in 1997 the Kyoto protocol (in the Third Conference of the Parties, COP3) was signed by 193 countries being the first agreement to cut emissions in which already set medium- and long-term greenhouse gases (GHG) reduction targets. These objectives had to be compatible with economic growth, and it was recognised that in order to achieve them it was essential to change the economic and energy model. Cooperation and collaboration mechanisms and programmes were created, and various commitments were established. The Millennium Development Goals (MDGs) for 2000 to 2015 (Colglazier 2015), were proposed as an umbrella to cover the social pillar which accompanied the environmental and economic mechanisms and goals. The MDGs failed and were showed as unfairness to the most developing parts (Easterly 2009), revealing the great challenge of reaching intergovernmental agreements and the need to work intensively to improve geopolitical relations and cooperation between parties.

The 2015 Paris Agreement (UNFCCC 2015) which brought together the Conference of the Parties (COP) to the UNFCCC, was a milestone in the global fight against climate change as it secured the commitment of the signatory Parties to contain the Earth's temperature increase- Limiting warming to no more than 2°C (preferably to 1.5°C) compared to pre-industrial values (1850-1900) has become the target for global climate policy. This target is aimed to prevent long-lasting or irreversible changes, including the loss of vital ecosystems.

From 2015, an urgent call to act was spread from UN, but also from society (civil organisations, non-governmental organization (NGOs), etc.). As consequence, and in contrast with previous decades of slower international action, beyond to setting the goals (the knowns as Nationally Determined Contributions (NDCs)), in the years after 2015, countries have developed roadmaps, strategies and specific plans for short, medium and long-time horizons by enabling secure and perdurable energy and societal transition.

A large number of governments adopted the 2030 Agenda for Sustainable Development (UN 2015), which includes a set of 17 Sustainable Development Goals (SDGs) aimed at ending poverty, combating inequality and injustice, and tackling climate change by 2030. These ambitious goals involve environmental, social and economic interactions, considered to be the main pillars or dimensions of sustainability (Purvis, Mao, Robinson 2019). The SDG 7 (<https://sdgs.un.org/goals/goal7>), which aims to "*Ensure access to affordable, reliable, sustainable and modern energy for all*", is particularly important as it links to other goals (Lyu et al. 2022). A focus on universal energy access, increased energy efficiency and greater penetration of renewable energy, creating economic and employment opportunities, is essential to creating more sustainable, inclusive and resilient communities.

The global sustainable development agenda needs to be comprehensive, systemic, and transformative (UN 2021). However, the COP27 of Sharm el-Sheikh (Arab Republic of Egypt, November 2022) was described as disappointing (Jensen, Svensson 2022). Although the 1.5°C limit and carbon phase-out target of the COP26 of (UK, Glasgow, 2021) was hold and other related aspects to the Agenda 2030 were dealt (food security, climate tipping points and financial system reforms), the main outcome was the "loss and damage" fund creation and the work program creation for pooling ideas to accelerate action on mitigation. However, there were a lack of binding elements and new mitigation targets, as well as an absence of a commitment to move away from fossil fuels globally. For the specific field of energy, a Global Renewables Alliance (GRA) was launched. The GRA encompasses organizations representing wind, solar, hydropower, green hydrogen, long duration energy storage and geothermal energy

industries and aims to position renewable energy as a pillar of sustainable development and economic growth.

In Europe, the joint strategy to decarbonize and transform the European Union is named Green Deal (European Commission 2019b). This looks for achieve a resource-efficient and competitive economy, reducing at least a 55% less net GHG emissions by 2030 and ensuring zero net emissions (also named carbon-neutral, climate-neutral and NetZero 2050 objective) of GHG by 2050 compared to 1990 levels, and an economic growth decoupled from resource use and based on the “no person and no place left behind” policy. Within the Green Deal umbrella many sectoral funds and policies are being developed and implemented.

Recently, the world has faced another crisis in parallel. Both the COVID pandemic (happened for the period 2020-2021), and the Russia's invasion of Ukraine (year 2022-today) has caused a dramatic disruption on business as usual. The pandemic also revealed connections between the current COVID-19 crisis and the less abrupt but no less urgent climate crisis (UN 2021). It has uncovered the vulnerabilities intrinsic in an economic system, especially in Occident and Europe. In fact, these recent events have brought back the debate of energy dependence on foreign supply that seemed to be forgotten or of minor relevance given the established scenario of globalization, neoliberalism and the dominant role of corporations in the economy and trade of goods and services (Hathaway 2020; Manyika et al. 2021). From a debate focused on technological development of the new energy models with small reference to the changes in the geopolitical arena before Russia's invasion of Ukraine, it has shifted to an absolute accent on energy security and dependence of the current model as well as the implications to the transition to a new model (e.g. rare earth, etc.). In Europe, in response to the hardships and global energy market disruption caused by Russia's invasion of Ukraine, the European Commission presented the REPowerEU Plan (EC 2022) which is a plan for saving energy, producing clean energy and diversifying our energy supplies (Figure 4) . Smart investment to allow a fast reform and plans implementation would be need. Far from being simple, these investments must be based on informed decisions, broad integrated assessment and consensus at once it happen fast and preventing that the urgency and immediacy of the current energy crisis from crowding out sustainability efforts, i.e. sustainability criteria must be kept in mind to implement the actions framed in the REPowerEU Plan.

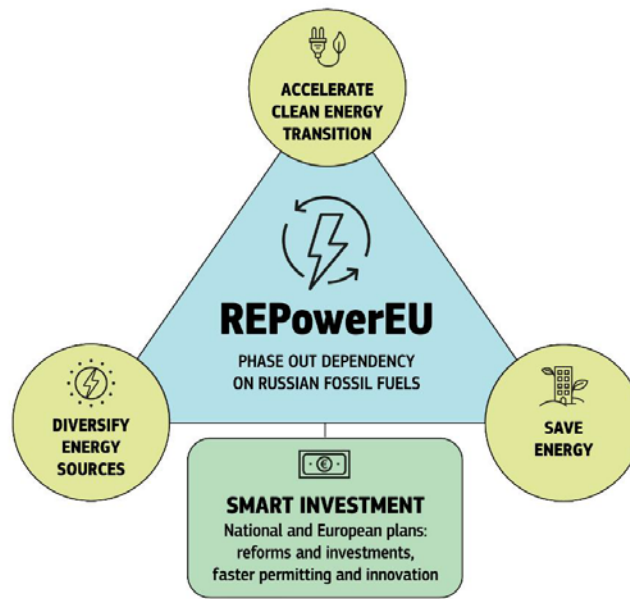


Figure 4. REPowerEU Plan scheme.

Source: (EC 2022)

3. SUSTAINABILITY ASSESSMENT

As a response to these challenges, sustainability assessment (considered as a way of showing how decisions are made towards sustainability performance (Hacking, Guthrie 2008)) has become a rapidly developing research area. Its aim is to deliver net benefits that will contribute positively to sustainability. Sustainability assessment techniques are designed and applied primarily for the purpose of demonstrating the extent to which policies can achieve results and to what extent. Sustainability assessment is applied for many purposes, and new developments to quantify a wide range of measurements seem to emerge as part of the analysis of the different components, aspects or dimensions¹ of sustainability.

Methods for sustainability assessment to support the decision-making process ideally need to identify and decompose the diverse economic, environmental and social impacts along the whole value chain. Considering this, diverse methodologies have been proposed (see Section 5.1 for an extensive review). For example, for the Mexican case, Rodríguez-Serrano (Rodríguez-Serrano, Caldés, De La Rúa, et al. 2017) showed that investing in CSP could reduce CO₂, contribute to economic growth and help create new high-quality jobs; at the same time, CSP could also reduce the overall employment because many CSP components are imported. Nonetheless, there are other aspects that could affect the sustainability of an investment such as the geopolitical risks associated to the economies involved in the value chain. In spite the pivotal role of these aspects in the policy making process and the development of regulations, there are not many attempts to integrate the supply risk analysis in the sustainability assessment methods.

Therefore, new approaches to assess sustainability along the global value chains have to be investigated (Cazcarro et al. 2022). In this respect, considering the definition of geopolitics provided by Cohen: “the analysis of the interaction between, on the one hand, geographical settings and perspectives and, on the other, political processes” (Cohen 2015), the dependence and governance aspects would be two fundamental components of geopolitics to be considered. Measuring both components along the value chain would reflect the geopolitics aspect of a determined intervention/action, at least the endogenous ones.

¹ Dimensions, component, pillars, perspectives, aspects would be interchangeable in a wide sample of literature, according to the review of the origin and conceptualization (Purvis, Mao, Robinson 2019). Some of the examples of the understanding of this prevalent three-orthogonal description of ‘sustainability’ with three interconnected elements called in a different manner are found as “dimensions” by (Stirling 1999; Lehtonen 2004; Moir, Carter 2012); as “pillars” by (Basiago 1998; Gibson 2006; Boyer et al. 2016; Rodríguez-Serrano, Caldés, Rúa, et al. 2017; Ranjbari et al. 2021; Caputo et al. 2022), as “components” by (Du Pisani 2006; Hansmann, Mieg, Frischknecht 2012), as “aspects” by (Sikdar 2003; Lozano 2008; Faber, Jorna, Van Engelen 2011); as “perspectives” (Brown et al. 1987; Garnett 2013) or as elements (Harris 2003)

4. ENERGY TRANSITION

Energy supply is closely intertwined with the ability to meet basic human needs and economic growth, national and international security and with many of the most damaging and dangerous environmental problems. The multiplicity and importance of these linkages make energy a special field to focus on (Holdren 2007). Energy transition and sustainable development are closely interlinked. There are two main facts at basement of this link. On the one hand, energy is at the core of almost every major challenge and opportunity facing the world today. Whether for climate change, food supply or jobs, security, wealth growth, access to energy is essential for the development in any economy and society. Therefore, the sustainable development model requires the supply of energy from cleaner sources assuring the maximum environmental, economic and social guarantees. On the other hand, the success of the sustainable development and climate change fighting strongly depends on the energy transition as the energy sector accounts for more than two-thirds of total GHG emissions globally (IEA 2016).

4.1. Key energy technologies for a sustainable energy transition

Energy has been in the core of the conceptualisation and boost of the sustainable development. From the first books including the word *sustainability* in its title (Stivers 1976; Pirages 1977; Brown 1981), the literature of sustainability has paid special attention to energy as main element to support society.

The limited nature of fossil resources that have generated so much economic wealth in recent centuries in certain regions and social groups, is threatening the foundations of a global sustainable development. Therefore, alternative energy sources for the energy transition should be implemented. For decades, renewable energy has been incorporated into generation systems through a multitude of technologies and energy alternatives around the world (IRENA 2021). To achieve the replacement of fossil fuels with renewable sources, a multitude of technological solutions are continuously being improved in terms of predictability, seasonality and temporality of the resource as well as storage possibilities.

Photovoltaic (PV) and wind power have become the main drivers of renewable energy implementation around the world. Nevertheless, their capacity to confront the challenge of substituting fossil sources is limited by the mismatch between resource availability and energy demand. Major advances are being made in the field of energy storage for several applications to provide flexibility and reduce supply uncertainty (Worku 2022; Lechón et al. 2023), or in the production of cleaner fuels that are easily transportable and adaptable to pre-existing systems (Malode et al. 2021; Detsios et al. 2023).

Storage technologies have a large variety of different technological pathways (Behabtu et al. 2020) and end-use applications (known as Power-to-X (P2X), being X the different applications) each of them with different decarbonization potential. Stored energy could be used to produce electricity again at high demand times or to regulate electricity grid, for mobility uses, either in the form of electricity for electric or hybrid vehicles (batteries) or to support the synthetic fuels production. Stored power can be employed to produce heat for thermal end use applications or could be used to produce H₂ and synthetic chemicals. Lechón et al (Lechón et al. 2023) assessed carbon benefits of different energy storage alternative end uses, applied to Spanish context.

Concentrated solar power (CSP) offers the advantage of storing the heat collected in the solar field, which is much simpler than storing electricity and can be converted to electricity when requested by the demand. This Thermal Energy Storage (TES) technology is a cost-effective solution for moving away from fossil fuels and transforming intermittent energy into dispatchable clean energy (Achhari, El Fadar 2020; Schöniger et al. 2021). This maximizes the amount of renewable energy in the mix, reducing curtailment and the need for fossil backup. Particularly in the current European context, CSP deployment in Spain can play a significant role in facilitating the energy transition (Gamarra, Banacloche, et al. 2023). This is why CSP has been here selected as a key technology to test the application of the methodologies developed in this thesis.

There are additional barriers beyond the technical requirements, such as the deployment of complementary infrastructure along territories, market acceptance of the different solutions, and globalised manufacture and dependence. The energy transition can be achieved if renewable energy becomes an integral part of countries' climate pledges (IRENA 2019; IISD 2019) as multi-level transition management is needed. Success requires not only technological innovation, but must be found in the so-called window of opportunity at the regime (dominant practices, regulation and infrastructure of socio-technical systems) and landscape level (political, cultural and economic context) (Geels, Schot 2007; Geels 2018) for new solutions to take off and become established.

4.2. The role of supply chain in the energy transition

The key energy technologies for the transition, mainly the renewable energies, widely differ from fossil fuels, not only at the technology level, but also when it comes to the geopolitical consequences of their production and consumption (Commission on Geopolitics of Energy Transformation 2019; Goldthau, Keim, Westphal 2018; Scholten, Bosman 2016). The classical risks of fossil resources which are determined by their geographical availability around the world

would not be as relevant for renewables (Overland 2019) whose availability is more widespread (Criekemans 2018). However, other challenges associated to a large-scale renewable energy deployment have emerged. As pointed out by Kim and Karpinsky (Kim, Karpinski 2020), the Covid-19 outbreak has underlined the need to watch out for the security of supply of critical minerals for a clean energy future. In this regard, the geopolitical analysis of energy issues should also be adapted to the new world of renewables in which the demand for some materials will increase significantly, making this the most vulnerable step for renewable energy systems (components manufacturing, storage, and required smart/digital technologies) (European Commission 2020). Therefore, energy policies should carefully address geopolitical issues that revolve around the security of supply (trade, environmental and economic and resource management policies) (Bouzarovski, Bradshaw, Wochnik 2015).

The supply of raw materials could threaten the urgent need for a fast European energy transition towards carbon neutrality due to an increasing demand around the world in the present and foreseen future (OECD 2018a). Many of the decarbonization strategies rely on the availability of several raw materials, many of them classified as critical due to economic importance and supply risks criteria (IEA 2021b; Rietveld et al. 2022). Electricity networks deployment needs a huge amount of copper and aluminium, with copper being a cornerstone for all electricity-related technologies. 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 (EV) engines (IEA 2021b). In line with the above, according to the International Energy Agency (IEA) the energy transition requires substantial quantities of critical and non-critical minerals, and their supply emerges as a significant growth area. In the net zero pathway for 2050, the (IEA 2021a) foreseen the total market size of critical minerals like copper, cobalt, manganese and various rare earth metals will grow almost sevenfold between 2020 and 2030. Furthermore, a greater diversity of metals will be required to implement low-carbon energy technologies than the needed by conventional energy technologies (IEA 2021a). At European level, as the EU nurtures its clean energy manufacturing ambitions (REPower Plan, (EC 2022)), the reliance on imports of critical materials remains a cause for concern. While Europe is responsible for over one-quarter of global EV production, it is home to very little of the materials that feed into them. For example, according to figures from (IEA 2023), China accounts for over 80% of global production of graphite used in batteries and has a dominant position in the processing and refining of many other minerals and metals: it processes almost two-thirds of rare earth elements, critical to a plethora of technologies including wind turbines and EV motors; the Democratic Republic of Congo mines

70% of the world's cobalt; and Russia is a major producer of battery-grade nickel and platinum. The recent crisis of resources of certain minerals and metals needed for the deployment of renewable energies is even more important considering the need to deal with the current energy crisis in Europe, boosted by the Russia-Ukraine conflict. Raw materials are strategically crucial for European economy, job creation (Llorente-González, Vence 2018) and social transition to green, digital and sustainable society (IndustriAll Europe Executive Committee 2021), but also for energy system security. The European Union (EU) could be in a favourable position to benefit from this process, reducing its dependency on external supply and enhancing its energy security, with the inherent geopolitical dividends this would bring (Rangel Hernández 2022). However, the concentration of these resources in a few countries (mainly in non-EU countries), the prone to value chain shocks causing supply disruptions as seen in the recent world history (COVID pandemic crisis (Willy C. 2020), semiconductors crisis (Schuh, Schnellbacher 2022; Aboagye et al. 2022), or the Maritime's channel bottlenecks, among others), and the current low rates of recycling and substitution of some scarce materials, reveal the potential weakness of the supply chain of key materials for renewables deployment in Europe. In addition, new dependencies could be arising along the supply chain. While most literature focus on the raw materials dependencies other authors have provided a wider view of dependencies along the supply chain. Filho (Filho 2022) suggests that countries can become resource and equipment importers from external actors that, achieving a leading role in the clean energy sector, would become price makers in this technological segment. The methods used to address the assessment of energy security have included the geopolitics risks assessment of value chains in the social science field. There is a broad body of literature which reviews and redefines the concept of energy security and the dimensions involved. Azzuni and Breyer (Azzuni, Breyer 2018) found 66 different definitions, in 104 literature sources. Some of these include large lists of physical, economic, social and environmental dimensions and components, proposing complex and long sets of indicators (Sovacool, Mukherjee 2011; Jansen, Seebregts 2010; Narula, Reddy 2016; Sovacool 2011; Vivoda 2009). Particularly relevant is the work of Cherp and Jewel (Cherp, Jewell 2014a), who purely define energy security as *"low vulnerability of the vital energy systems"*. The minimisation of vulnerabilities along the value chain becomes a prerequisite for sustainability. Sustainability is about ensuring long-term prosperity while contributing to social and economic development, a healthy environment and a prosperous society - a society that allows future generations to thrive and prosper. In fact, the ability as a human race to resist, recover and adapt to shocks is fundamental to the concept of sustainability (IEA 2023).

The World Energy Council (WEC)'s definition of energy sustainability is based on three core dimensions: Energy Security, Energy Equity, and Environmental Sustainability of Energy Systems. The balance among the three goals or components constitutes the "Energy Trilemma" and enable prosperity and competitiveness of individual countries. The WEC annually propose an index measuring a set of 32 indicators to assess energy security of countries (WEC 2019; 2022). Some developments and frameworks have been proposed in the energy security field (Sovacool, Mukherjee 2011; Krut et al. 2009) and improved in recent research (Cox 2017).

Considering the previous literature on geopolitics and this later definition focused on the identification of vital components involved, three main orthogonal dimensions can be identified as the basement of the security of supply chain: availability of resources, dependence on suppliers and resilience of the supply chain. In the confluence of these three, the vulnerability would tend to zero (Figure 5).

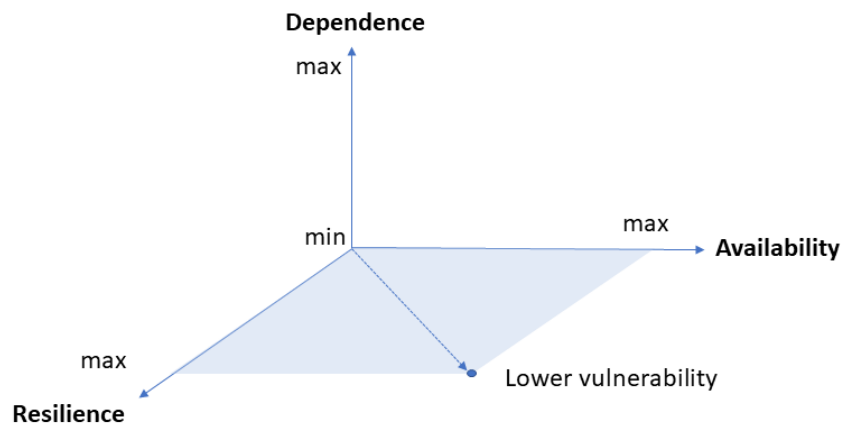


Figure 5. Three orthogonal dimensions of energy security to minimise vulnerability of the energy systems supply chain.

Parallels can be found in the literature with the three-orthogonal dimension scheme presented in Figure 5. The three mentioned orthogonal dimensions were included by Alonso (Alonso et al. 2007) to describe the two mechanisms that would result in a situation of materials scarcity: physical constraints, i.e., the amount and quality of a resource that is physically determined and ultimately limits resource availability (availability and dependence); and institutional inefficiency, such as failures of markets, firms and governments that can result in transitory resource unavailability (aspects of circularity and dependence in countries with weak level of governance would be included here). Finally, supply chain is evolving and economy needs to move from the linear economy to the circular economy (CE). The concept of the CE describes the utilization of material in societal cycles so as to minimize related environmental impacts. The transformation of a fossil-based energy system towards a low-carbon one is inevitably linked to

a shift in resource use and raw material availability. Not only do new low-carbon energy technologies affect raw material use, but resource use also has an influence on the energy system's design (Kullmann et al. 2021). The fast and huge deployment of clean energies will have consequences in the value chains and, in this context, the Circularity policies and cyclic use of materials can play a crucial role. The three dimensions identified as key for the energy supply chain security (Figure 5) are closely linked with the CE since a higher efficiency of materials use can increase the availability, reduce the dependence and increase the resilience of the supply chain. Several metrics and indicators have been proposed for these three key aspects (availability, dependence, resilience) of supply risks of materials along the value chain.

5. STATE-OF-THE ART OF SUSTAINABILITY ASSESSMENT AND RATIONALE

There are several methods and tools for assessing the sustainability of technologies and projects at the micro-level as well as strategies and policies at the macro-level. These methodologies are aimed at assessing the three pillars of sustainability and are conditioned by many factors such as the goal, the target audience, the available data, the scale of assessment, etc. The methodologies to quantify impacts on sustainability do not provide unequivocal answers to complex decision-making situations, but they generate the data for the design and modelling scenarios, increase the understanding of the phenomena assessed and provide a basis for evaluation to support decision making.

The sustainability evaluation, used to link the vision of sustainable development with the own implementation of sustainability solutions, such as renewable energy technologies, would have three functions (Stockmann 2012): (1) It can be a management instrument for controlling the entire policy-making process, (2) it can be part of the implementation of policy strategies, and (3) it can be an instrument of self-reflection.

Questions of how to harmonize these three dimensions and what strategies and tools should be used for realizing sustainable development are just as controversial as the definition of the concept (as seen in the previous section). Some of the main difficulties with sustainability assessments are (Stevens 2014): giving equal attention to the three spheres and adequate attention to the longer-term; assigning monetary values to environmental and social assets for comparisons; identifying trade-offs – presenting positive vs. negative assessments in the three spheres on a comparable basis; and, reconciling conflicts between economic, environmental and social goals and providing the basis for political decisions. Equally controversial is the question of how these three dimensions, or target dimensions, of sustainability can be operationalized in order to become accessible to evaluations (Stockmann 2012). Various different aspects and indicators have been given more weight by the methods and tools depending upon the scientific discipline of the authors, the research traditions and interests to which they are bound, their understanding of nature and their overriding perceptions of value.

The analysis of the background literature on sustainability assessment methods has been split in two sections: the recent literature on methods and tools for sustainability assessment, and the state of the art of the analysis of energy security and geopolitics indicators and indices.

5.1. Methods and tools for sustainability assessment

Integrated Assessment, Triple Bottom-Line (TBL) Assessment, Sustainability Assessment and variations of these terms, have been used in the literature promoting the use of impact assessment as a means of directing planning and decision-making towards sustainable development (Hacking, Guthrie 2008). There are five main categories of sustainability assessment methods commonly applied to sustainability assessments. They are namely: Input-output (IO) methods, Life cycle Sustainability analysis methods (LCSA, LCA, LCC, SLCA)², Material flow analysis (MFA), Multi-criteria analysis (MCA) and Cost-benefit analysis (CBA). Each of these methodologies has advantages and limitations, and their integration, combination and/or hybridisation has been proposed in literature in order to achieve a holistic assessment of the impacts of different activities on sustainability. The classification of the sustainability assessment methods and tools can respond to many criteria. Table 1 shows a summary of potential alternative classifications and the variants in relation with sustainability assessments based on (Stevens 2014; Sala et al. 2020).

Table 1. Classifications by criteria in relation with sustainability assessments.
Based on (Stevens 2014; Sala et al. 2020) and own contributions.

CRITERION	VARIANTS
TYPE	Sustainability, integrated, regulatory, environmental, economic
LEVEL	Local, national, regional, sectoral, international, global
TARGET	Policies, programs, projects, regulations, agreements, processes
TIMING	Before (ex-ante), during, after (ex-post)
MODELING APPROACH	Bottom-up, Top-down
FUNDATIONS AND METHODS	Economic (Cost Benefit Analysis, Input-Output modelling, regressions, etc.) Environmental (LCA, Material flow analysis (MFA), resource accounting, national accounting matrix including environmental accounts (NAMEA)) Social (sustainable livelihoods, human and social capital measurement, participatory processes)
PERSPECTIVE	Production-based, Consumption-based, Territorial-based
ABILITY TO BE CONNECTED WITH OTHER	Integrate sustainability criteria into other assessment approaches Conduct assessments separately and integrate them in a sustainability assessment Merge all approaches into overarching sustainability assessments Develop general methodology for "impact assessments"

Table 2 depicts the sustainability assessment methods with their orientations according to criteria of Table 1 and examples of their extensions and combinations with other tools, and Table 3 presents the main strengths and weaknesses combining insights from Table 1 and Table 2. Both tables are tailored using insights from (Karvonen et al., 2017) and own contributions.

² Life Cycle Sustainability analysis (LCSA) methods are the group of methods measuring the three pillars individually and together. Those are based on the Life Cycle Thinking philosophy ((Remmen, Münster 2003). Those are: Life cycle assessment (LCA), Life cycle Costing (LCC) and Social Life Cycle Assessment (SLCA). LCASA and LCA are widely explained in section 5.1.1.2.

Table 2. Sustainability assessment tools shown with their main orientations and examples of their extensions and combinations with other tools.
From (Karvonen et al. 2017) and own contributions.

TOOL	FUNDATION	MODELLING APPROACH	TYPE	LEVEL	TARGET	TIMING	EXTENSIONS & COMBINATIONS
INPUT-OUTPUT (IO) METHODS	Economic (IO and MRIO)	Top-down	Economic Sustainability, Integrated	Global, National, Regional, Sectoral, International	Policies, programs, projects, regulations, agreements	Ex ante During, Ex post	Scenarios development for ex-ante assessment. Extensions to environmental dimension (EE-IO). Computable general equilibrium models (CGE), econometric-input-output models, and linear programming models
	Environmental, socioeconomic and social (extended IO/MRIO)	Top-down	Economic Sustainability, Integrated	Global, National, Regional, Sectoral, International	Policies, programs, projects, regulations, agreements	Ex ante During, Ex post	LCA databases or MFA calculations may be applied. Scenarios development for ex-ante assessment. Extensions to environmental dimension (EE-IO). Computable general equilibrium models (CGE)
COMPUTABLE GENERAL EQUILIBRIUM (CGE)	Economic	Top-down	Economic Sustainability, Integrated	Global, National, Regional, Sectoral, International	Policies, programs, projects, regulations, agreements	During, Ex post	
LIFE CYCLE SUSTAINABILITY ANALYSIS METHODS (LCSA, LCA, LCC, SLCA)	Environmental (LCA)	Bottom-up	Environmental, Sustainability, Integrated Regulatory	National, Regional, Sectoral, International	Mainly processes, but all	Ex ante, During, Ex post	Combination with MFA and external costs for CBA.
	Social (SLCA)	Bottom-up	Economic Sustainability, Integrated	National, Regional, Sectoral, International	Mainly processes, but all	Ex ante, During, Ex post	Data from other LCA and IO methods, sectoral accounts and studies CBA, external costs
	Economic (LCC)	Bottom-up	Environmental, Sustainability, Integrated	National, Regional, Sectoral, International	Mainly processes, but all	Ex ante, During, Ex post	Combining with OI, MFA or the other LCA methods is possible. Also with CBA, external costs
MATERIAL FLOW ANALYSIS (MFA)	Environment	Bottom-up	Environmental, Sustainability, Regulatory		All		MFA-model tools are capable to add many different indicators if the functional unit permits it. Combination with LCA is possible. CBA, external costs

TOOL	FUNDATION	MODELLING APPROACH	TYPE	LEVEL	TARGET	TIMING	EXTENSIONS & COMBINATIONS
(cont. table 2)							
MULTI-CRITERIA ANALYSIS (MCA)	Any	Both	All		All		Multi-criteria analysis can use results of any impact assessment method. MCA method then has to be chosen accordingly to the task complexity and data availability. It can take insights from MFA, LCA, IO, MRIO, GCE, linear metrics, regressions.
COST-BENEFIT ANALYSIS (CBA)	Economic	Both	All		All		Combination with other tools to monetize the non-monetary values and vice versa, for example, with input-output or LCA.

Table 3. Strengths and weaknesses of the main sustainability assessment tools.
From (Karvonen et al. 2017) and own contributions.

TOOL	STRENGTHS	WEAKNESSES
INPUT-OUTPUT (IO) METHODS	Economic development (sectors, products, industries) tables of transactions are commonly available Well and reliably documented. Preciseness depends on well-known data on markets. High territorial defining Multirregional tables IO (MRIO) with planetary boundaries Able to incorporate indirect impacts along the whole supply chain Advantages of IO. Environmental extension (satellite accounts) from reliable statistics. Many environmental accounts available (water, emissions, resources, employment, etc.)	Low technology detail of the sectors, industries. Assumption of linear market responses. Markets need to be well known (data availability). It is not able to reflect price fluctuations as static structure of the matrix of transactions. Shares the weaknesses of IO. In addition, authors referred EE-IO may produce large datasets which are cumbersome to operate.
COMPUTABLE GENERAL EQUILIBRIUM (CGE)	Advantages of IO Flexibility of the matrix Allow to substitution while keep an equilibrium in the product and factor markets with the rest of elements (households consumption, etc....)	Assume optimal ("rational") behaviour, introducing optimizing behaviours in the energy sector. Uncertainty of the non-linear equations
LIFE CYCLE SUSTAINABILITY ANALYSIS METHODS (LCSA, LCA, LCC, SLCA)	Comprehensive consideration of all inputs and emissions of a product during its life-cycle Standardized method (ISO 14040 and 14044, 2006) and comprehensive and specialized databases are available. Social aspects are often connected to economic (IO) and ecological issues. Much data available High interest to any decision maker Market product	Highly demanding in data and large data sets. Datasets not always available, but access only via costly licenses. Datasets outdate fast. Datasets not fully transparent in documentation Often, there is a truncation in the assessment. Methods to assess and derive social impacts are not mature. High site-specific nature of social impacts, low detailed (count) Some economic information may be difficult to obtain because of trade secrets. Market price fluctuations and changes in consumption patterns cause uncertainties
MATERIAL FLOW ANALYSIS (MFA)	Focus on loads of materials needed in production of a specific (end) product enables identification of inefficient material uses and production phases. Comprehensive, yet simple to operate.	May inherit a limited view in respect to inclusion of externalities outside the examined system.
MULTI-CRITERIA ANALYSIS (MCA)	Number of approaches available. Enables thorough evaluation and balancing between alternatives with respect to indicators, dimensions and stakeholders via outranking, weighting, voting, for example. Inclusion of intangible and highly subjective aspects is possible.	Known unsustainable alternatives need to be excluded beforehand. Preferences have to be obtained e.g. via questionnaires which may make the MCA. Stakeholders' lack of knowledge and risk of personally biased preferences may corrupt the evaluation.
COST-BENEFIT ANALYSIS (CBA)	Monetary valuation of gained benefits. Monetized impacts are especially suitable to policy making. The total of benefits for society is possible to make well illustrated.	Problems in ethical and democratic considerations. Value is often subjective. Allocation of total costs to one benefit is invalid - e.g. odor reduction itself does not cost the full value of the investment.

The top-down methods are Input-Output (IO) and Multiregional Input-Output (MRIO) models and its extensions. They offer a systemic, multisectoral, multiregional view, in which it is possible to include a wide range of socioeconomic, ecological and social indicators to inform policy making (Tukker, Dietzenbacher 2013; Wood et al. 2020; Vanham et al. 2019; Banacloche, Cadarso, et al. 2020; Kucukvar, Egilmez, Tatari 2014; Hahn Menacho, Rodrigues, Behrens 2022; Zafrilla et al. 2019; Purvis, Mao, Robinson 2019; Rodríguez-Serrano, Caldés, Rúa, et al. 2017). These indicators are: environmental impacts (emissions), resource requirements (water, land), socio-economic impacts (employment, qualifications), and social risks along the value chains (Benoît-Norris, Norris 2015). They can help to define and quantify synergies and trade-offs between different measures and investments. In addition, Input-output components are nested within broader modelling frameworks; these would include computable general equilibrium models (CGE), econometric-input-output models, and linear programming models. These developments have preserved the advantages of the input-output framework (e.g., the focus on interdependency) while introducing more flexibility into the way in which the production system is modelled.

In CGE models, substitution is allowed, scale economies can be introduced, and consideration given to different market structures (imperfect competition or monopolistic competition) (Hewings, Sonis 2009). The overall model is generally set up to simulate an overall equilibrium in the product and factor markets with household consumption driven by household income and intermediate consumption driven by an input-output (social accounting) matrix. A set of simultaneous nonlinear equations characterizes this equilibrium (Bessler et al. 2014). However, CGE models have been criticized for assuming optimal (“rational”) behaviour, introducing optimizing behaviours in the energy sector but not anywhere else in the modelling would be inconsistent as well. Additionally, depending on the scale of application and the dimension of analysis, other modelling types should be implemented (Cazcarro et al. 2022).

As for bottom up methodological approaches, Life Cycle Approaches and, in particular, Life Cycle Sustainability Assessment (LCSA) stands out as a mean to understanding the implications of alternative investment options, policies and product innovations in broader sustainability aspects (Cerrato, Miguel 2020; Valente, Iribarren, Dufour 2021; Ben Hnich et al. 2021). LCSA typically consists of an environmental life cycle assessment (LCA), a life cycle costing, and a social life cycle assessment (S-LCA) within a consistent and the holistic approach which integrates (and not substitutes) the reductionist approach of the single part of the analysis (Sala et al. 2013). A possible view it as “simply” addition of LCA, LCC and SLCA has been discussed it more ambitiously as an integration framework of models rather than a model in itself.

Material flow analysis is one of the core methodologies of industrial ecology. Through MFA, an "industrial metabolism" (the flows of resources into and out of a particular entity in human society) can be mapped and quantified, just as an accountant determines and quantifies monetary deposits and withdrawals. Dynamic MFAs (those dealing with a particular region or system over time) go further; they allow one to determine the in-use and "hibernating" stocks of materials in an industry or society (the material version of the accountant's "assets and liabilities"). However, often MFA confronts with a wide diversity of raw materials transactions which are inadequately described (e.g., "iron and aluminium alloys"), different named, high aggregated categories (e.g., "plastics") and uncaptured or unmeasured waste flows or emissions to the environment (Graedel 2019), as well as temporary and spatial limitation to trace and measure material flows. Material flow models can assess circular economy measures and evaluate recycling policies or material efficiency strategies. These models, however, do not consider the entire energy system, or cover only individual energy flows, and so a holistic assessment of material and energy flow interaction is impossible (Kullmann et al. 2021). The Cost-Benefit Analysis (CBA) is an analytical tool to be used to appraise an investment decision in order to assess the welfare change attributable to it, and its purpose is to facilitate a more efficient allocation of resources, demonstrating the convenience for society of a particular intervention rather than possible alternatives (European Commission 2014). In CBA, benefits are defined as increases in human well-being (or "utility") and costs are defined as reductions in that well-being; for a project or policy to qualify on cost-benefit grounds, its social benefits must exceed its social costs (OECD 2018b). The costs and benefits into consideration are present and future, but the outcome of the CBA is given as Net Present Value (discounted net result), what involves discounting rates assumptions. Also, the non-marketable effects (externalities - costs or benefit) are included in CBA. This methodology has been object of criticism in recent times ("valuation of valueless" or valuation of non-marketable good and services - e.g. justice and ethics issues (Pal 2015), species, ecosystems and cultures (Martino, Kenter 2023)) and has important limitations and uncertainties related to timescale (discount rate is both crucial and controversial), distribution of wealth can heighten equity considerations; and, uncertainty of outcome is high (Kolstad et al. 2014). While there are some pathways widely studied (e.g. emissions to air and water of energy production) and impact valuations deeply studied (e.g. health impacts valuation (OCDE 2014; Roy, Braathen 2017)) there is a range of impacts which are difficult to estimate. And even some marketable costs or benefits are not easy to estimate due to volatility of market prices of raw materials in the recent decade (Juliano et al. 2022; EC 2020; ChAI 2019). Still, the CBA is widely used increasing influence of sustainability sciences (O'Mahony 2021), such as technological alternatives comparison (Corona 2016) and mainly for

environmental policy ex-ante assessment (such as (Holland 2014)) or for being combined with many other approaches (as LCA (e.g. (Faragò et al. 2022; Li, Chalvatzis, Stephanides 2018; Hoogmartens et al. 2014) or IO (as seen in e.g. (Muller 2016))). According to the identified needs, the integration of the pre-existing framework for sustainability assessment, the bottom-up (LCA, LCC, SLCA and LCSA) and top-down models (IO, MRIO and expanded MRIO (EMRIO), as well as other derivate models) in tools could bring the advantages of both approaches. Besides, MFA approaches linked with environmental input-output assessment and life cycle assessment to develop comprehensive assessments frameworks can help to enhance the development of methods and tools for sustainable development and circular economy studies (Graedel 2019). Finally, CBA can be combined with both bottom-up and top-down methods, broadening the range of tools supporting sustainability assessment for decision-making.

5.1.1. Main sustainability assessment methods

The following subsections describe the methods, departing from the formulation of IO and further developments (and MRIO and EMRIO), and the LCA, (and related LCC, SLCA, for complete LCSA). Advantages, limitations, and further developments by overreach those, by the pathway of integration of methods found in the literature is presented.

5.1.1.1. Multiregional Input-output analysis and its extensions

The IO analysis methodology emerged with the main objective of analysing the interdependence of different industries in an economy, at the national or regional level (Miller, Blair 2009). Input-Output (IO) analysis is a tool where an input (a resource) is converted into some output (a product) and the interdependencies between the various sectors of the economy are assessed for their impacts. For example, the input of wood to a sawmill resulting in outputs from the sawmill may be a direct part of the forestry sector, although it utilizes inputs from other sectors such as energy and transportation. Naturally, other inputs (e.g. labour, water or chemicals) are also needed in these processes (Mattila, Pakarinen, Sokka 2010).

The input-output framework consists of a system of tables that show the accounting of an economic system, including the links that exist between the different activities. From pairs of Supply-Use tables, symmetric or square tables are constructed in which the accounting is condensed and squared, and which are called Input-Output tables. The symmetrical structure of these tables, with the same number of rows and columns, represents the productive structure of an economy composed of some sectors that produce and demand from others at a given time (they often refer to a specific year and are drawn up at the national level). This generates a

matrix of intermediate consumption between sectors (see Figure 6), i.e. a matrix of intersectoral transactions of products for the production of other products.

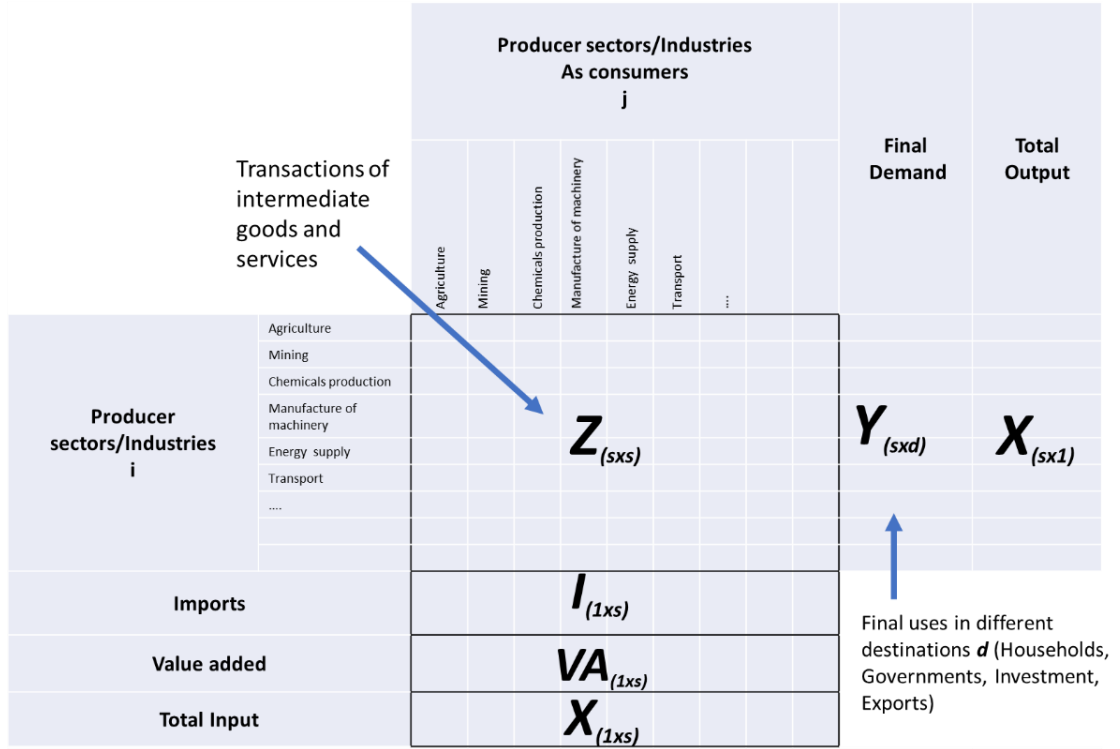


Figure 6. Input-output table structure.

Subindices (e.g. sxs) represent the dimension of the vector or matrixes being s the number of sectors or industries.

Considering the IOT as national, the total production of a sector i (x_i , 1×1) is calculated as the cumulative addition of the intermediate products to satisfy the sectors j , noted as Z_{ij} , and the final demand y_i (sum of row) according to equation 1; and therefore, the total production of the country (X , $s \times 1$) can be represented as the sum of the production of all sectors and total final demand (equation 2).

$$x_i = \sum_{j=1}^N Z_{ij} + y_i \quad (\text{Eq. 1})$$

$$X = Z + Y \quad (\text{Eq. 2})$$

Bearing in mind the information collected in the IOT, the technical coefficients a_{ij} that indicate the amount of monetary input of the producing industry i (rows) necessary to produce one monetary unit in the producing industry j (columns) are obtained (Eq. 3).

$$a_{ij} = z_{ij} / x_j \quad (\text{Eq. 3})$$

The matrix A which consists of the corresponding technical coefficients a_{ij} provides the basement for the IOA method. The method departs from the Leontief model developed by matrixial formulation and algebra resolution as follows:

$$x = Ax + y \Rightarrow x - Ax = y \Rightarrow (I - A)x = y \Rightarrow x = (I - A)^{-1}y \text{ (Eq. 4)}$$

Where I is the identity matrix. The expression $(I - A)^{-1}$ is named Leontief inverse matrix, representing direct and indirect effects, i.e. the total output of each sector required to satisfy final demand. The equation illustrates how a stimulation of final demand has a multiplier effect on output. Considering equation 5, applied to the addition of the demand y_s as new investment in the economy, the x_s is the additional output produced as consequence:

$$x_s = (I - A)^{-1}y_s \quad \text{(Eq. 5)}$$

x_s is the total (direct and indirect) impact on production.

In addition, the methodology allows for its extension by linking the stimulation of productive sectors with employment information or environmental emissions at sector and country level. Through environmental, socioeconomic and social satellite accounts, a relationship is established with the demand for goods and services and it is possible to estimate the impacts of investments. This extension can be done by adding a socio-economic or environmental vector, expressing the impacts per monetary unit produced. Equation 6 shows the calculation method:

$$q_s = R_s(I - A)^{-1}y_s \quad \text{(Eq. 6)}$$

Where q_s is the total socio-economic or environmental effect of the investment and R_s is the socio-economic or environmental vector per unit of output. Finally, there are other so-called induced effects. Induced effects capture the effect on the consumption of goods and services resulting from changes in the economic compensation of employees and can also be calculated by means of a new expansion.

Further developments of the IOT, combining the data at regional and global scale, have conducted to the Multiregional Input-Output Tables (MRIOT) which includes several countries and regions. Following the same IOA maths, but using a MRIOT, the MRIO model allows to capture the total, direct and indirect effects, of any investment and identify the sectoral-origin of the effect. Therefore, by applying the extended model, the method provides the impacts (environmental, socioeconomic, etc.) by sectors and regions.

There are different MRIOTs developed with different spatial, sectoral and temporal resolutions such as WIOD (Dietzenbacher et al. 2013) or Exiobase (Wood et al. 2014; Stadler et al. 2018; Merciai, Schmidt 2018).

Extensions of the methodology exist to simultaneously assess direct and indirect effects on some environmental, socioeconomic and social indicators, for instance, carbon emissions, job creation or the quality of the labour. An example is the framework of integrated sustainability analysis (FISA) (Figure 7) developed by Rodríguez-Serrano (Rodríguez-Serrano, Caldés, Rúa, et al. 2017; Rodríguez-Serrano, Caldés, De La Rúa, et al. 2017; Rodríguez-Serrano 2017).

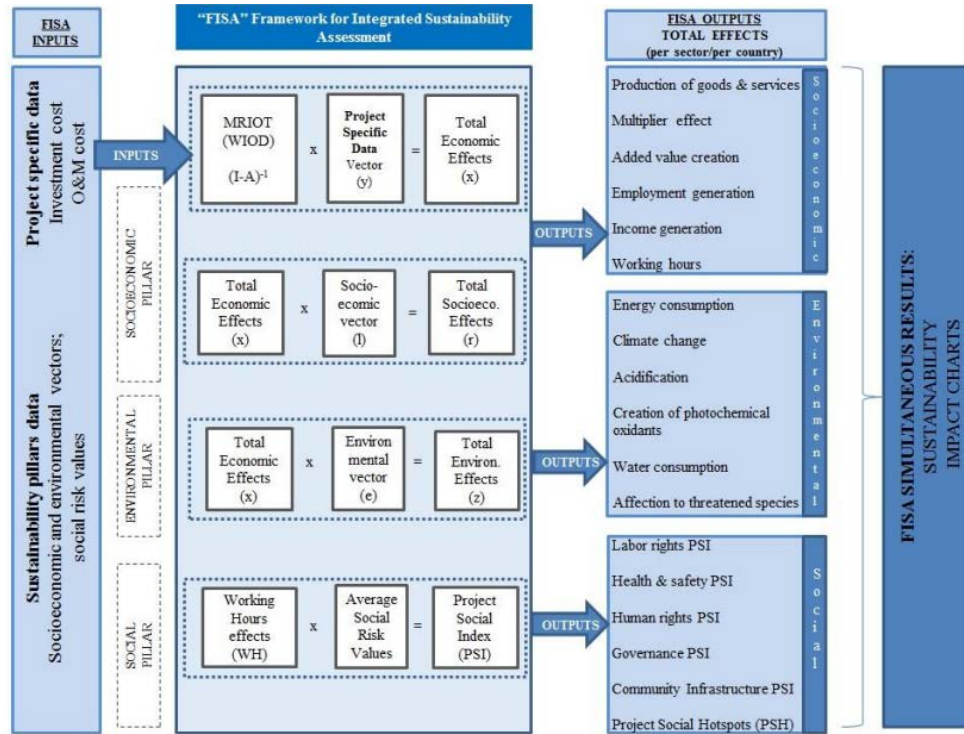


Figure 7. Framework of integrated sustainability analysis (FISA)
Source: (Rodríguez-Serrano, 2017; Rodríguez-Serrano et al., 2017c, 2017a).

5.1.1.2. Life cycle assessment (LCA) and Life Cycle Sustainability Assessment (LCSA)

LCA is a methodology that seeks to identify the environmental impacts of a product or process throughout its life cycle using a holistic approach. Analytical efforts to quantify life cycle emissions and resource loss date back to the decades of 60s and 70s (Brusseau 2019) but the rapid growth of LCA and its close relationship to industrial ecology began around 1990, especially in Sweden (Hunt, Franklin 1996; Steen et al. 1999; Rydberg 1996). In Europe, the stimulus for the development of a standard methodology came from the adoption of LCA as a basis for product labelling. An extensive literature has been developed on the method, highlighting the key role of the Society of Environmental Toxicology and Chemistry (SETAC) in its development (Klöppfer 2006). The adoption of LCA as an industrial ecology tool became increasingly widespread, both in industry and in general decision-making (Harsch et al. 1996; Brusseau 2019).

LCA is a standardised methodology according to international standards. Firstly, ISO 14040:2006 (ISO 2006a), which describes the principles and framework for LCA. Secondly, ISO 14044: 2006 (ISO 2006b) specifies the requirements and provides guidelines for LCA. LCA has a number of fundamental elements. The functional unit to which the system (process, product, service) refers is representative of the function that the system performs. The objectives and scope (temporal and physical/geographical) determine the rest of the analysis and must be clear. The boundaries of the system under study are a consequence of the scope and objectives, and are decisive in establishing the limitations and interpreting the results. The methodology consists of four phases:

- 1) Definition of objectives and scope: the functional unit and system boundaries are established.
- 2) Life cycle inventory (LCI) analysis: quantifying the inputs and outputs of materials and energy of the system during the life cycle phases.
- 3) Life Cycle Impact Assessment (LCIA): the process of characterising the inventory results in relation to impacts determined according to a method.
- 4) Interpretation of the results.

The relationship between the phases makes LCA an iterative process, i.e. each phase can be reformulated and redefined based on the findings, limitations and interpretation achieved in another phase to give coherence, robustness and transparency to the analysis.

In the inventory phase, difficulties may be encountered in finding primary and even secondary data, so the availability of information in this phase may also determine the variation of the system boundaries. In the LCI, in terms of information sources, published databases of recognised prestige (such as Ecoinvent (Wernet et al. 2016), among others) contain information on life cycle material and energy flows of a multitude of products in great detail, as well as emission factors related to certain processes and activities. Together with the use of specialised software (such as Simapro™ or Gabi), these commercial information sources are widely used.

LCA covers a diversity of environmental impacts and may include comparison across impact categories (Finnveden et al. 2009). In the LCIA phase, the inventory of inputs (raw materials, energy) and outputs (gaseous emissions, effluents and waste) developed in the previous phase is related to one or more impacts (ranking). Then, using the characterisation factors defined by a given method, the substances or items in the inventory that have an effect on the impact to be assessed are grouped together. There are several methods dedicated to the assessment of individual impacts, such as the IPCC Climate Change (Stocker, T.F., D. Qin, G.-K. Plattner, M.

Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, (eds.) 2013) and others that group several impacts together, such as the ILCD method (Zampori, Pant 2019) or TRACI (Bare 2011).

Each characterisation factor is expressed in equivalent units and each impact has its own representative unit depending on the characterisation method. In this way, the total contribution that various substances have on an impact can be summed and compared, allowing a total impact to be established and identifying the key points along the life cycle where the impact is greatest.

The impacts caused by an emission depend on 1) the quantity of substance emitted, 2) the properties of the substance, 3) the characteristics of the emitting source and 4) the receiving environment. Some characterization methods are deficient on the spatial differentiation of the impact as only includes the first two aspects, inherently assuming a global set of average/standard conditions as regards the properties of the source and the receiving environment (Finnveden et al. 2009). For global impact categories (climate change or ozone layer depletion) this did not a problem but for regional or local in nature is not the same (variations and different conditions. In this regards, efforts have been done related to some impacts (e.g. water (Boulay et al. 2018)).

Finally, in the LCIA phase, according to the standards referred to, there are a number of optional elements when assessing various impacts: normalisation (the ratio of the quantified magnitude for an impact category to a reference value either on a geographical and/or temporal scale), grouping and cataloguing, and weighting (giving relative importance to the different impact categories and then summing them up to obtain a single overall index of the impact result). Finally, it is necessary at this stage to carry out a data quality analysis to understand the reliability of the results.

There are two LCA approaches to life cycle assessment, which are defined as follows in the UNEP/SETAC Shonan guide on LCA (UNEP/SETAC Lyfe cycle initiative 2011): Attributional approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or dividing the unit processes of the system according to a normative rule; and consequential approach, in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit. In a practical sense, the purpose of attributional modelling is to track a specific aspect of the product based on common allocation rules. On the other hand, consequential LCA is the relevant method to reflect the consequences of choosing one or the other product or one or the other process to make a wise decision (Ekvall, Weidema

2004). Many authors agree that consequential is more relevant for decision-making (Weidema 2003). However, the uncertainty of consequential modelling can be higher as it is highly dependent on the understanding of the product chain, the envision of the rebound effects and the time horizon. In consequential LCAs marginal data are used when relevant for the purpose of assessing the consequences (ibid). A decision can affect the production systems, at the margin, very far into the future. When a consequential LCA includes marginal effects that occur far into the future, the uncertainty added can be larger than marginal effect itself and their results can also be very sensitive to assumptions (Finnveden et al. 2009).

In addition to the environmental assessment of a product or service, the LCA methodology serves as a source of data for an assessment in terms of external costs or environmental externalities. The quantification of external costs is based on the "impact pathway" methodology that has been developed in the ExternE series of projects (Bickel, Friedrich 2005), and improved in other projects such as NEEDS (NEEDS 2009) and CASES (European Commission 2008). Impact pathway analysis aims to model the causal chain of interactions from the emission of a pollutant through transport and chemical conversion in the atmosphere to the impacts on various receptors, such as humans, crops, building materials or ecosystems. Damages resulting from these impacts are monetised using valuation techniques. The reasons for the interest in economic valuation of environmental impacts are basically twofold. First, monetisation of environmental impact results in clear and understandable comparisons between direct cost and external environmental cost and can be aggregated into a total. Second, monetisation allows for consistency, treatment and evaluation of environmental problems in a way that other methods do not in the decision support sphere (Nguyen et al. 2016).

According to Guinée (Guinée 2015), the first use of the term LCSA was done by Zhou et al (Zhou, Jiang, Qin 2007) in order to provide a sustainability analysis of the fuels value chain and give an overview of the potential on multi-criteria assessment. However, they only presented the environmental impact categories of climate change and resource depletion impacts in their LCA and combined it with an LCC, which does not cover the three-dimension model. According to this definition, LCSA would converge with the TBL approach, and thus broadens the popular LCA to also add economic and social dimensions with the life cycle approach behind them.

A bit later, (Kloepffer 2008) offered a definition of LCSA, and later on, it was further developed by (Guinée, Heijungs 2011). LCSA links 'life cycle sustainability questions to knowledge needed for addressing them, identifying available knowledge and related models, knowledge gaps and defining research programs to fill these gaps. [...] It broadens the scope of current LCA from mainly environmental impacts only to covering all three dimensions of sustainability (people,

planet and prosperity). It also broadens the object (or level) of analysis from predominantly product-related questions (product level) to questions related to sector (sector level) or even economy-wide levels (economy level). In addition, it deepens current LCA to also include other than just technological relations, e.g. physical relations (including limitations in available resources and land), economic and behavioural relations, etc. [...] LCSA is a trans-disciplinary framework for integration of models rather than a model in itself. LCSA works with a plethora of disciplinary models and guides selecting the proper ones, given a specific sustainability question'. This further developed of the definition in comparison with LCA of the LCSA broadens the impacts assessed as combined LCA, LCC and SLCA; broadening level of analysis: product-, sector- and economy-wide questions and analyses; and, deep in the analysis including other than just technological relations, such as physical, economic and behavioural relations. In this last, many others can be included as the results of the LCA, LCC and SLCA can be linked to many indicators (social, socioeconomic, market-oriented, and geopolitical). At the core of LCSA is the development of appropriate, quantitative, and practical indicators related to the three dimensions (Gloria et al. 2017), but can include dynamic and regional analysis, integrated assessments and comprehensive approaches providing also vulnerabilities, cross-linking indicators, inter- and intradimensional (Wu et al. 2017; Plevin 2017; Kua 2017).

The review of sustainability assessment methods and tools carried out in the framework of the European SAMT (Sustainability Assessment Methods and Tools to Support Decision-Making In the Process Industries) highlighted that a large number of tools implement a small number of methods. They concluded that the Life Cycle Assessment methodology, and related analysis (LCC, SLCA, LCSA) were the wider applied sustainability assessment methodology in the industry (Saurat, Ritthoff, Smith 2015). Another contribution of SAMT researchers was future needs identification. In the medium term, they identified that would be need to deepen the flexible integration and implementation of different assessment methods and tools as many actors agree (Finnveden et al. 2009; Graedel et al. 2015; Crawford et al. 2017). This would enable sustainability assessment for different purposes and from different actor perspectives useful for integrated product policies (such as product environmental footprints (Zampori, Pant 2019) or for macro-level policy support (Finnveden et al. 2009)). In the longer term, SAMT project findings highlighted the need to incorporate the use of methods as part of regular systems and activities, to increase the overall awareness of all value chain actors, and knowledge about relevant sustainability aspects in different contexts. Efforts on this line of research have been done from the LCSA perspective broadening the scope of analysis. The ongoing (2020-2023) European project ORIENTING (<https://orienting.eu/>) is a research project to develop an

operational methodology for product Life Cycle Sustainability Assessment, integrating a life cycle approach that includes the analysis of environmental, social and economic impacts. The starting point for the ORIENTING LCSA methodology is the framework proposed by UNEP/SETAC Life Cycle Initiative (UNEP/SETAC Life cycle initiative 2011) (i.e. $LCSA = LCA + S-LCA + LCC$). The need to focus on how market, regulations and socio-political aspects of the supply chain may affect the resource availability in the product system through Criticality Assessment (CA) has been also identified as crucial for sustainability assessment framework (Horn, Till 2022). In addition to the three pillars addressed in the original LCSA framework, the ORIENTING LCSA methodology includes indicators and methods that enable a coherent and practical assessment of product circularity and raw material criticality in the context of an LCSA study. Figure 8 depicts the ORIENTING LCSA approach. The approach follows the same structure of phases of LCA (goal and scope definition, inventory, impacts assessment and interpretation) plus the integration of results step, incorporating the 3 pillars and the both criticality and circularity assessments.

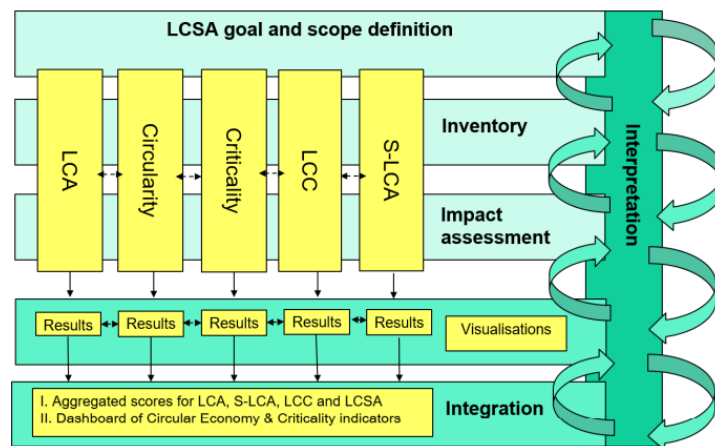


Figure 8. Simplified illustration of the ORIENTING LCSA approach.

Source: (Horn, Till 2022)

5.1.2. Advantages and disadvantages of LCA and MRIO methodologies

As discussed in the previous sections, LCSA and MRIO analysis are widely applied to quantify the impact on different dimensions of the sustainability of supply chains of consumed goods and services. Both are suitable for quantifying embodied environmental impacts, also called environmental footprints, as well as economic and social impacts, and are often combined in so-called hybrid models (Crawford et al. 2018).

Unlike LCA, where each unit process has a defined homogeneous reference product, in IO (and MRIO), the output of a sector is a mixture of the production of the different products aggregated together and/or by different technologies, and the final and intermediate sectoral production (e.g. iron, cast steel, and steel products for the iron and steel sector and even in a broader metal

sector). This leads to **aggregation errors** that can cause important deviations in estimates of energy and emissions embodied (Lenzen 2011; Zhang, Caron, Winchester 2019)

LCA and MRIO also differ in their spatial resolution and their ability to reproduce the value chains. The accuracy of environmental implications of products as quantified in LCA depends upon the geographical and technological representativeness of the production models since production conditions vary between regions and nations (Yang, Ingwersen, Meyer 2018). In LCA, it is difficult to accurately represent the actual regions involved in the supply chain specially when it relates to the “background system” made of secondary data, which are generic information derived by a variety of sources (Ciroth et al. 2019). MRIO methods are much more comprehensive in their representation of the value chains, although they suffer from the aggregation problems explained above.

There are also differences in their unit of measurement in LCA and MRIO methods. Monetary units are widely used in MRIO, while process and life cycle inventory (LCI) databases are quantified in mass, energy, number of items, volume, and other equivalent units such as tonne-km. The development of hybrid databases with high sectoral and spatial disaggregation facilitates the connection between the methods with respect to these differences, but conceptual differences and unresolved challenges still remain. To build a hybrid multi-sector and multi-regional database, while retaining the specificity of the PLCA database, among the major categories of outstanding challenges need to be addressed is the structural and ontological discrepancies between economic and process databases (i.e. geography, distribution of goods, intra-establishment flows, etc.) (Agez, Wood, et al. 2020).

LCA and MRIO databases also show different degrees of completeness. As all economic activities are linked to each other, to accurately describe any value chain the entire economy should ideally be inventoried. While MRIOs are compatible with the accounting and environmental systems (emission inventories, material flows, etc.) of countries or regions, including all market transactions and all emissions, in the process databases used in LCA there is no such completeness, necessarily setting system boundaries that leave some processes out of the analysis. On the other hand, the process data used in LCA although more accurate and representative of the process, are completed according to their availability. This leads to gaps in coverage (Majeau-Bettez, Strømman, Hertwich 2011) and thus to **truncation errors** (Lenzen 2000; Suh et al. 2004) simply because some relevant processes or products are not included and the supply associated with these life cycle links are null. This difference in completeness between LCA and MRIO, combined with the differences in granularity, are one of the main motivations for performing a hybrid LCA.

Finally, another difference is that the LCA and MRIO databases have different time coverage. The process and LCI databases contain updatable data according to the need of the modeller. In contrast, an MRIO table is constructed for a reference year. When calculating footprints with an MRIO table, the current global trade network and intermediate requirements serve as a proxy for the actual supply chain of products, which may extend over several years. This aspect has an impact on the temporal system boundaries. While in LCA the impacts of a product are modelled over its life cycle, in EEIOA the impacts of a product group relate to a specific year. This difference may not matter for short-lived products, but it may lead to very different results for product groups where capital goods used in production are important (Steubing et al. 2022).

5.1.3. Hybrid IO-LCA approaches

Developments and approaches for combining IO and LCA have been studied since the 1980s (Crawford et al. 2018). A first approach would be to use IO tables for LCA. As described by (Suh et al. 2004) the major problem with this approach is that the inventory analysis is limited to products and services in the sectoral classifications defined by the MRIO table. The major advantage of using IO tables for LCA is that the system boundaries for the analysis comprehensively cover the economy of a country or region. The downside is that, because it is comprehensive, the degree of sectoral resolution is low; in other words, the classification of goods and industries becomes coarser.

MRIO and LCA hybridisation is an approach that can overcome these limitations. In this method, process data are collected separately on goods for which conventional IO tables cannot reflect the appropriate production processes due to their coarse sectoral classifications, and then added as a supplement to the IO tables. It is called a hybrid method because it combines bottom-up LCA inventory analysis based on a stacking method with top-down IO table inventory analysis. There are three methodologies for hybrid LCA: tiered hybrid analysis, IO-based hybrid analysis (IO-based LCA) and integrated hybrid analysis. By using a MRIOT, the system boundaries are extended from one country to several countries, including international trade. In order to potentiate the advantages and limit the disadvantages of the methods, hybrid approaches have been proposed. These hybridization proposals are reviewed (Crawford et al. 2018; Nakamura, Nansai 2016) and discussed (Agez, Majeau-Bettez, et al. 2020; Nakamura, Nansai 2016; Pomponi, Lenzen 2018; Yang, Heijungs, Brandão 2017) in the literature. They had been typically grouped in three categories (Heijungs, Suh 2002) but recent reviews have proposed four approaches (Crawford et al. 2018):

- i) tiered hybrid analysis,
- ii) path exchange hybrid analysis (PXC),
- iii) matrix augmentation (or IO-based LCA) and
- iv) integrated hybrid analysis.

Tiered hybrid analysis can be conducted by simply adding IO-based life cycle inventories (LCI) to process-based LCA results (Suh, Huppes 2005a). This hybridization system has several limitations. First, the IO-based LCI should be restricted to non-important processes for which there is no process-based information available. Otherwise, significant errors can be introduced if important processes are modelled using the aggregated IO information. Second, there could be double-counting problems in tiered hybrid analysis that should be avoided and some algorithms and methods to deal with them have been proposed in the literature with limitations (Lenzen 2009; Strømman, Peters, Hertwich 2009). Additionally, this hybrid method only remediates the truncation of foreground processes specific to each case study (for example, adding services not included in LCA inventories), but background processes are still truncated (Agez, Wood, et al. 2020)

PXC was conceptualized by (Lenzen, Crawford 2009) and relies on a conventional EEIO approach, including a Structural Path Analysis (SPA). The method consists of disaggregating the IOT into a series of mutually exclusive nodes that represent a good or service provided by a particular sector. A series of nodes is referred to as the pathway. In this method, a specific node can be modified using process data related to the value or the environmental flow associated with the transaction (Crawford et al. 2017). This method has been applied to the estimation of the carbon footprint of nuclear energy by (Zafrilla et al. 2014). As disadvantage, the complexity of this method and the amount of data to be handled have made it difficult to become a widely used (Crawford et al. 2018).

The economic IO-based LCA model (later renamed in literature as Matrix Augmentation method) was developed by (Joshi 1999) and later by (Suh, Huppes 2005a) as a means to analyse product systems. IO-based hybrid LCA consists of disaggregating industry sectors to improve process specificity. The environmental extension vectors should be disaggregated as well using detailed emission data of the disaggregated processes using life cycle inventories (ibid). The main weakness is the uncertainty in altering the MIOT, as the new sectors are completely proportional to the original sector, which limits the potential benefits of hybridization per se. Finally, integrated hybrid LCA departs from constructing a hybrid matrix in which input-output and physical flows are fully incorporated at the unit process level. The main concern with this method is the potential for double counting. In the field of renewable energies, some examples

can be found. E.g., Some authors (e.g. (Gibon et al. 2015; Li et al. 2019; Whitaker et al. 2013)) applied the integrated hybrid approach to the specific case of CSP technology. Other works assessed wind power case studies, in Colombia and in UK (Vélez-Henao, Vivanco 2021; Wiedmann et al. 2011).

5.2. State of the art of energy security and geopolitical risks assessment along the value chain

Due to the existing global economic structures and resource provision chains, production processes are fragmented across regions in complex global value chains (GVC). Recent events, COVID-19 outbreak and various geopolitical crises, have demonstrated the vulnerability of these value chains and the increased risk of propagating shocks across sectors and countries (Banacloche Sánchez 2022). Different authors have adopted different methods to assess supply risks (Sun 2022) and have used combined indices focused on different aspects (Choudhary et al. 2022). Dependence on the supply of raw materials or intermediates from other countries, as well as the characteristics and stability of the supplying countries, influences the desirability of implementing future energy projects in a country or region, so the origin and distribution of the chain are also aspects that help in the analysis of sustainability in decision making.

Focusing on the challenge of renewables deployment, some authors indicate that the deployment of renewable energy sources will require new infrastructures and industries that will use different raw materials than conventional energy sources, both common materials and scarce resources (Ali et al. 2017). Rare earth elements and metals, used in the manufacturing of renewables, create new dependencies in the value chain and could represent potential future obstacles or threatens to deploying renewables (van Exter et al. 2018; Viebahn et al. 2015; Grandell et al. 2016; Valero et al. 2018; Frenzel et al. 2017). For some critical raw materials, mining is strongly concentrated in a few countries (Rabe, Kostka, Smith Stegen 2017; Mathieux et al. 2017), which makes the inclusion of dependence analysis integrated with a sustainability assessment especially relevant.

As for availability and demand of minerals, most of methods are based on MFA and LCA studies. These methods provide highly detailed figures of the involved flows but have other disadvantages. Among these are the time-consuming data collection, the need of establishing system boundaries (with the associated limitations such as the cut-off and certain level of truncation) and the poor regionalization of the resources production existing in the LCA databases. EMRIO method is specially suitable for the analysis of the supply chain as it allows identifying the countries involved and can be extended to focus on several key aspects, such as

the amount of materials consumed in a region or the quantification of governance levels in the supply chain and the dependence on imports (Gamarra, Y. Lechón, et al. 2022; Yamamoto et al. 2022). In sustainability analysis this model has been used for the quantification of environmental impacts, quantifying the material requirement involved in the deployment of energy policies as part of sustainability impact assessment (Banacloche, Cadarso, et al. 2020; Gamarra, Banacloche, et al. 2023), and for the accounting of the abiotic depletion potential (ADP) involved in the value chain (Beylot, Corrado, Sala 2020; Castellani et al. 2019). In addition, hybrid approaches LCA-EMRIO have also been used for the specific analysis of some concrete minerals (Hertwich et al. 2015; Gamarra, Yolanda Lechón, et al. 2022).

Valero et al (Valero et al. 2018) and Frenzel (Frenzel et al. 2017) analysed the global material requirements for the energy transition from fossil sources to renewable technologies. They concluded that avoiding energy dependence on fossil fuels will mean accepting dependence on certain feedstocks, some of which have significant supply risks associated with them due to lack of governance in supplier countries (Ali et al. 2017). In addition, there is the potential for energy to become much more decentralised. These factors could have a positive impact on geopolitical relations in the world, but also entail risks (Criekemans 2018). The higher the number of countries providing goods and services to assessed energy technology, the lower the dependence risk. Diversification reduces the vulnerability against unpredicted perturbations in the supply of any exporting country. Diversification is a significant, and sometimes the only, source of risk mitigation and protection against large losses in case of unpredicted events risk (Anand 2015).

In addition, an important aspect to consider is the level of governance prevailing in the countries involved in the value chain. A common way to characterize a country in this regard has been the use of governance assessment. Usually “good governance” includes features such as an efficient public system, an independent judiciary and legal framework to guarantee agreements; responsible administration of public funds; an independent public audit system, accountable to a representative legislature; integral respect for the law and human rights; a pluralistic institutional structure, as well as a free press. In the practical definition provided by the World Bank Institute, governance is the traditions and institutions by which authority is exercised; that includes the processes of government selection, control and renewal, the capacity of government to design and apply policies effectively and the relationship of citizens and the state with the institutions that manage and regulate the economic and social dynamics (Kaufmann, Kraay 2018).

Countries with strong institutions often have an enabling environment that facilitates private sector growth and foreign investments, and, in consequence produce valuable goods and services. These countries tend to be stable and experience stronger and more consistent growth, because they have an environment of low risk, controlled by the rule of law and an independent judiciary. Thus, depending on goods and services from countries with strong governance protects from risks associated with supply shortages or price volatility. It is important to note that this does not make countries immune to some kind of geopolitical risks, especially not exogenous risks, but the political value chain risks are much lower than in countries with weak institutions (Keping 2018).

There are different indicators in the literature to characterize the level of governance of countries or regions with different purposes. Some sources for these indicators are, among others, the Worldwide Governance Indicators (WGI) (Kaufmann, Kraay, Mastruzzi 2011; Kaufmann, Kraay 2018), the CIRI Human Rights Dataset (Cingranelli, Richards, Clay 2014), the Bertelsmann Stiftung's Transformation Index (BTI) (Sabine Donner et al. 2018) or the WJP Rule of Law Index (Botero et al. 2018). Besides, there are other specialised indexes such as Resource Governance Index (Natural Resource Governance Institute 2017) applied to resource governance. The bad or failing governance of exporters has been used in an ex-post analysis to identify whether the effectiveness of EU measures have improved the transparency in the extractive sector (Escribano, Paredes-Gazquez, San-Martín 2020). For our approach, the WGIs are the most suitable indicators because they are specifically oriented to governance gradation of countries, cover most countries and regions around the world and include key criteria such as the regulatory quality and rule of law, as well as the political stability or the accountability. WGI indicators are based on the methodology developed in the WGI project supported by the Knowledge for Change Program of the World Bank (Kaufmann, Kraay, Mastruzzi 2011). The six composite WGI measures for 200 countries and territories over the period 1996-2018 are annually published. The WGIs are research datasets summarizing the quality of governance from the view of several sources (survey institutes, non-governmental and international organizations, and private firms).

Novel indicators have been proposed in this sense. Previous developments in EMRIO literature handle the governance assessment differently. Rodríguez-Serrano et al (Rodríguez-Serrano, Caldés, De La Rúa, et al. 2017; Rodríguez-Serrano 2017; Rodríguez-Serrano, Caldés, Rúa, et al. 2017) assessed the governance using the SHDB for the social assessment. The governance category is assessed on the basis of Legal System and Corruption indicators calculated by combining methodologies (WGI, BTI, CIRI Human Rights, etc.) or by experts' judgments.

However, the combination of different governance methodologies makes the analysis and interpretation quite complex. Besides, some difficulties could arise such as a lack of data for this indicator in the SHDB. Methodological developments in Life Cycle Assessment are considering aspects such as supply concentration and governance of producing countries (Mancini, De Camillis, Pennington 2013). From the point of view of the material flows vulnerability, (Adibi et al. 2017) identified four groups of indicators in the literature. The Global Resources Index (GRI) that combines ADP, recycling and governance metrics is one example. However, GRI is not able to reflect the unequal and heterogenous 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 (Blengini et al. 2017) includes dependence by incorporating a metric of concentration of supply. This last one, have been recently applied to the analysis of PV and wind power production (Talens Peiró et al. 2022) with success, reflecting weakness and risks associated to both power technologies.

5.2.1. Indexes and combined indicators

Among the indices and combined indicators is, for example, the European Commission (EC)'s supply risk assessment index that combines the supply concentration, the import reliance, some criteria of governance performance, adjusted trade parameter, and a substitution index (Blengini et al. 2017; Talens Peiró et al. 2022). The "Geopolrisk" tool applies a different approach in a combined index based on LCA (Cyvi Group-ISM-University of Bordeaux 2021) and provides a value for the geopolitical supply risk. The tool is based on the development of characterization factors for the midpoint indicator 'Supply Risk Potential' that combine concentration of the supply, imports and prices. The inclusion of governance and import dependence aspects in MRIO assessments is partially included through the analysis of international carbon trade. For example, dependence on traded carbon is analysed by an MRIO methodology by (Andrew, Davis, Peters 2013). Mancini et al. (Mancini 2018) review the social-oriented assessment of global value chains including a wide range of indicators including indicators to assess the actors value chain involved in raw materials flows around the world. Additionally, in a social analysis of CSP deployment (Rodríguez-Serrano, Caldés, De La Rúa, et al. 2017) included governance as an aggregated social indicator by using the Social Hotspot Database (SHDB) (Benoit Norris, Norris, Aulizio 2013).

Other examples are those focused on resource criticality measurement such as the one developed for the Chinese context by (Yan et al. 2021) that analysed three types of supply risks, i.e., sustainability risk, reliance risk, and tolerance risk, in identifying the critical metals for China.

Another is the one proposed by the U.S. Department of Energy that is 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 to other markets. Later, the U.S. framework was further developed by Graedel (Graedel et al. 2015) where medium-term risks and long-term risks are differentiated. The ESSENZ method (Bach et al. 2016) quantifies eleven geopolitical and socioeconomic accessibility constraints (i.e., country concentration of reserves and mine production, price variation, co-production, political stability, demand growth, feasibility of exploration projects, company concentration, primary material use, mining capacity, and trade barriers), and its main critique is the restriction to global level and limitation to primary resources (Bachmann et al. 2021). 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 renewables, e.g.) whose trade flows are not being characterized at global scale and are based on MFA an 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 (Watari, Nansai, Nakajima 2020).

6. RESEARCH GAP AND RATIONALE FOR THIS THESIS

Given the above exposed arguments, in the context and state of the art of sustainability assessment, it becomes clear that it is crucial to expand the traditional sustainability assessment of energy investments to include supply chain risk analysis, including the identification and analysis of new and hidden dependences. The extension and integration of the supply risks analysis within probed pre-existing frameworks can facilitate the application and usefulness for the decision-making support. The support of decision taking encourage the relevance of having a clear and scientifically-sound information base around which decisions can be made (Usubiaga-Liaño, Ekins 2021). In this sense, sustainability assessment frameworks represent a powerful tool for identify the possible risks and strengths of the supply chains of the energy scenarios. From a system perspective, environmental implications aside from GHG emissions need to be addressed to ensure the implementation of the most sustainable energy systems. Up to date, policy makers and regulators count with methods such as LCSA (Life Cycle Sustainability Analysis) or EMRIO which provide triple bottom analysis (3 pillars of sustainability: Economic, Environmental and Social sustainability) of the supply chain of renewables. These provide a wide range of indicators in a wide range of impacts such as employment or value-added creation per MW or kg CO₂/MWh, etc. However, methods for the assessment of the risks and strengths of renewable value chains are still to be developed. Therefore, developing methods for the assessment of supply risks is one of the backbones aims of this thesis.

Another topic that emerges as needing further research has been LCA-MRIO hybridization. As explained above, several methods have been proposed in literature, each with its own drawbacks that limit the usefulness and applicability of this approach in sustainability assessment. Therefore, the other main backbone aim of this thesis has been the development of a comprehensive but still easy to implement method for hybridizing LCA and MRIO in sustainability assessments.

A bibliometric analysis has been carried out with aim of supporting the decision to define the main topic of research undertaken in the thesis. Details of the analysis can be found in the [Annex 1. Bibliometric search results.](#)

7. GOALS AND RESEARCH QUESTIONS

The main aim of this thesis is to develop a methodological proposal for the comprehensive evaluation of the sustainability impacts of any kind of energy investments, from projects and strategies to policies, making the most of existing assessment methods, and including the analysis of key geopolitical risks on supply along the value chain.

The specific objectives are:

1) To develop methodological proposals that simultaneously allow:

- to assess the risks on supply along the whole value chain, considering the key energy security and geopolitical aspects (SO1);
- to integrate the advantages and disadvantages of the current methodologies of sustainability assessment analysis in a new hybrid framework (SO2).

2) Demonstrate the methodological proposal by applying it to various case studies of investments in key renewable energy technologies driving the energy transition (SO3).

The research questions addressed to achieve the objectives presented are the follows (Table 4):

Table 4. Research Questions (RQ).

Research Question	Objectives
RQ1. What are the main components of risks of supply along the value chain?	SO1, SO3
RQ2. How can the existing EMRIO methodology be used to assess the risks of supply along the value chain?	SO1, SO3
RQ3. How can a complete and simpler hybrid method incorporating the pros and cons of the existing sustainability methodologies (EMRIO and LCSA) be developed?	SO2, SO3
RQ4. Which results are obtained from the assessment of sustainability and supply risks of key energy technologies for the energy transition?	SO1, SO3

8. PUBLICATIONS

The following research articles have been published from the work developed in this thesis. These peer-reviewed papers contain the main research and results obtained to achieve the objectives by addressing the investigated research questions (Table 5).

Table 5. Main publications.

Publication	Quartile and IF ³	Research Question	Objectives
Gamarra, A.R., Lechón, Y., Escibano, G., Lilliestam, J., Lázaro L., Caldés, N. Assessing dependence and governance as value chain risks: Natural Gas versus Concentrated Solar power plants in Mexico, <i>Environmental Impact Assessment Review</i> , Volume 93, 2022, 106708, ISSN 0195-9255, https://doi.org/10.1016/j.eiar.2021.106708 .	Q1 IF 6.122	RQ1, RQ4	SO1, SO3
Gamarra, A.R., Banacloche, S., Lechon, Y., del Río, P. Assessing the sustainability impacts of concentrated solar power deployment in Europe in the context of global value chains, <i>Renewable and Sustainable Energy Reviews</i> , Volume 171, 2023, 113004, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2022.113004	Q1 IF 16.799	RQ2, RQ4	SO1, SO3
Gamarra, A.R., Lechón, Y., Banacloche, S., Corona, B., de Andrés, J.M. A comparison and methodological proposal for hybrid approaches to quantify environmental impacts: A case study for renewable energies, <i>Science of The Total Environment</i> , Volume 867, 2023, 161502, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2023.161502	Q1 IF 10.754	RQ3	SO2, SO3
Gamarra, A.R., Lechón, Y., Banacloche, S., de Andrés, J.M. Metals' supply chain risk analysis of renewable energy investments. A methodological proposal and a case study of solar power plants in Spain. <i>UNDER REVIEW in the Journal of Cleaner Production</i> .	Q1 IF 11.072	RQ1, RQ2, RQ4	SO2, SO3

[Annex 2](#) includes the complete list of publications and research works (books chapters, papers and conferences) developed from the year 2018 to the present.

³ Impact factor (IF) and quartile of the Scientific Journal according to Journal Citation Report published by Clarivate in 2022.

II. METHODOLOGY

1. METHODOLOGICAL OVERVIEW

1.1. Methodological scheme

Figure 9 depicts the methodological scheme followed in this research. As it can be seen, two parallel and interconnected lines of research have been developed (Figure 9):

- Line I: Developments of key indicators and measurements addressed to assess risks and strengths of value chains
- Line II: Development of new hybrid methodologies for sustainability assessment: departing from the existing frameworks new hybrid methods are proposed and tested (Orange items in Figure 9).

Figure 9 depicts the methodological scheme followed in this research. Each of the research line evolve from the top to the bottom adding elements and complexities to the research until reaching the final expected the results. The links among the methodological elements developed within each research line and the results obtained are shown by the arrows. The elements of each research line that are involved in the investigation of each research questions are clustered and represented with discontinuous lines.

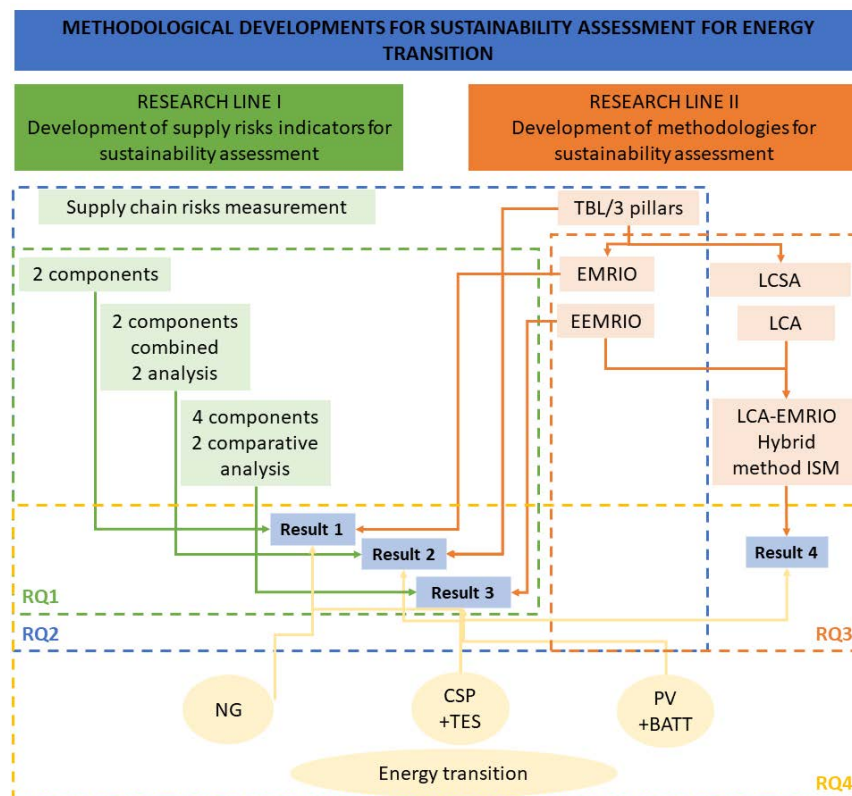


Figure 9. Methodological scheme followed in the research.

TBL: Triple bottom line; LCSA: Life cycle sustainability assessment; LCA: Life Cycle Analysis; EMRIO: Extended multiregional input-output; EEMRIO: Environmentally Extended multiregional input-output; ISM: hybrid tiered Identification and Subtraction method; CSP+TES: Concentrated Solar Power plus Thermal Energy Storage; PV+BATT; RQ: Research question.

Energy transition and renewable energy deployments are included at the bottom of the Figure 9 as the general framework of the analysis (cases studies). CSP, in comparison with a fossil technology (natural gas - NG) and other renewable technology (PV) has been used for methodological testing and validation.

2. RESEARCH LINE I. METHODOLOGICAL PROPOSALS FOR EXPANDING PREEXISTING SUSTAINABILITY ASSESSMENT FRAMEWORKS BY INCLUDING RISKS ANALYSIS

Due to the fact that the EMRIO framework is able to offer the regional details of demand and supply transaction the two lines of developments on sustainability assessment used in this research depart from that framework. The MRIO framework can track the direct imports but also the hidden indirect dependencies from different sectors and countries, allowing to assess the degree of diversity in the value chains. The methodological development is structured in three consecutive steps (Figure 10).

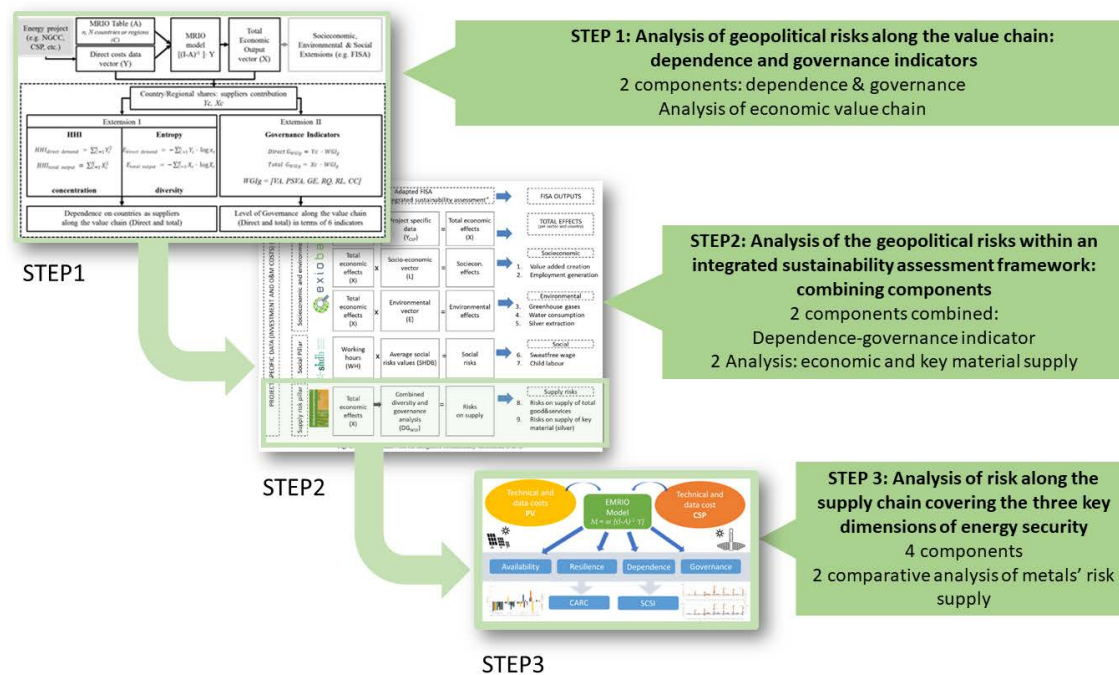


Figure 10. Steps in the development of the Research Line II

2.1. STEP 1: Analysis of geopolitical risks along the value chain: dependence and governance indicators

There will be energy technology value chains more sustainable from the point of view of dependence and governance than others, entailing less risk, a priori, being an aspect to be evaluated among alternatives of energy investment. For the integration of these geopolitical aspects in pre-existing sustainability frameworks, the use of dependence and governance indicators was investigated. Not only the dependence linked to the supply of energy resources

should be assessed but also the dependence arising from the imported supply of goods and services. The heterogeneous availability of resources around the world, the displacement of production and manufacture of technological goods to countries with lower cost of production and laxer regulation, and the existing trade policies generate differences in the origin of the supply of goods and services between technologies. By adopting a value chain perspective, it is possible to assess whether countries are dependent on other countries not only for the supply of fuels, but also for a range of intermediate materials, components, technologies, processes, and services on different steps of the energy system value chain (Högselius, Kaijser 2019).

On the one hand, the proposed methodology allows identifying which value chain maximizes direct and indirect diversification thus preventing relying in a limited number of direct and indirect suppliers. On the other hand, it allows establishing the quality of those supplier economies in terms of governance thus avoiding the inclusion of low governance countries in the value chain of components.

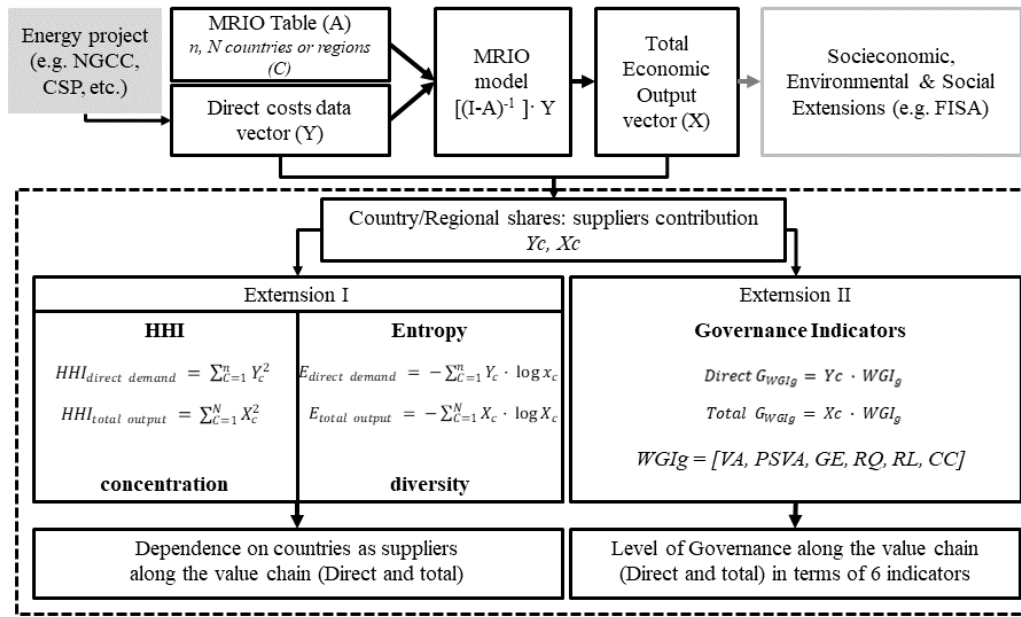


Figure 11. Methodological scheme of the assessment proposed in STEP 1 of the Research Line II. (Gamarra, Y. Lechón, et al. 2022). HHI: Herfindahl-Hirschman Index; FISA framework. The six governance indicators correspond to the six Worldwide Governance Indicators (WGI) (Kaufmann, Kraay, Mastruzzi 2011; Kaufmann, Kraay 2018)

Dependence indicators

The higher the number of countries providing goods and services to assessed energy technology, the lower the dependence risk. Diversification reduces the vulnerability against unpredicted perturbations in the supply of any exporting country. Diversification is a significant, and sometimes the only, source of risk mitigation and protection against large losses in case of unpredicted events risk (Anand 2015). The results of the MRIO analysis provide the input information for diversification metrics.

Two classical market diversification indicators are applied here: The Herfindahl-Hirschman Index (*HHI*) and the Entropy (*E*). While *HHI* is a measurement of concentration (as opposite to diversification), entropy is a diversification indicator that can be compared to a maximum value. Both indicators were explored. The concentration of the direct supply can be calculated by equation 7:

$$HHI_{direct\ demand} = \sum_{c=1}^n Y_c^2 \quad (\text{Eq. 7})$$

where Y_c is the direct demand (cost vector) from the country c expressed as a percentage of the total demand being n the total number of countries involved. Similarly, the *HHI* of the total output is computed applying Eq. 8:

$$HHI_{total\ output} = \sum_{c=1}^N X_c^2 \quad (\text{Eq. 8})$$

Here, X_c is the share of the total output of country c (stemming from the MRIO analysis) and N here is the total number of countries and regions included in the MRIO table (i.e. WIOD table). The interpretation of the value of this indicator is that the higher the concentration level (higher values of *HHI*), the lower the diversification. Here, instead of a market, the global international value chain is composed by the countries and their economies (sectors) stimulated by the deployment of an energy investment.

The second metric investigated is the entropy (*E*), is a direct measure of diversity rather than concentration. The entropy metric has been used and studied as an indicator of diversity in several disciplines, from physics to ecology, and more recently to economics and environmental studies (Corsetti, Lafarguette, Mehl 2019; Teza, Caraglio, Stella 2021; 2018; Többen et al. 2018). Values of entropy are larger when the supply chain for the value chain is more diverse. Entropy is calculated according to equations 9 and 10.

$$E_{direct\ demand} = -\sum_{c=1}^n Y_c \cdot \log x_c \quad (\text{Eq. 9})$$

$$E_{total\ output} = -\sum_{c=1}^N X_c \cdot \log X_c \quad (\text{Eq. 10})$$

If one country is the only supplier, then the index would reach a value of 0, and the higher the number of suppliers the higher the value of *E*. The maximum possible value of entropy (E_{max}) would be reached when the total possible suppliers, i.e. n or N countries, contribute with an equal share (of Y or X). Therefore, the closer the value of entropy ($E_{direct\ demand}$ demand or $E_{total\ output}$, in this case) is to the maximum value (E_{max}), the more diverse the value chain is.

Governance indicators

The use of the governance criteria to assess the risk associated to suppliers, as a quantitative proxy for political risks throughout the value chain is proposed. The Worldwide Governance Indicators (WGI) dataset provides information on governance values ranging from -2.5 (weak governance) to 2.5 (strong governance). One of the advantages of using WGI is the valuation of governance of each indicator and country in a fine-tune valuation. The WGI indicators are summarized in Table 6.

Table 6. Worldwide Governance Indicators (WGI).

INDICATOR		DESCRIPTION
VOICE AND ACCOUNTABILITY	VA	Reflects perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media.
POLITICAL STABILITY AND ABSENCE OF VIOLENCE/TERRORISM	PSVA	Political Stability and Absence of Violence/Terrorism measures perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism.
GOVERNMENT EFFECTIVENESS	GE	Reflects perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.
REGULATORY QUALITY	RQ	Reflects perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development.
RULE OF LAW	RL	Reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.
CONTROL OF CORRUPTION	CC	Reflects perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests.

The WGI are used for weighting each country's direct and indirect demand for goods and services, i.e. the monetary input (Y_c) or output resulting from the MRIO analysis (X_c) is multiplied by the indicator. Applying Equation 11, the level of governance of direct demand for each of the six governance indicators ($Direct\ G_{WGIg}$) is obtained. Likewise, total governance ($Total\ G_{WGIg}$) along the supply chain is calculated by applying equation 12 using the total output (X_c). The results will show the presence (direct or indirect) of each country or region in the value chain, as well as its relevance (quantitative combination of monetary contribution to production per country and level of governance) for each governance indicator considered.

$$Direct\ G_{WGIg} = Y_c \cdot WGI_g \quad (Eq. 11)$$

$$Total\ G_{WGIg} = X_c \cdot WGI_g \quad (Eq. 12)$$

where WGI_g is the governance value of each indicator for the six indicators analysed ($g = VA, PSVA, GE, RQ, RL$ and CC) and Y_c is the demand vector coming from this specific country. Due

to the linear relationship, positive and high scores correspond to high levels of governance for each indicator and negative high scores will reveal very low levels of governance. Therefore, the framework offers a way to provide a quantitative value of the endogenous risk along the supply chain in terms of six independent indicators of governance. Note that, the weighting is applied individually for each indicator avoiding aggregation since, *a priori*, different features of governance could not be necessarily additive.

This methodological proposal was applied in publication noted as [Result 1](#) (Gamarra, Y. Lechón, et al. 2022) where metrics and indicators to assess these geopolitical aspects were tested and validated by applying them in a comparative analysis of a Concentrated Solar Power (CSP) power plant and a Natural Gas (NG) power plant in Mexico as case study. Also, the methodology was presented in the International Input-Output Association Conference (Gamarra et al. 2019) where preliminary results of the value chain analysis with some proposed metrics and indicators were presented.

2.2. STEP 2: Analysis of the geopolitical risks along the value and supply chain within an integrated sustainability assessment framework: combining components

In this second step of the line of Research Line I, a supply risks analysis of the global value chains in terms of dependence and governance levels is conducted again, but in this case, three additional achievements have been undertaken, which have been going in three directions (Gamarra, Banacloche, et al. 2023):

- 1) The integration of the dependence-governance analysis presented above within the EMRIO analysis to test the suitability of this inclusion in the integrated sustainability assessment framework.
- 2) The development of combined indicator for dependence and governance.
- 3) The analysis of supply risks over both economic and material outputs.

The complete EMRIO-based framework developed is showed in the Figure 12. This is called Adapted FISA since it is formulated departing from the Framework of Integrated Sustainability Assessment (FISA) (Rodríguez-Serrano 2017).

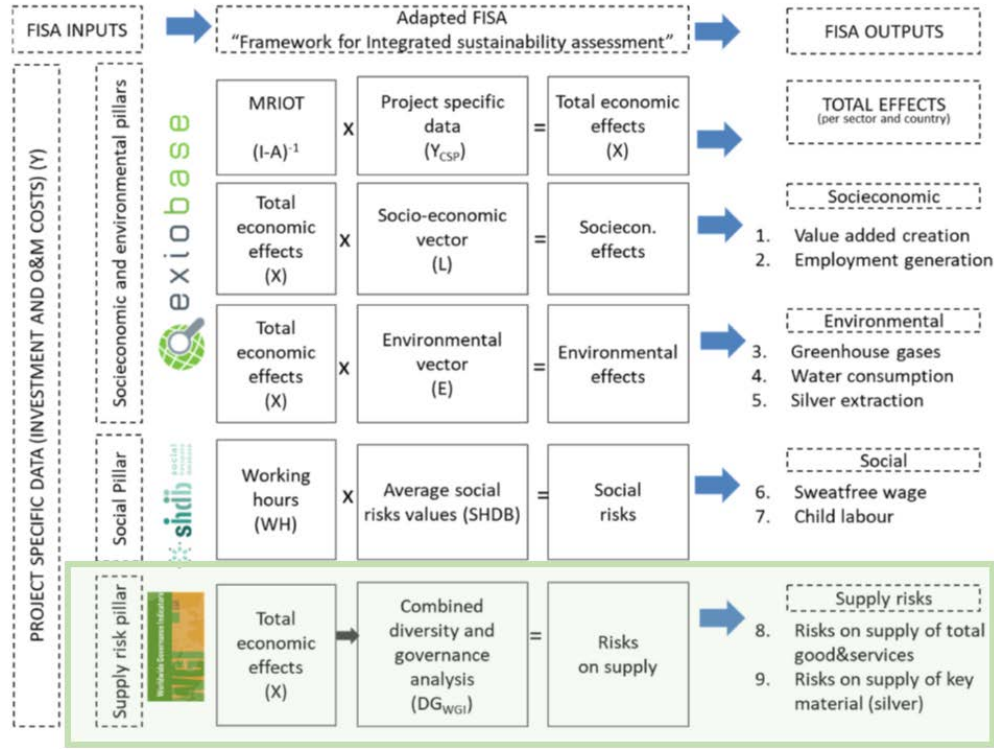


Figure 12. Adapted FISA including the Supply risk analysis followed in the Step 2 of the Research Line I.
 Source: Result 2 (Gamarra, Banacloche, et al. 2023).

For the analysis of material supply risks the MRIOT Exiobase V3.4 (Stadler et al. 2018) has been used. It includes the satellite account related to the domestic extraction of a set of materials by sector and/or region. Specifically, the analysis of dependence and the level of governance along the supply chain is assessed considering the total demand of goods and services (i.e. total output or economic effects, direct and indirect, in monetary units) as well as the extraction of silver which is considered a key raw material for the deployment of the solar according to findings in the literature (Pihl et al. 2012; Capellán-Pérez, de Castro, Miguel González 2019).

By applying equation 13, the level of governance based on the six composite indicators (WGI) (Kaufmann, Kraay, Mastruzzi 2011; Kaufmann, Kraay 2018) are used in combination with the diversity indicator to obtain the Diversity-Governance indicator of risks supply (DG_{WGIx}). This combined indicator has been applied to (1) the total output and (2) the silver extraction required by the value chain around the world. This combined indicator is built adding a component for measuring the level of governance along the value chain that is used as a weighting factor in the contribution of the countries/regions as suppliers in the Entropy equation. This leads to an indicator which combines the diversity metric and the level of governance. Then, the lowest risks would be associated to higher levels of diversity and better levels of governance.

$$DG_{WGIx} = -\sum_{c=1}^N P_{xc} \cdot WGI_{ic} \cdot \log P_{xc} \quad (\text{Eq.13})$$

Where WGI_{ic} is the governance value of each indicator for the six indicators analysed ($i = VA, PSVA, GE, RQ, RL$ and CC) for the country or region c , and P_{xc} is the share of output (economic values) or the share of contribution to the impact, in that case, the impact of the domestic silver extraction required (mass of silver).

The adapted EMRIO framework for sustainability assessment (Adapted FISA) is applied, including the supply risks analysis described above, to the two dominant CSP technologies (parabolic trough and central receiver) as case study in the publication noted as [Result 2](#) (Gamarra, Banacloche, et al. 2023).

2.3. STEP3: Analysis of risk along the supply chain covering the three key dimensions of energy security

In this third step, the developed research is focused on the analysis of the risks associated to the material supply chain of energy investments. 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 introductory section namely availability, dependence and resilience. The measurable components propose to measure each dimension are abundance, circularity and diversity. Additionally, as demonstrated in the previous steps, the inclusion of governance aspects is important to address geopolitical risks in origin. The complete framework is depicted in the Figure 13.

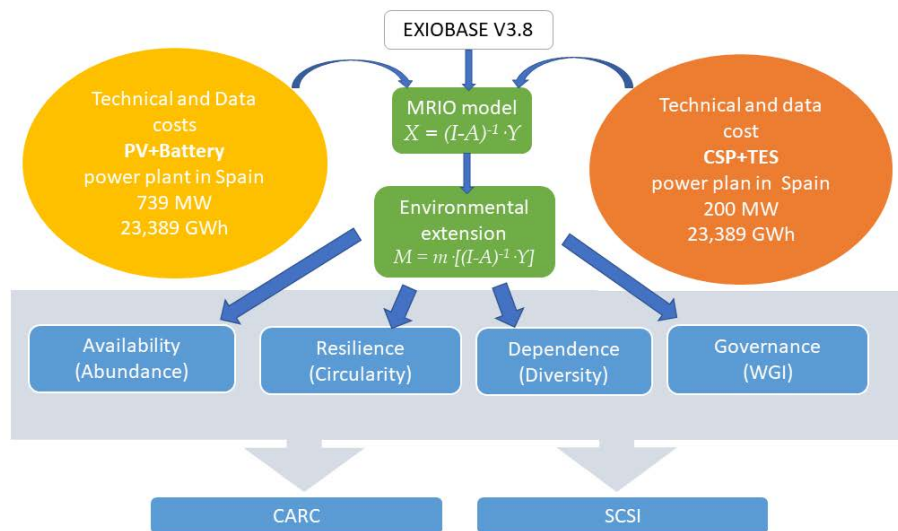


Figure 13. Methodological scheme for the supply of metals risks assessment in the STEP 3 (Research Line I).
 MRIO: Multi-regional input-output; X: output; Y: costs vector; A: MRIOT; M: amount of domestic extraction used (mass) of each raw material (mineral or metal in our case); m: environmental vector of domestic extraction (mass) of each raw material (amount of metal in our case per economic output; EOLRIR: End-of-life recycling input rate; ADP: Abiotic Depletion Potential. CARC: Comparative Analysis of individual Risks Component; SCSi; Alternative I and II would be two alternative of energy investments.

In this research, the main data source used for the EMRIO assessment is the MRIOT Exiobase v3.8. corresponding to the 2018 year was used (noted as A in Figure 13) that includes the total worldwide Domestic extraction of a set of metals (M_i) per country and sector. The results of the EMRIO model provided the inputs to assess the four components of the analysis as follows.

- **Availability:** Very often depletion is measured using the Abiotic Depletion Potential (ADP) of ultimate reserves (Berger et al. 2020), 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 et al. 2002). This factor is derived for each extraction of elements as a relative measure, with the depletion of the element antimony (Sb) as a reference (see Equation 14).

$$ADP_m = \frac{DR_m / R_m^2}{DR_{ref} / R_{ref}^2} \quad (\text{Eq. 14})$$

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

- **Resilience:** The resilience of the supply chain to provide each resource can be increased by circular economy practices. Therefore, an indicator of circularity is proposed here. The indicator of circularity of the materials provided by the European Commission (EC-DG GROW 2021) and known as end-of-life recycling input rates in Europe ($EOLRIR_m$) reflects the use of secondary raw materials. These indicators deem appropriate for the analysis of European investments while investments in other regions would need appropriate rates. Multiplying these $EOLRIR_m$ by the share of each metal in the total amount of metals extracted considering the set of assessed metals (e.g. kg Fe/ kg total metals extracted) a measure of circularity is obtained. That would be a way to a measure of the portion of each metal extracted in the deployment of each technology that could be potentially recycled considering the rates of secondary reprocessing in Europe, according to equation 15 and equation 16.

$$ERPR_m = \left(M_m / M_t \right) \cdot EOLRIR_m \quad (\text{Eq. 15})$$

$$ERPR = \sum_m^n ERPR_m \quad (\text{Eq. 16})$$

Where $ERPR_m$ is the European recycling potential rate, and M_m/M_t is the share of the mass of each of the extracted metal m (of the sample of n number of metals) with respect to the total mass of metals (quantified) required by each energy technology deployment. The total ($ERPR$) is the sum of $ERPR_m$ (equation 15).

- **Dependence:** Dependence is included in the methodological framework by measuring the diversity of supply in terms of variety of origins and its distribution throughout the world (i.e, from how many origins and how much from each of them). The diversity metric Entropy (E_m) is applied. The more diverse (higher value of E_m) the value chain is, the less dependent on a few suppliers, and therefore, the lower the supply risk. The entropy is calculated according to equation 17:

$$E_m = -\sum_{c=1}^N S_{m,c} \cdot \log S_{m,c} \quad (\text{Eq. 17})$$

Where $S_{m,c}$ is the share of the contribution of each country or region to each considered mineral or metal m . One of the advantages of using this metric is that it can be compared with a maximum value, E_{mmax} , being the maximum value the one obtained using the total number of exporters countries or regions of the 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 the total entropy (E_t/E_{tmax}).

- **Governance**

Following the logic exposed in the STEP I and STEP II, not only the number and share of suppliers is relevant in the dependence relationship between exporters and importers, but governance level in the country origin has a relevant role. The six-composite Worldwide Governance Indicators, WGI (Kaufmann, Kraay, Mastruzzi 2011; Kaufmann, Kraay 2018) are used here to weight the supply from the different regions and countries. By applying equation 18, the governance index of the total extraction of each material per each of the six governance criteria is obtained (G_{WGImi}). Thus, a component that measures the level of governance along the value chain is added 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.

$$G_{WGImi} = -\sum_{c=1}^N M_{m,c} \cdot WGI_{i,c} \quad (\text{Eq.18})$$

where WGI_{ic} is the governance value of each indicator for the six indicators analysed ($i = VA, PSVA, GE, RQ, RL$ and CC) in the country or region c , and M_{mc} is Mg of each metal per MW of capacity, resulting a value of governance weighted demand of metals/MW.

Once the main components to characterize the risks associated to the supply chain, two analyses are proposed and undertaken:

- 1) **A comparative analysis of individual risk components (CARC):** The comparative analysis of individual criteria provides a global picture of the value chain risks associated to each investment. Table 7 shows the criteria and indicators. The formulation of these indicators facilitates the interpretation 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 7. 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_{WGlim}

- 2) **A combined analysis with the Supply Chain Strength Indicator (SCSI):** the proposed index incorporates the four elements Availability-Resilience-Dependence-Governance (A-R-D-G) combined to measure the three orthogonal dimensions of security of energy supply traditionally discussed in the literature: dependence, availability and resilience. Governance is introduced as an additional component to each dimension that qualifies the geopolitical risks associated to the supply chain. This is calculated using equation 20. The three terms include the measure of diversity and each of them is focused on one of the three other components. The first term would reflect dependence and governance by considering the contribution of each country to the required metal extraction multiplied by the governance indicator (DG_{WGlix}) as previously presented in the STEP II. The second term would reflect availability. For that, in order to be able to regionalized the availability and take into account the probed available and reserves, the indicator economic reserve-production ratio ($eRPR_{mc}$) is proposed (calculated by equation 19). It is the ratio between ultimate reserves and production for each metal which is non-dimensional and represents the abundance for each metal.

$$eRPR_{m,c} = \frac{\frac{eR_{m,c}}{DR_{m,c}}}{\frac{eR_{mglobal}}{DR_{mglobal}}} \quad (\text{Eq. 19})$$

And the third term of $SCSI_{mi}$ (equation 20) would measure resilience by considering the end-of-life recycling input rates in Europe ($EOLRIR_m$) that in turn measures 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_{mEUR} , 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.

$$SCSI_{mi} = [-\sum_{c=1}^N S_{m,c} \cdot WGI_{ic} \cdot \log S_{m,c}] + [-\sum_{c=1}^N eRPR_{m,c} \cdot S_{m,c} \cdot WGI_{ic} \cdot \log eRPR_{m,c}] + [\sum_{c=1}^N S_{m,c} \cdot EOLRIR_m \cdot WGI_{m,EUR} \cdot \log S_{m,c}] \quad (\text{Eq. 20})$$

$$SCSI_{ti} = \sum_{c=1}^N SCSI_{m,i} \quad (\text{Eq. 21})$$

The result of the addition of the three terms is a non-dimensional 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 which positive scores of governances and lower risks. The size of the value depends on the governance scores and the diversity of the supply, of the reserve availability (economic reserve production ratio for each metal and country), and of the supply weighted by the 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.

This methodological proposal for the analysis of the risks associated to the material supply chain of energy investments has been tested in two case studies of solar energy investments in Spain: a CSP plant with energy storage and a PV installation with batteries as case study in the publication noted as [Result 3](#).

3. RESEARCH LINE II. METHODOLOGICAL PROPOSAL OF NEW HYBRID SUSTAINABILITY ASSESSMENT METHODS: THE TIERED HYBRID ISM METHOD

In the Research Line II of this thesis, a pathway to improve the quantification of environmental impacts on sustainability is investigated and a methodological proposal is developed and tested.

The main disadvantage of MRIO and its corresponding extensions is the high aggregation of processes and activities within the economy, since they are clustered in economic sectors assumed to be uniform in terms of technology and performance. As a consequence, the values reported in the MRIOT and the associated environmental accounts do not correctly reflect a particular process or product belonging to heterogeneous sectors (EU-JRC 2012). As described in the introduction, in order to potentiate the advantages and limit the disadvantages of the MRIO, several hybrid approaches with LCA have been proposed. They had been grouped in four categories (Crawford et al., 2018): i) tiered hybrid analysis, ii) path exchange hybrid analysis (PXC), iii) matrix augmentation (or IO-based LCA) and iv) integrated hybrid analysis.

In this thesis, a new approach for making a tiered hybrid analysis that seeks to expand the boundaries of an LCA using EMRIO, increasing the completeness of the assessment while reducing the double-counting potential problems of the classical tiered method, has been proposed and applied. The method avoids the complexity of the MRIOT alteration proposed in IO-based LCA, the integrated hybrid LCA or the PXC method.

As case study, a CSP power plant with storage for renewable electricity generation has been selected.

The Figure 14 illustrates the research undertaken in this Line II of research of the thesis.

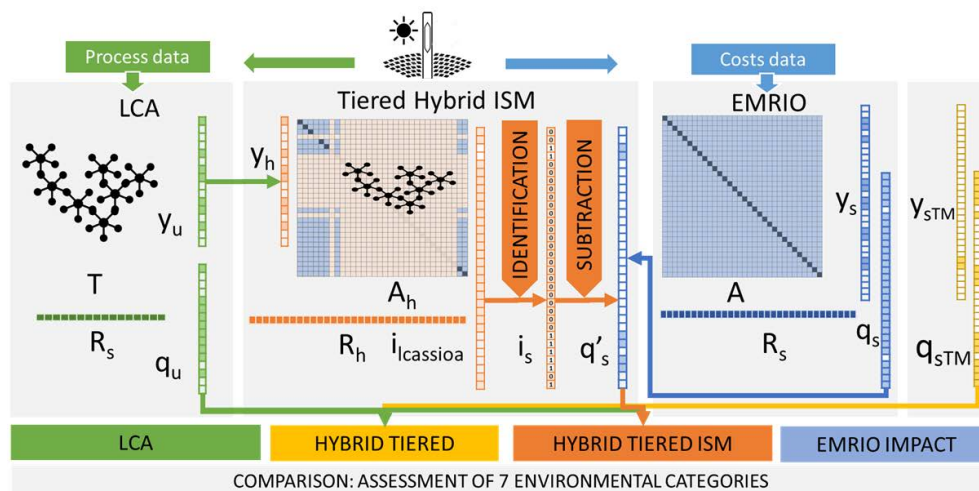


Figure 14. Graphical abstract of the research work undertaken in the LINE II development of the ISM method.

The maths of the life cycle analysis (LCA), original classical hybrid tiered method and the proposed method are described. As EMRIO method has been described and exemplified at the beginning of the methodology no new sections are dedicated.

3.1. LCA and Original Classical Tiered mathematical formulation

- **Life cycle analysis (LCA)**

The LCA mathematical formulation can be expressed as:

$$q_u = R_u T^{-1} y_u \quad (\text{Eq. 22})$$

Where :

q_u is the process component of the hybrid model

T is the LCA processes technological matrix (from Ecoinvent in this case).

y_u is the vector of unit processes;

In LCA language the vector of demand for the unit processes (y_u) would corresponds with the inventory data tailored to the specific case study according to the scope and goal definition. Then, q_u would provide the results of the inventory analysis providing the total consumption, emissions, effluents and wastes. Usually, in LCA results are disaggregated by the stage of the life cycle.

- **Original Classical Tiered:** This method is based on a process analysis and uses input-output data to fill any remaining higher order gaps in the analysis and reduce, mainly, upstream truncation errors. The mathematical formulation can be expressed as follows:

$$q_h = q_s + q_u \quad (\text{Eq. 23})$$

$$q_h = R_s(I - A)^{-1} y_s + R_u T^{-1} y_u \quad (\text{Eq. 24})$$

$$q_{h_{ism}} = q_s' + q_u \quad (\text{Eq. 25})$$

$$q_s' = q_s \circ i_s \text{ (Hadamard product}^4\text{)} \quad (\text{Eq. 26})$$

Where:

q_s and q_u : input-output and process components of the hybrid model, respectively;

q_h : total result of the model

⁴ the Hadamard product (also known as the element-wise product, entrywise product or Schur product) is a binary operation that takes two matrices of the same dimensions and produces another matrix of the same dimension as the operands, where each element i, j is the product of elements i, j of the original two matrices. It is to be distinguished from the more common matrix product. It is attributed to, and named after, either French mathematician Jacques Hadamard or German Russian mathematician Issai Schur. The Hadamard product is commutative (when working with a commutative ring), associative and distributive over addition.

R_u : matrix of environmental burden per unit of process of dimension z processes of the LCA database;

T : is the LCA processes technological matrix (from Ecoinvent in this case).

R_s : matrix of environmental burden per unit of output of dimension $sr \times sr$ of the MRIO database (Exiobase in this case) (s: sectors, r: regions);

I : the identity matrix of dimension $(sr \times sr)$;

A : the input-output matrix of dimension (e.g. Exiobase (economic), $sr \times sr$);

y_s and y_u : the vector of demand ($sr \times 1$), and vector of unit processes.

3.2. Proposed hybrid method: Tiered Identification and Subtraction Method

The method consists of the combination of the results obtained from the analysis of the same case study using LCA (process) and EMRIO by following two steps (identification and subtraction) in order to extend the scope, reducing the truncation errors, and simultaneously, avoid the double counting.

As basis for the development of the ISM approach, EMRIO is assumed as the most complete in terms of background flows along the value chain, and LCA as more precise in quantifying the foreground processes.

An additional analysis should be conducted to be used as the link between both methods. Some IOT and MRIOT databases are included in LCA software to support the environmental analysis of production processes and value chains and it is called in this research LCA software supported analysis (LCASSIOA). Kerkhof and Goedkoop (Kerkhof, Goedkoop 2010) described and exemplified the application of these databases to the environmental assessment of products in the LCA Software Simapro™. IO data by sectors and/or countries, and their associated environmental satellite accounts, are incorporated in the mentioned software in the same way as the LCA processes or materials from LCI databases - such as Ecoinvent.

The results of the LCASSIOA allows the identification of the sectors (in the specific country or region) demanded within the LCA scope. Then, the Identification step assumes that the sectors contributing to the inventory in the LCASSIOA are those already included in the process-based model, and the rest of them correspond to those activities (and their impact) which are out of the LCA boundaries. Therefore, these activities would need to be added from the EMRIO results. Thus, in the second step of Subtraction, the coincidental sectors among LCASSIOA and EMRIO are removed from the EMRIO results, i.e. the contribution of the sectors already included in each stage of the LCA are identified and subtracted from the EMRIO results.

Then, once subtracted the overlapping sectors, the results from both LCA and EMRIO are added. The final results obtained through this hybrid approach combine process-based LCA and EMRIO outcomes avoiding the overlap of sectors (i.e., double counting). With this approach, the technical representativeness of the foreground processes included (LCA results) is guaranteed while also maximizing the assessment's completeness by adding through EMRIO the missing sector contributions. The maths of the method in each step is described below.

• **Step 1: Identification:** building the vector i_s (identification)

The vector i_s is built departing from the identification of the portion of q_s which would have been included in the q_u component. For that, an IO-LCI is compiled in the LCA software to support the process (so that the analysis is called LCA Software supported IOA, LCASSIOA) by using a hybrid input-output table. The IO-LCA is formulated as follows:

$$i_{lcassioa} = (I - A_h)^{-1} y_h \quad (\text{Eq. 27})$$

$$q_{lcassioa} = R_h (I - A_h)^{-1} y_h \quad (\text{Eq. 28})$$

$q_{lcassioa}$: “input-output life cycle analysis” vector of environmental impact estimated by the LCASSIOA method;

$i_{lcassioa}$: output vector in hybrid units calculated by the LCASSIOA method;

A_h : Hybrid matrix Exiobase (hybrid units, economical and physical units) implemented in the LCA software;

y_h : IO-LCI vector of demand in hybrid units, economical and physical units;

R_h : Matrix of environmental burdens of dimension $s \times r$ implemented in the LCA software.

As a limitation, the implementation of the IOA in LCA software is incomplete, as it consumes a lot of resources due to the demanding calculation process and data management in the LCA software. Then, the LCASSIOA has a certain truncation. As an advantage, the use of the LCA software facilitates the work of scenario building and proxy settings between process-LCI and IO-LCI with highly detailed inventory. Besides, LCASSIOA allows the environmental impact calculation to be automated considering several environmental characterization methods. As a result, the output vector, $i_{lcassioa}$ in hybrid units, and the impact vector $q_{lcassioa}$ are obtained. The elements, $i_{lcassioa_{sc}}$, of the output vector ($i_{lcassioa}$) are the output of each sector s of the country c . And the elements $q_{lcassioa_{sc}}$, of the output vector, ($q_{lcassioa}$) are the environmental impact of the sector s and country c .

Assuming that $i_{lcassioa}$ represents the same scope included in q_u , since y_h has been built basing on y_u , this is used in order to identify the overlapped sectors between q_u and q_s . Those overlapped sectors would be those sectors of the q_s already included in $i_{lcassioa}$.

Then, an additional vector of subtraction is built, i_s , departing from $i_{lcassioa}$:

- Condition 1: If $i_{lcassioa_{nm}} \neq 0 \Rightarrow$ then $i_{s_{sr}} = 0$ ($n = 1, \dots, s$; $m = 1, \dots, r$ regions), since those flows would be included in the LCA scope.
- Condition 2: If $i_{lcassioa_{nm}} = 0 \Rightarrow$ then $i_{s_{sr}} = 1$ ($n = 1, \dots, s$; $m = 1, \dots, r$ regions), since those flows would not be included in the LCA scope.

Considering n number of sectors included in the input-output matrix, and m number of regions included in the input-output matrix. Thus, the vector of subtraction is obtained, whose components $i_{s_{sr}}$ have values of 0 and 1.

• Step 2: Subtraction

Then, the vector q_s is multiplied (scalar, no vectorial) by the vector i_s to obtain a q'_s . Therefore, the elements with zero value ($i_{s_{nm}} = 0$) are subtracted (turn to zero) in the q_s .

$$q_h = (R_s (I - A)^{-1} y_s) \circ i_s + R_u T^{-1} y_u \quad (\text{Eq. 29})$$

T : the technological matrix (Ecoinvent, e.g.);

I : the identity matrix of dimension ($sr \times sr$);

A : the input-output matrix of dimension (e.g. Exiobase (economic), $sr \times sr$);

y_s and y_u : the vector of final demand of dimension $sr \times 1$, and the vector of final demand for the unit processes;

R_s : matrix of environmental burden per unit of output of dimension associated to the input-output matrix (s : sectors, r : regions);

R_u : matrix of environmental burden per unit of process the dimension z processes of the LCA database (e.g. Ecoinvent).

Note the symbol $\circ$ means Hadamard product

Once the q_{hism} is obtained (pollutants, MJ, etc.) those are characterized to be turn into an indicator of an impact category (Climate Change, Acidification, etc.). Further explanation of the Characterization of the Impact is found the [Annex 3](#).

This methodological proposal for a new tiered hybrid approach has been tested in a case study of a CSP power plant in the publication noted as [Result 4](#) (Gamarra, Lechón, et al. 2023).

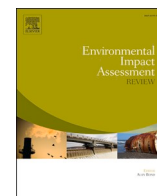
III. RESULTS

The detailed application of each methodological proposal described in Methodology and the obtained results are presented in this section.

The section is split in subsections corresponding to four individual and interconnected research works contributions (see Figure 9 in the Methodology). At the end, the analysis of similarities of the publications with the recent research is presented in the fifth section of the chapter.

**1. RESULT 1: ASSESSING DEPENDENCE AND GOVERNANCE AS VALUE CHAIN RISKS:
NATURAL GAS VERSUS CONCENTRATED SOLAR POWER PLANTS IN MEXICO**

Gamarra, A.R., Lechón, Y., Escribano, G., Lilliestam, J., Lázaro L., Caldés, N. Assessing dependence and governance as value chain risks: Natural Gas versus Concentrated Solar power plants in Mexico, Environmental Impact Assessment Review, Volume 93, 2022, 106708, ISSN 0195-9255, <https://doi.org/10.1016/j.eiar.2021.106708>.



Assessing dependence and governance as value chain risks: Natural Gas versus Concentrated Solar power plants in Mexico

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ABSTRACT

Despite geopolitics play a pivotal role in the energy sector, geopolitical aspects are often not considered in the quantitative assessment models aimed at supporting the energy investment decision-making process. To address this issue, this work proposes an Extended Multi-regional Input-Output model (EMRIO) that incorporates import dependence and governance along the value chain. As case study, two alternative energy investments in Mexico – a Natural Gas Power plant (NG) and a Concentrated Solar Power plant (CSP) – are assessed. The method quantifies the geographical diversification of suppliers and the quality of governance. The assessment of the case study shows that the supply chain of the CSP plant includes more countries and with better governance levels than the supply chain of the NG power plant. That means, a priori, that the supply risks of investing in CSP power plants will be lower, as will suppliers' endogenous geopolitical risk. However, a sensitivity analysis considering different providers of the solar plant components reveals that CSP plant value chain could also entail similar or even higher governance risks levels as the NG plant. The scenario where China provides some of the components entails a much higher governance risks, even higher than the NG base case. In consequence, we have proved that the method proposed allows the identification of hidden geopolitical risks that would otherwise go unnoticed. This paper enlarges the existing knowledge on assessment methodologies for energy policy decision-support by measuring diversification and imports dependence from countries with different levels of governance along the whole value chain.

1. Introduction

Mexican policy-makers have sought to address the challenge of transforming the Mexican economy and its energy system to meet the Nationally Determined Contribution (NDC) pledge under the Paris Agreement (SEMARNAT MEXICO, 2015). Under the former government, one of the most ambitious initiatives was the energy reform.¹ Among its main goals was to deliver a low(er) carbon and self-sufficient

power system based on clean production, transmission and distribution of electricity (Banacloche et al., 2020a) which included broad targets in renewable investments (SENER, 2018). The new administration² has side-lined the development of renewables in favour of fossil fuel generation, especially natural gas combined cycle power plants (Secretaría de Energía and Gobierno de México, 2019). Mexico's new energy policy is not aligned with the achievement of the well below 2 °C and 1.5 °C limits established in the Paris Agreement (Climate Action Tracker, 2020;

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¹ The former Government of the United Mexican States (Mexico) under the Enrique Peña Nieto's Government Office (from 2012 to 2018) launched the Energy Reform (Gobierno de México, 2013; SENER, 2014). The reform was accompanied by 21 secondary laws and the national energy strategy (ENE 2014–2028, from the Spanish acronym, Estrategia Nacional de Energía), updated on an annual basis.

² Mexican Administration headed by President Andres Manuel Lopez Obrador in office as of 2018.

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Rebecca, 2021).

Besides the negative impact of increasing carbon emissions, this change in the energy policy also implies changes in trade patterns and higher dependence on imports. The country has a wide range of energy resources, including oil, gas and a vast potential for the development of renewables, especially solar (IRENA, 2015). While Mexico is within the top ten oil producing countries, it is highly vulnerable to oil price volatility, and it is dependent on NG imports from the USA (EIA, 2020). For this reason, the recent shift to a more fossil fuel-based power system could aggravate the vulnerabilities associated with this situation. As an alternative, concentrated solar power (CSP) could contribute to a decarbonised Mexican power system while reducing the country's high fossil fuel energy dependence. CSP's attractiveness is based on its decarbonisation (Arancibia-Bulnes et al., 2014; Kabir et al., 2018; SENER, 2012) as well as its dispatchability via thermal energy storage (Achkari and El Fadar, 2020; Mehos et al., 2016). Additionally, the economics of CSP are also improving showing a costs decline over the period 2010–2019 at 60%, which will likely continue (Lilliestam et al., 2020).

Integrated sustainability assessment to support the decision making process allows to identify and decompose diverse economic, environmental and social impacts. For example, for the Mexican case, Rodríguez-Serrano (Rodríguez-Serrano et al., 2017a) showed that investing in CSP could reduce CO₂, contribute to economic growth and help create new high-quality jobs; at the same time, CSP could also reduce the overall employment because many CSP components are imported. Nonetheless, there are other aspects essential for a low-carbon energy transition that renewables deployment could affect such as geopolitical risks associated to the economies involved in the value chain. These effects have not yet been thoroughly investigated in combination with the mentioned assessment methods. Among other possible variables, in this work we focus on dependence and governance aspects of the value chain as important aspects affecting the geopolitics, defined as “the analysis of the interaction between, on the one hand, geographical settings and perspectives and, on the other, political processes” (Cohen, 2015). This approach offers two main advantages. On the one side, it allows identifying which value chain maximizes direct and indirect diversification thus preventing relying in a limited number of direct and indirect suppliers. On the other side, it allows establishing the quality of those supplier economies in terms of governance thus avoiding the inclusion of low governance countries in the value chain of components.

The research on how to address geopolitical aspects along the value chain is relevant in the assessment of energy investments for several reasons found in the literature. Renewable energies differ in many respects from fossil fuels and so do the geopolitical consequences of their production and consumption (Commission on Geopolitics of Energy Transformation, 2019; Goldthau et al., 2018; Scholten and Bosman, 2016). Valero et al. (2018) and Frenzel et al. (2017) analysed the global material requirements of the energy transition from fossil sources to renewables and concluded that it will imply accepting the dependence on raw materials, some of which may entail significant supply risks due to the lack of governance in supplying countries (Ali et al., 2017).

The geopolitics of renewables are likely to be different. The risks of fossil resources which are determined by their geographical availability around the world would not be as relevant for renewables (Overland, 2019) and in case, could be positive due to more decentralize (Crieke-mans, 2018). As pointed out by Kim and Karpinsky (Kim and Karpinski, 2020), the Covid-19 outbreak has underlined the need to watch out for the security of supply of critical minerals for a clean energy future. In this regard, the geopolitical analysis of energy issues should also be adapted to the new world of renewables in which the demand for materials will increase significantly, making this the most vulnerable step for renewable energy system (components manufacturing, storage, and required smart/digital technologies) (European Commission, 2020). Energy policies must simultaneously address geopolitical issues that

revolve around the security of supply (trade, environmental and economic and resource management policies) (Bouzarovski et al., 2015).

Given the above, it is important to expand the traditional sustainability assessment of energy projects to include geopolitical analysis for the entire value chain of energy projects, including the identification and analysis of new and hidden dependences, but also the governance quality in the countries involved in the supply chain. In this paper, we expand the existing Multiregional Input Output (MRIO) method (Leontief, 1936; Wiedmann et al., 2007; Wiedmann and Lenzen, 2018, 2008) to include these issues. MRIO methodologies are well suited to assess these aspects due to the explicit consideration of the transnational value chains between different countries and sectors in the global economy. The inclusion of governance and import dependence aspects in MRIO assessments is partially included through the analysis of international carbon trade (e.g. dependence on traded carbon is analysed by an MRIO methodology (Andrew et al., 2013). Mancini et al. (Mancini, 2018) review the social-oriented assessment of global value chains including a wide range of indicators including a kind of actors value chain involved in raw materials flows around the world. Additionally, the social analysis of CSP deployment (Rodríguez-Serrano et al., 2017a) included governance as an aggregated social indicator by using the Social Hotspot Database (SHDB) (Benoit Norris et al., 2013). As a way to improve existing frameworks, we propose to deeper geopolitical approach by quantifying dependence and governance along the value chain. As such, two methodological contributions are developed. First, we add the consideration of geopolitics by including the analysis of diversification and governance along the entire value chain. Second, specifically for governance indicators, we improve the approach from previous works by incorporating a wider range of governance indicators without aggregation, more clearly interpretable. Furthermore, to probe the proposed method, we apply the proposed extended model to a case study of CSP power plant investments in Mexico, in comparison to a NG power.

The novelty of the proposed method combined with its application to compare two relevant energy technologies in Mexico contributes to enlarge the existing body of knowledge in many ways. First, the proposed method enlarges and improves the existing literature on sustainability assessment of global value chains (MRIO) by considering diversification and governance indicators. By doing so, the proposed method allows to assess and compare alternative energy investment projects. This is done considering not only the traditional sustainability impact indicators but also governance and diversity quantitative indicators associated to the direct demand of goods and services as well as the embedded contribution of indirect suppliers. Furthermore, in order to validate and illustrate the proposed method with a case study, two alternative energy technologies in Mexico have been assessed and compared: a CSP power plant and natural gas combined cycle (NGCC) power plant. Two sensitivity scenarios based on the insights from the literature and stakeholder consultation have been conducted.

2. Method: Extension of the MRIO model

The methodological basis of this paper is the extension of the MRIO model by including indicators to measure import dependence and governance quality levels along the value chain. The reason to focus on dependence and governance arises from the concept of geopolitics. The first component of the analysis is the dependence relationship between countries along the value chain in their roles as importers and exporters. The potential relevant role of one supplier drives to a dependence on it, so the higher the number of suppliers along the value chain, the lower the dependence risk. The second component is governance, understood as the forces and practices that operate at the domestic level, which can lead to endogenous risks. So that, the better the quality of those practices of good governance the lower the endogenous risk.

2.1. From MRIO to EMRIO

The MRIO model analyses regional and national relationships across economic sectors and the impact of such interactions on economic growth by analysing changes in the demand of goods and services (G&S) of different investments (Leontief, 1936; Wiedmann et al., 2007). MRIO tables consist of the inputs (consumption) and the outputs (production) of economic sectors of a country or region. Using the information contained in the input-output tables, a technical coefficient matrix (matrix A in eq. 1) is built which contains a compilation of technical coefficients which represent the value of products that sectors need from other sectors per unit of output. The total production of G&S (output) is calculated using the following equation:

$$X = [(I - A)]^{-1} \cdot Y \quad (1)$$

where X is the production of G&S, A is the technical coefficient matrix, $[(I - A)]^{-1}$ is the inverse Leontief matrix (Leontief, 1936); and Y is the demand vector. Total effects (X) include direct (direct demands) and indirect effects (the G&S required to satisfy the direct demand). The MRIO framework has been extended (EMRIO modelling) allowing the estimation of socioeconomic or environmental effects, by adding vectors that describe the impact of said effects per monetary unit in each sector of the economy (e.g. CO₂/US\$, etc.) in the formulation of eq. 2.

$$Z_t = z_i \cdot X_i = z_i \cdot [(I - A)]^{-1} \cdot Y \quad (2)$$

where Z_t is the total socioeconomic or environmental effects and z_i is the environmental or socioeconomic vector.

An example of EMRIO is the Framework of Integrated Sustainability Assessment (FISA) (Rodríguez-Serrano et al., 2017b, 2017a). They used the MRIO table World Input-Output Database³ (WIOD) (Dietzenbacher et al., 2013) and the related time-series of socioeconomic and environmental information. WIOD analyses/includes information on 40 countries and the Rest of the World (RoW) region, and includes 35 sectors. Social risk analysis was included on FISA through the SHDB (Benoit Norris et al., 2013). So, FISA allows for the comparison of investments, including the macroeconomic impacts and their environmental and social risks implications. Thus, taking the EMRIO model as a starting point, we propose to extend the model to undertake a dependence (extension I) and governance (extension II) analysis to incorporate the geopolitical risks along the value chain (Fig. 1).

2.2. Extension I: Dependence analysis

We aim to analyse not only the dependence linked to the supply of energy resources but also the dependence arising from the imported supply of goods and services. The heterogeneous availability of resources around the world, the displacement of production and manufacture of technological goods to countries with lower cost of production and laxer regulation, and the existing trade policies generate differences in the origin of the supply of goods and services between technologies. By adopting a value chain perspective, it is possible to assess whether countries are dependent on other countries not only for the supply of fuels, but also for a range of materials, components, technologies, processes, and services on different steps of the energy system value chain (Högselius and Kaijser, 2019). Some authors indicate that the deployment of renewable energy sources will require new infrastructures and industries that will use different raw materials than conventional energy sources, both common materials and scarce resources (Ali et al., 2017). Rare earth elements and metals, used in the manufacturing of renewables, create new dependencies in the value chain and could represent potential future obstacles or threatens to deploying renewables (Frenzel et al., 2017; Grandell et al., 2016; Valero et al., 2018; van Exter et al.,

2018; Viebahn et al., 2015). For some critical raw materials, mining is concentrated in a few countries (Mathieux et al., 2017; Rabe et al., 2017), which makes the inclusion of dependence analysis integrated with a sustainability assessment especially relevant.

When data included in the demand vector is sufficiently detailed, an MRIO framework can track the direct imports but also the hidden indirect dependencies from different sectors and countries, allowing to assess the degree of diversification in the value chains. The higher the number of countries providing goods and services to assessed energy technology, the lower the dependence risk. Diversification reduces the vulnerability against unpredicted perturbations in the supply of any exporting country. Diversification is a significant, and sometimes the only, source of risk mitigation and protection against large losses in case of unpredicted events risk (Anand, 2015). The results of the MRIO analysis provide the input information for diversification metrics. Two classical market diversification indicators are applied here: The Herfindahl-Hirschman Index (HHI) and the Entropy (E). While HHI is a measurement of concentration (as opposite to diversification), entropy is a diversification indicator that can be compared to a maximum value. Both indicators are used in this work.

The first metric, HHI is commonly used in economic studies aimed at analysing market concentration. It measures the number of companies that operate and their market power or control capacity. As such, HHI is frequently used by authorities responsible to assess the competitiveness of markets (Council of European Energy Regulators, 2018; EU Council, 2014; OECD, 2018; U.S. Department of Justice and the Federal Trade Commission, 2010). HHI is a classical measure used in geopolitics of fossil resources to evaluate the diversification of supply as an advantage for the consumer. The HHI of the direct supply of goods and services is computed applying Eq. 3:

$$HHI_{direct\ demand} = \sum_{c=1}^n Y_c^2 \quad (3)$$

where Y_c is the direct demand from country c expressed as a percentage of the total demand being n the total number of countries involved. Similarly, the HHI of the total output is computed applying Eq. 4:

$$HHI_{total\ output} = \sum_{c=1}^N X_c^2 \quad (4)$$

Here, X_c is the share of the total output of country c (stemming from the MRIO analysis) and N here is the total number of countries and regions included in the MRIO table (i.e. WIOD table).

The interpretation of the value of this indicator is that the higher the concentration level (higher values of HHI), the lower the diversification. In market terms, values over 10,000 represent a monopoly situation. Here, instead of a market, we have the global international value chain composed by the countries and their economies (sectors) stimulated by the deployment of an energy investment.

The second metric, entropy (E), is a direct measure of diversity rather than concentration. Values of entropy are larger when the supply chain for the project is more diverse. The entropy metric has been used and studied as an indicator of diversity in several disciplines, from physics to ecology, and more recently to economics in publications of European Central Bank (Corsetti et al., 2019) and scientific literature (Teza et al., 2021, 2018), and environmental studies (Többen et al., 2018). Entropy is calculated according to eqs. 5 and 6.

$$E_{direct\ demand} = - \sum_{c=1}^n Y_c \cdot \log x_c \quad (5)$$

$$E_{total\ output} = - \sum_{c=1}^N X_c \cdot \log X_c \quad (6)$$

where x represents the demand and X the output share from the individual country c , n the total number of suppliers and N the total number

³ World Input-Output Database website: <http://www.wiod.org/home>

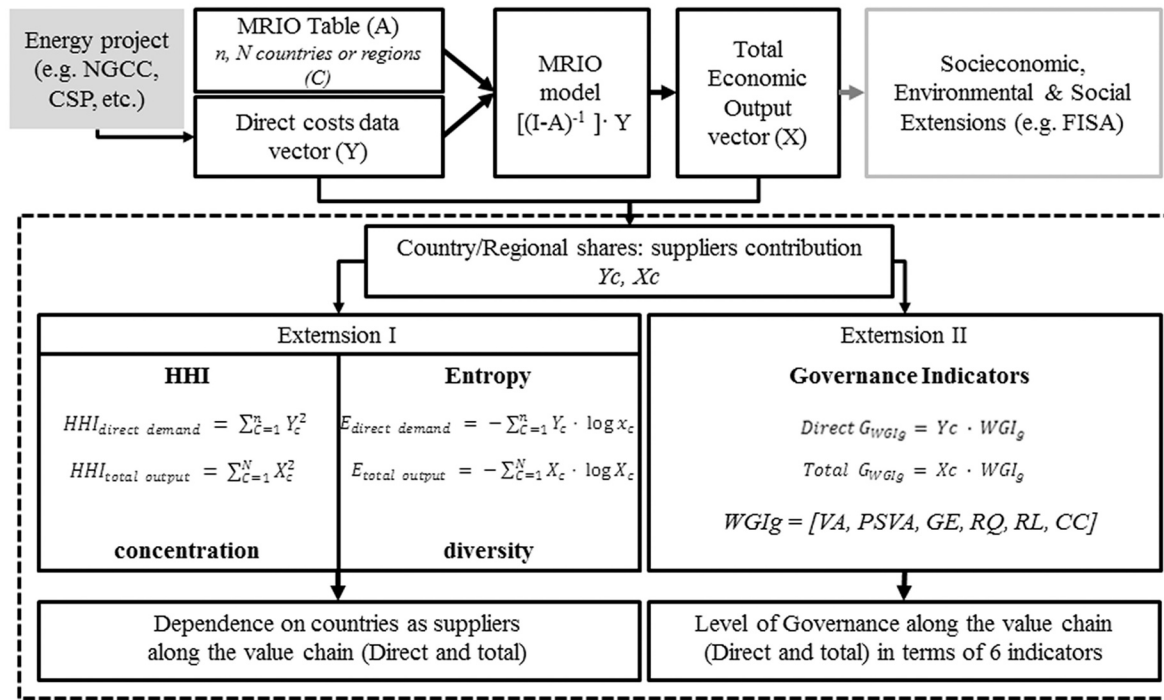


Fig. 1. Methodological scheme of the assessment proposed (discontinuous red line area) by extending MRIO model. HHI: Herfindahl-Hirschman Index; FISA framework developed by (Rodríguez-Serrano et al., 2017a). The six governance indicators correspond to the six Worldwide Governance Indicators (WGI) (Kaufmann et al., 2011; Kaufmann and Kraay, 2018). They are further discussed in the next subsections. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of countries and regions included in the MRIO table. If one country is the only supplier, then the index would reach a value of 0, and the higher the number of suppliers the higher the value of E . The maximum possible value of entropy (E_{max}) would be reached when the total possible suppliers, i.e. n or N countries, contribute with an equal share (of Y or X). Therefore, the closer the value of entropy ($E_{direct\ demand}$ or $E_{total\ output}$, in this case) is to the maximum value (E_{max}), the more diverse the value chain is.

It has been argued that none of these metrics measures disparity, understood as “the manner and degree in which the options differ from each other” (Lilliestam, 2013) between the different suppliers and then cannot capture the complete concept of diversity (Stirling, 2010; Stirling and Waxman, 1999). In this application of the HHI and E indexes, the different categories of suppliers are different countries (or regions that aggregate various countries). Disparity between these countries is not measured in the proposed indexes as the same HHI or E value can be obtained by any scenario with the same number of direct and indirect suppliers. However, it is not the same to depend on a group of for example 10 European suppliers than on a group of 10 developing countries. Therefore, results can be misleading for energy dependence analysis. To address this limitation, we introduce governance indicators described in the next section into the analysis.

2.3. Extension II: Governance assessment

For the second extension, we apply the governance criteria to assess the risk associated to exporting countries, as a quantitative proxy for political risks throughout the value chain. Governance is a term widely used but not always accurately. Different scholars have sought to define and clarify the term (Colebatch, 2017; Van Kersbergen and Van Waarden, 2004; Rhodes, 1996). Usually “good governance” includes features such as an efficient public system, an independent judiciary and legal framework to guarantee agreements; responsible administration of public funds; an independent public audit system, accountable to a representative legislature; integral respect for the law and human rights;

a pluralistic institutional structure, as well as a free press. In the practical definition provided by the World Bank Institute, governance is the traditions and institutions by which authority is exercised; that includes the processes of government selection, control and renewal, the capacity of government to design and apply policies effectively and the relationship of citizens and the state with the institutions that manage and regulate the economic and social dynamics (Kaufmann and Kraay, 2018).

Countries with strong institutions often have an enabling environment that facilitates private sector growth and foreign investments, and, in consequence produce valuable goods and services. These countries tend to be stable and experience stronger and more consistent growth, because they have an environment of low risk, controlled by the rule of law and an independent judiciary. Thus, depending on goods and services from countries with strong governance protects from risks associated with supply shortages or price volatility. It is important to note that this does not make countries immune to some kind of geopolitical risks, especially not exogenous risks, but the political value chain risks are much lower than in countries with weak institutions (Keping, 2018).

Some sources for these indicators are, among others, the Worldwide Governance Indicators (WGI) (Kaufmann et al., 2011; Kaufmann and Kraay, 2018), the CIRI Human Rights Dataset (Cingranelli et al., 2014), the Bertelsmann Stiftung’s Transformation Index (BTI) (Sabine Donner et al., 2018) or the WJP Rule of Law Index (Botero et al., 2018). Besides, there are other specialised indexes such as Resource Governance Index (Natural Resource Governance Institute, 2017) applied to resource governance. The bad or failing governance of exporters has been used in an *ex-post* analysis to identify whether the effectiveness of EU measures have improved the transparency in the extractive sector (Escobano et al., 2020). For our approach, the WGIs are the most suitable indicators because they are specifically oriented to governance gradation of countries, cover most countries and regions around the world and include key criteria such as the regulatory quality and rule of law, as well as the political stability or the accountability. WGI indicators are based on the methodology developed in the WGI project supported by the Knowledge for Change Program of the World Bank (Kaufmann et al.,

2011). The six composite WGI measures for 200 countries and territories over the period 1996–2018 are annually published. The WGIs are research datasets summarizing the quality of governance from the view of several sources (survey institutes, non-governmental and international organizations, and private firms).

From the impact assessment perspective, methodological developments in Life Cycle Assessment are considering aspects such as supply concentration and governance of producing countries (Mancini et al., 2013). However, Life Cycle Assessment methodology does not capture the indirect effects of the flows in the multiregional value chains. On the contrary, MRIO capture and quantifies those effects. Previous developments in MRIO literature handle the governance assessment differently. Rodríguez-Serrano et al. (Rodríguez-Serrano, 2017; Rodríguez-Serrano et al., 2017b, 2017a) assessed the governance using the SHDB for the social assessment. The governance category is assessed on the basis of Legal System and Corruption indicators calculated by combining methodologies (WGI, BTI, CIRI Human Rights, etc.) or by experts' judgments. Each country scores according to the ranked values of governance indicators (1, 2, 3, or 4, depending on quartile). However, the combination of different governance methodologies makes the analysis and interpretation quite complex. Besides, some difficulties could arise such as a lack of data for this indicator in the SHDB (Rodríguez-Serrano, 2017; Rodríguez-Serrano et al., 2017b, 2017a).

The WGI dataset provides information on governance values ranging from −2.5 (weak governance) to 2.5 (strong governance). One of the advantages of using WGI is the valuation of governance of each indicator and country in a fine-tune valuation. The WGI indicators are summarized in Table 1. A detailed description is provided in the supplementary data (SD).

The WGI allows for weighting the direct and indirect demand for G&S from each country according to the value of each indicator. The monetary value stemming from the MRIO analysis is multiplied by the indicator, resulting in a quantitative measure of governance.

By applying eq. 7, the governance level of the direct demand per each of the six governance indicator (*Direct G_{WGIg}*) is obtained.

$$\text{Direct } G_{WGIg} = Y_c \cdot WGI_g \quad (7)$$

where *WGI_g* is the governance value of each indicator for the six indicators analysed (*g* = VA, PSVA, GE, RQ, RL and CC) and *Y_c* is the demand vector coming from this specific country.

Similarly, total governance (*Total G_{WGIg}*) along the supply chain is obtained by applying eq. 8 using in this case the total output per country stemming from the MRIO analysis (*X_c*).

$$\text{Total } G_{WGIg} = X_c \cdot WGI_g \quad (8)$$

That means that the amount of monetary value of the demand (or total output) of each country is weighted by the governance score of this country. Due to the linear relationship, positive and high scores correspond to high levels of governance for each indicator and negative high scores will render very low levels of governance. For instance, if the deployment is associated to 1 million dollar of output in a country in a weak governance setting (e.g. a score −2 for voice and accountability (VA) indicator), the results is a value of −2 VA weighted million dollars.

These equations are applied independently for each indicator

avoiding aggregation. These results are not additive as they refer to different features of governance not necessarily additive and they are therefore analysed in isolation. Thus, the framework offers a way to provide a quantitative value of the endogenous risk along the supply chain in terms of six independent indicators of governance.

Results will show the presence (directly or indirectly) of each country in the value chain as well as its relevance (quantitative combination of the monetary contribution to the output per country and level of governance) for each governance indicator considered.

2.4. Application: CSP vs. NG power plants in Mexico

In order to validate and illustrate the method with an example, we apply it to two alternative energy technologies investments: a CSP power plant and natural gas combined cycle (NGCC) power plant. Mexico is a country with abundant solar resources for power production and a high dependence on natural gas imports for electricity generation. Given the growing natural gas and coal imports the country's dependence on NG for power generation has become a major concern (Alemán-Nava et al., 2014; International Renewable Energy Agency, 2015). Due to its fast growing economy, Mexico's energy demand expanding and currently accounts for around 20% of all energy use in Latin America (EY/GIZ. Alianza energética (BMW-SENER), 2018). On the one hand, there is a growing shift towards natural gas, mainly imported from the United States and to a lesser extent from other countries (in the form of liquefied natural gas). On the other hand, this growing demand trend allows for the increasing penetration of renewables into the power sector (Renkamp et al., 2017).

Thus, by applying the method to these case studies we are able to compare these two alternative energy investments in Mexico considering their supply risks. The direct demand for goods and services of both technologies was obtained from Rodríguez et al. (Rodríguez-Serrano, 2017; Rodríguez-Serrano et al., 2017a). These studies carried out a sustainability assessment of two technologies by estimating the environmental, economic, and social impacts of CSP and NGCC plants for electricity production in Mexico through an EMRIO model. The CSP plant consists of a hypothetical CSP power plant of 100 MW with 5 h storage.⁴ The NGCC plant is a 200 MW plant. The configuration details of these plants are summarized in the SD (Table B.1.1 and B.1.2). These plants are not fully comparable and then results will be normalized per total economic output and per total electricity production.

Additionally, as a sensitivity analysis two other scenarios varying the origin for the solar technology components have been analysed. One of them considers China as the country providing some components at a 20% lower cost ("CSP CHN Supply"), as it has been recently proposed in the research undertook for the deployment of CSP in Spain (Banacloche et al., 2020b) in the frame of the MUSTEC Project.⁵ Among those components would be parts of the heliostat field (mirrors, drives and a fraction of materials for pedestal and supports); a part of some components for the tower; the steam generation heat exchangers and equipment, as well as the steam turbine generator and the hot salt pump). Apart from those components which are supposed to come from Europe in the baseline scenario, the second sensitivity scenario considers that some of the solar components would be supplied from the European

Table 1
Worldwide Governance Indicators (WGI).

Indicator	Acronym
Voice and accountability	VA
Political stability and violence absence	PSVA
Government effectiveness	GE
Regulatory quality	RQ
Rule of law	RL
Control of corruption	CC

⁴ As of today, a new CSP plant could have another configuration than the one presented in Rodríguez-Serrano et al. (2017), as well as the value chain could have change in the last five years.

⁵ MUSTEC Project: <https://www.mustec.eu/>. Market uptake of Solar Thermal Electricity through Cooperation started in October 2017, and was funded by the EU Horizon 2020 program. MUSTEC aimed to explore and propose concrete solutions to overcome the various factors that hinder the deployment of concentrated solar power (CSP) projects in Southern Europe capable of supplying renewable electricity on demand to Central and Northern European countries.

market (“CSP EUR Supply”) instead of from USA. Specifically, in this scenario we assume that the origin of the heliostat field components (mirrors, drives and a fraction of materials for pedestal and supports), the steam generation heat exchangers and equipment, as well as the steam turbine generator, would be from Germany; and some components for the central receiver and the hot salt pump would be supplied by Spain. In both sensitivity cases, we assume Chile as direct supplier of molten salts (instead of the Netherlands considered in the original reference).

Besides the pure economics and origin of the plant, technological alternatives and innovations in progress would have impact on costs vector, and so that, on the value chain and results of the analysis. For instance, improvements on heat absorption and transfer (Kang et al., 2018) or in the storage (Achkar and El Fadar, 2020; Palacios et al., 2020; Py et al., 2017), as well as the implementation new configurations of CSP plants (Islam et al., 2018; Loureiro et al., 2019).

2.4.1. Case study description and costs data

The main technical characteristics of the power plants studied are shown in Table 2. Nowadays there are a wide range of commercial CSP systems (Fernández et al., 2019) implemented around the world. Here we have used as case study a technically and mature CSP technology.

The direct cost distribution in the investment phase and the operation and maintenance phase (O&M) is different between technologies. While the NG is strongly dependant on supply throughout its whole lifetime because of the continuous demand for fuel, the CSP main costs are concentrated in the investment phase (Fig. 2).

The costs of the different components in the investment and O&M stages per component of all the scenarios (baseline CSP and NG, and sensitivity scenarios, of CSP Chinese or European supply) are detailed in the SD (Table B.2.1 to B.2.4) as well as the assumed supplier.

The demand cost vectors (Y) are described in Table B.3 of the SD. The monetary values for Y vectors have been updated to US\$2021 using the inflation rate. The costs of the transport of components vary depending on the sectors and country based on the percentage of output of the WIOD table (matrix A). WIOD database does not include Chile, so we assimilate that with the ROW region in order to calculate the output (X). While WIOD does not, WGI database does include values of governance indicators for Chile, so we use this value for the input and output governance analysis of the supply from Chile (sector chemicals and chemicals products). For the rest of output of ROW, since WGI database has data per country, values of governance indicators have been calculated (average of values of each WGI indicator of the countries which are not in WIOD). In the case of NG supply, all the components' supply origin are assumed to be USA, Germany and Mexico based on the original data from (Rodríguez-Serrano, 2017; Rodríguez-Serrano et al., 2017b).

The contribution of the different suppliers (countries) to the total direct cost in the different scenarios is depicted in the Fig. 3. A higher detailed di contribution to the direct demand (Y) from the direct suppliers by stage (investment or O&M) is graphically depicted in the section C of the SD.

Table 2
Main technical data of the power plants.

Technical parameter	CSP plant	NG plant	Unit
Power	100	200	MW
Annual power production	395,700	1,230,000	MWh/year
Energy generated along the lifespan	11,871	36,900	GWh
Technology	Molten salts central receiver/5 h storage Hybrid dry-wet	Natural Gas Cycle Combined (NGCC)	
Location	Mexico (DNI > 2600 kWh/m ² /year)	Mexico	

3. Results and discussion

The results, and corresponding discussion, have been split in three sub-sections according to the different aspects and level of analysis undertaken. Dependence analysis results are included in Table 3 where the results for the metrics HHI and E (for the direct demand and for the total output) are shown. Also, the ratios $E_{\text{direct demand}}/E_{\text{max}}$ and $E_{\text{total output}}/E_{\text{max}}$ are presented. The governance results are sub-divided by whole value chains analysis under study and the disaggregation by supplier. First, the results of whole value chains analysis are shown in radar graphs (each axis represents the investment weighted by each one of the six indicators) allowing the comparison between alternatives and indicators (Fig. 4 and Fig. 5). And second, the disaggregated results are presented in a combined graph, where points show the value of each indicator per each alternative and bars show the quantitative contribution of the main counties or regions (in colours), as well as the sign of this contribution (Fig. 6).

3.1. Dependence analysis results

Table 3 shows HHI results for the two analysed power plants and the two sensitivity scenarios, distinguishing the direct, indirect and total demand for goods and services. Results show a lower diversification of the demand in the case of the NG plant project. The NG plant has a HHI value of 5314 for total production of goods and services and 8668 for direct demand, a value that is very close to the “monopoly” situation. In the base case of CSP, the HHI values are 3802 for total production and 5853 for direct demand. As expected, a lower dependence values of total demand compared to those of direct demand is obtained as the countries providing intermediates in the supply chain are also considered. Under our base case assumptions, just 4 countries in the case of CSP and 3 countries in the case of NGCC are direct suppliers, being distributed between Mexico (MEX), the USA, Germany (DEU), and the Netherlands (NLD).

The sensitivity scenarios, the CSP CHN and the CSP EUR supply scenarios, have six direct suppliers since Chile (CHL) is added as molten salts direct supplier, and China (CHN) and Spain (ESP) as some solar components producer. The HHI values of direct demand in these scenarios are a 15% and 25% lower than the base case respectively. In the case of total demand of goods and services, the HHI values are a 19% and 31% lower than the base case.

Similarly, to the HHI, E values reveal a higher diversification of the CSP plant supply chain (Table 3) with higher values of entropy in its value chain. There is not a categorisation system by E values in order to define a market as ‘highly concentrated’, nor is there a threshold below which there is no concern (Brown, 2018). Nevertheless, the E values can be compared with the maximum possible entropy (E_{max}). The value of E for CSP is closer to the maximum than for NG, implying a more diversified system. Percentages reflect the relevance of the E values with respect to the maximum E that would be the highest diversification. Direct effects are more diverse in the case of the CSP plant (55.6% to 60%) than the NG plant (26.1%), which means that CSP is closer than NG to the maximum of diversification. Also, CSP total effect shows higher diversification (40.6%–51% for CSP and 31.6% for NG).

3.2. Governance analysis: Direct and total value chain

The governance analysis results are shown in Fig. 4, Fig. 5 and Fig. 6. The first figure illustrates the comparison in terms of governance levels between the two case studies, NGCC (NG, blue line) and CSP (CSP, red line), associated to the direct demand on the left (a) and the total production of goods and services (b) on the right. In both cases, CSP stimulates economies with a higher level of governance considering all the indicators. Focusing on the effects due to the direct demand (on the left, Fig. 4.a), the largest difference is found for the Rule of Law (RL) indicator and the lowest for the indicator related to Voice and Accountability

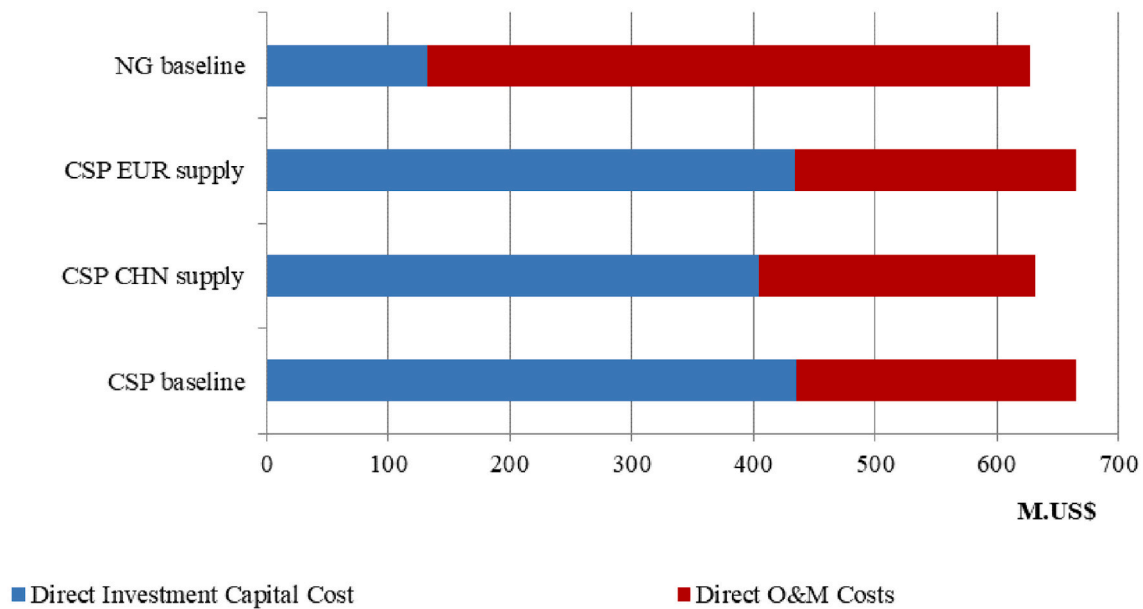


Fig. 2. Direct costs distribution of CSP and NG plants by investment and Operation and Maintenance (O&M) (Millions of US\$).

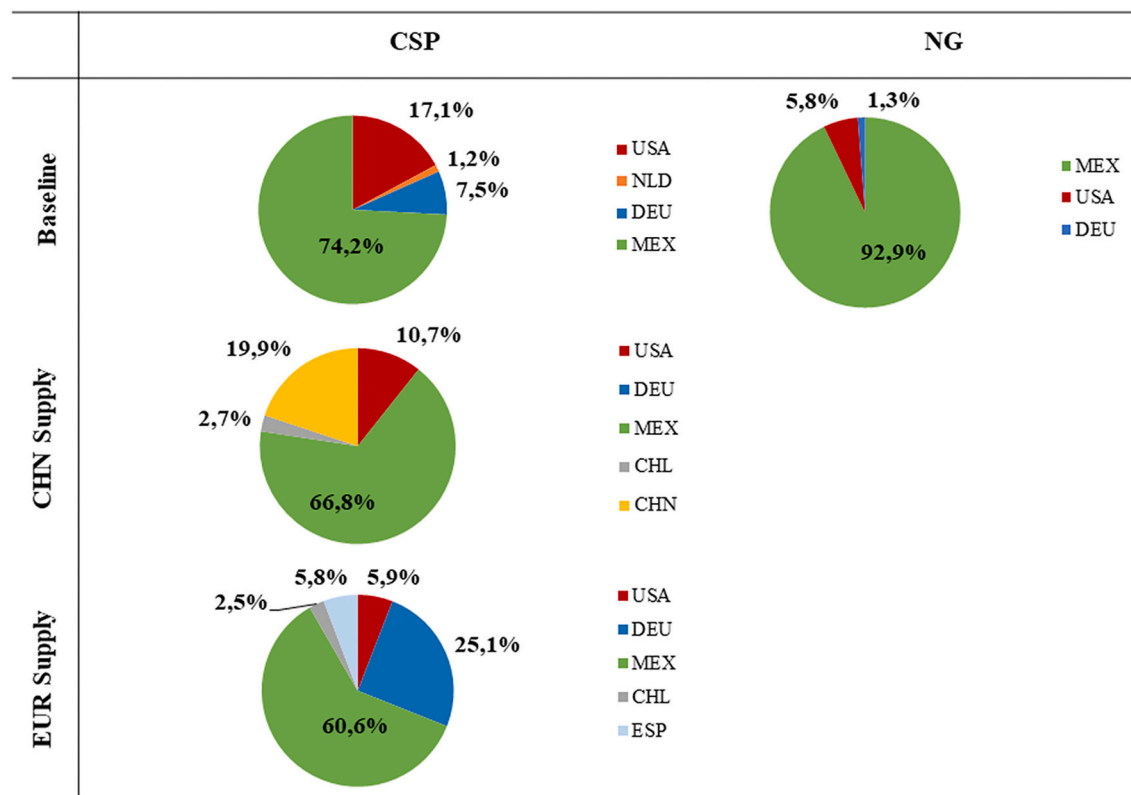


Fig. 3. Direct costs share by suppliers in each scenario. Baseline scenarios of CSP and NG (Rodríguez-Serrano, 2017) and the CSP sensitivity scenarios.

(VA). When the analysis considers the total effects (direct and indirect, on the right of Fig. 4b) the largest difference between both case studies is found for control of corruption (CC) with NG value chain scoring very negatively. When considering total effects, indicators related to Violence Absence (PSVA) are also considerably worsened in the case of NG while the other indicators are improved or remain at the same level. In the case of CSP, almost all of the indicators increase their value.

The analysis depicted in allows the comparison of both technologies

showing results per unit of economic output or per MWh of electricity produced. On the left-hand side of Fig. 5, the total Governance Effects normalized by the total costs are depicted and on the right-hand side the results per MWh of electricity produced along the life of the plant are shown. Fig. 4b) and Fig. 5a) are very similar in shape and relative scores of both technologies, just the magnitude of the indicators (axis) and the unit (the division by total costs made the result non-dimensional) are different. The explanation is that the total costs of both plants are

Table 3

HHI and Entropy (E) values of the value chain involved in the CSP scenarios and NG plants deployment. $E_{\max}$ is the maximum possible value of the entropy for the sample (number of suppliers). $E_{\max}$ is the higher possible value of E.

	CSP baseline	CSP CHN supply	CSP EUR Supply	NG baseline
No. Direct suppliers	4	6	6	3
No. Total suppliers along the value chain considered	41 (all the countries/regions in WIOD)			
HHI direct demand	5853	4973	4384	8668
HHI total output	3802	3092	2616	5314
E Direct demand	0.335	0.403	0.467	0.126
$E_{\max}$ (Direct Demand)	0.602	0.775	0.778	0.477
E Direct demand/ $E_{\max}$	55.6%	51.7%	60.0%	26.1%
E total output	0.655	0.678	0.823	0.509
$E_{\max}$ (Total output)	1.612			
E total output/ $E_{\max}$	40.6%	42.0%	51.0%	31.6%

similar, although the structure is completely different. The direct investment costs of the CSP plant are quite higher than those of the NGCC plant, but the direct O&M costs of CSP are lower, so considering total amounts both have a similar value (shown in Fig. 2).

On the other hand, Fig. 5b) shows very different results in the shape of the figure and in the relative scores for both technologies. The use of energy units as a reference allows the comparison of the lack of governance risks in the supply chain per unit of service provided by both projects. In terms of production, CSP reaches better levels of governance in the indicators related to Voice and accountability (VA), Government Effectiveness (GE), Regulatory Quality (RQ) and Rule of Law (RL), and slightly better for Control of Corruption (CC); but it scores worse in the indicator related to Political Stability and Absence of Violence (PSVA).

3.3. Governance analysis: Contribution by indicators and origin

The analysis displayed in Fig. 6 shows the direct governance analysis results (upper, Fig. 6a)) and the total governance (Fig. 6b)) along the value chain of the case studies split by country. The values have also been normalized to energy produced (MWh) along the lifetime of the plants to allow a meaningful comparison. Fig. 6a) shows the direct governance results in the case studies split by country. The values have

also been normalized to energy produced (MWh) along the lifetime of the plants to allow a meaningful comparison. Apart from the direct suppliers of goods and services- México, Germany, the Netherlands, and the USA in the base case and China and Spain in the additional sensitivity scenarios- other countries such as Canada or Japan, contribute to the aggregate results. The direct CSP Chinese supply scenario (CSP CHN supply) assessment reaches the lowest value for most governance indicators except for Government effectiveness (GE) and Regulatory quality (RQ), for which NGCC scenario would be the worst. The scenario fostering the European supply for the solar components gets the best results for all the indicators, except for political stability and absence of violence (PSVA), for which NG power plant gets a better result. The reason behind this result is that the much higher direct domestic supply (Mexico, in green) counteracts the positive values of the governance supply from DEU and ESP. In fact, results show that domestic (Mexican) contribution to the investments is a major source of negative governance values in most of the indicators. It can be argued that these internal effects cannot be considered a risk for Mexico and, therefore, the results cannot be used to exclude investments in the country that would in turn boost economic development. However, the recognition of these endogenous risks is important as disregarding them can result in unintended negative consequences of well-intentioned investment policies.

The analysis shown in Fig. 6b) corresponds to the total governance in the case studies and the distribution of the indicators contribution among countries along the whole value chain, normalized to energy produced (MWh) along the lifetime of the plants to allow the comparison between technologies. Some of the 40 countries with less than 5% of the total output have been aggregated in the ROW region to make the interpretation easier. We can see that, beyond the direct suppliers of goods and services to the power plants, other countries that are indirect suppliers in the value chain arise. In the CSP and NGCC base case scenarios in which CHN is not a direct supplier, this country has a relevant role for the assessment of some governance indicators along the value chain. Others, as Canada (CAN) and Japan (JPN) also affect the governance analysis of the value chain (indirect contribution to the supply chain higher than 5%). In general, the global result of each indicator (depicted by a rhombus in Fig. 6) shows important differences between CSP plants scenarios, and between them and those of NGCC.

Comparing the base case scenarios, CSP plants reach higher values of governance for all categories than NGCC except for political stability

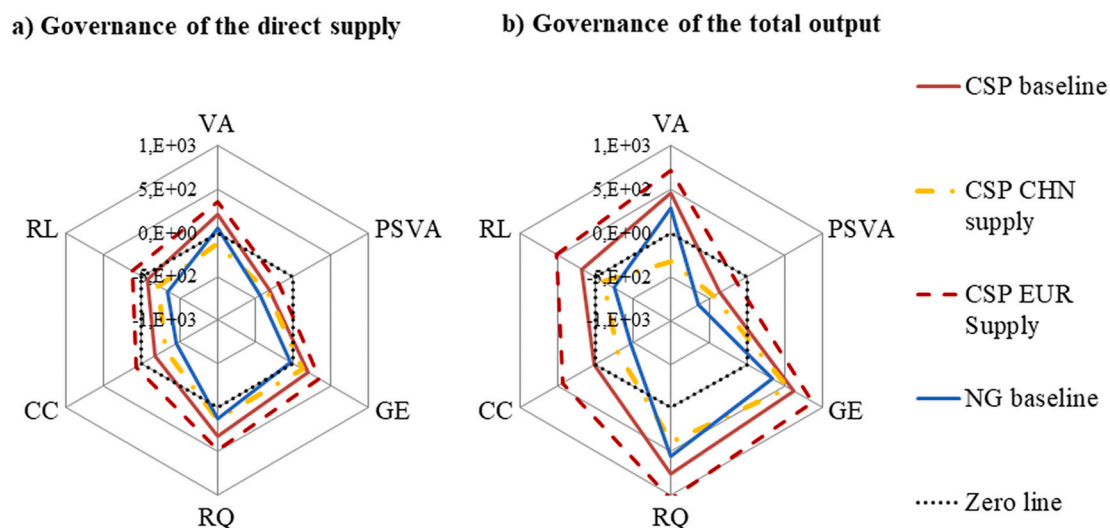


Fig. 4. Governance Analysis Results of the case studies: Natural Gas (NG, blue line) and Concentrated Solar Power (CSP base case) marked with continuous red line; CSP with solar components supply from China (CHN), marked with dash-point yellow line; CSP with solar components supply from Europe (EUR), marked with discontinuous red line, associated to the direct demand on the left (a) and to the total production of G&S (b) on the right. Unit: Millions of US\$*Indicator. Axis range is from 1000 to -1000 Millions of US\$*Indicator. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

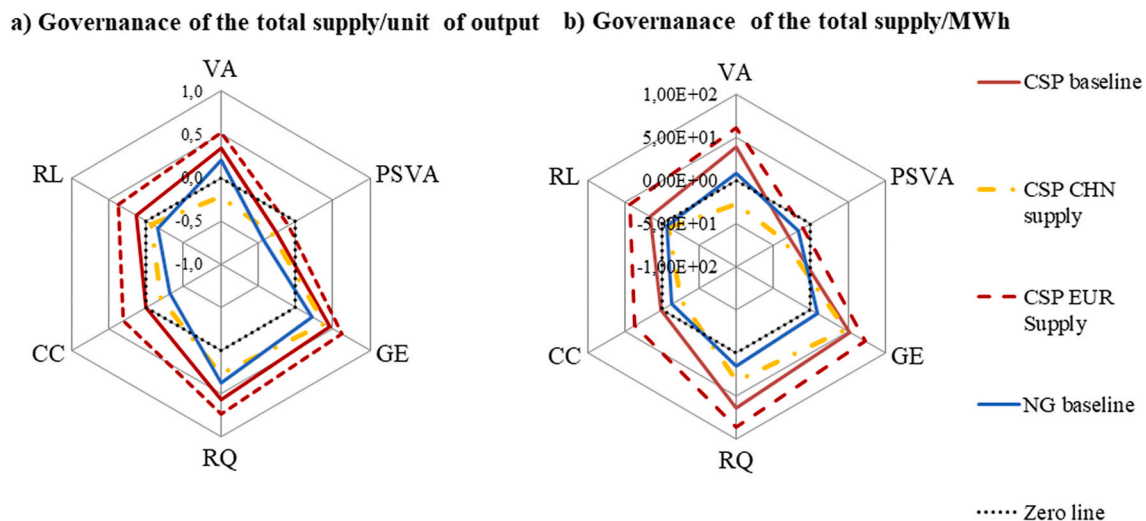


Fig. 5. Governance analysis results of the case studies: Natural Gas (NG, blue line) and Concentrated Solar Power (CSP, red line), associated to the total effect related to the total costs (a) and the total cost effect related to the power production (b) on the right. Units: Figure a) adimensional; Figure b) US\$/Indicator/MWh. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and violence absence (PSVA). The reason behind these results is again the higher contribution to the endogenous supply from Mexico in the CSP plant in combination with a poor WGIs score for this country. For Control of Corruption (CC) and PSVA indicators, Mexico has a low score (-0.65 ± 0.21 and -0.93 ± 0.12 , respectively), being even ranked into percentile 25 - or less - among all countries. The negative role of Mexico in CSP governance is relevant, but not sufficient to create a negative sign for all categories. Most of the governance categories per MWh for CSP are positive and higher than NG. Results for CSP's high governance values can be explained by the relevant contribution of the USA, and Germany as main drivers to increase the governance effects. Also, Japan and other European countries have a significant, albeit small, contribution that is negligible in the case of the NGCC plant. In the case of NGCC, four of the indicators have negative values also mainly motivated by the negative effects of Mexico in these indicators. In spite that in this scenario China is not a direct supplier, the role of China (CHN, yellow bar in Fig. 6) is remarkable in the Voice and Accountability (VA) indicator for CSP, even more than Mexico, and highly contributing to the negative value of governance. The Chinese sectors that worsen the VA indicator are, by order of share, "Electrical and Optical Equipment", "Basic Metals and Fabricated Metal", "Chemicals and Chemical Products" and "Mining and Quarrying".

As for the sensitivity scenarios, the results show relevant differences. The supply chain assessment of the CSP EUR supply scenario reaches the best results of governance for all the indicators among all scenarios. However, the CSP CHN supply scenario reaches lower results than NGCC in Voice and Accountability (VA), Political Stability (PSVA), Control of Corruption and slightly lower in Rule of Law (RL) while for the indicators Government effectiveness (GE) and Regulatory Quality (RQ), NGCC scores worse than the CSP CHN (and all the CSP scenarios).

The proposed method provides a quantitative measure not only of the risks associated with a direct supplier country, but also allows the identification of the countries which potentially can cause geopolitical risks linked to the indirect contribution to the supply chain, and which is the sector involved in the demand. In this case, results show that China, even as indirect supplier, has a relevant role. These results would be in line with the emerging post-COVID-19 concerns with long supply chains increasing technologies' vulnerability when having substantial Chinese content, which exceeds the scope of this research (EPRS, 2020; Willy, 2020).

The proposed assessment method is not exempt of limitations. First, the static nature of the analysis and the long time-lag in updating the IO

data tables is a common limitation of MRIO-based methods. Additionally, implicit limitations of the MRIO methodology do not allow for the analysis of dynamic scenarios with individual changes in the indirect demand. The MRIO analysis is static since MRIO tables and databases depicts the economy at a certain point in time (in this case, the assessment is based on the 2011 WIOD Input-Output table). Others resort to methodologies such as computable general equilibrium models (CGE) (Bekkers et al., 2019; Caceres et al., 2019; Itakura, 2019) or combine MRIO and CGE (Böhringer et al., 2016), but adding other limitations related to the uncertainties of assumptions. Second, the proposed metrics for dependence assumes that high diversity of suppliers always means low vulnerability. Finally, some geopolitics aspects –such as exogenous geopolitical risks associated with unstable neighbours or supranational influences on governance– are not captured by the assessment proposed. For instance, we cannot assess the fact that a country can have good governance at home but have low governance scored neighbours or being a rogue state (Russia) prone to conflict, or a global power (USA, China) with a power politics agenda. For example, in the case of the USA as a supplier of CSP plants in Mexico, the uncertainties as regards supply could emerge from the USA exerting power politics, and less probably from causes associated with the USA's governance standards. Future research lines will looking for incorporating in a somehow some exogenous geopolitical aspects (e.g. spatial statistical tools such as nearest neighbour analysis of governance or clustered analysis (Seyedan and Mafakheri, 2020).

Despite its limitations, the proposed method contributes to enlarge the existing body of knowledge aimed at considering and quantitatively assess geopolitical aspects and inform decision makers. In this sense, a future line of research is opened towards a deeper development of methodological approaches to completely combined formulation of an indicator including a diversification metric such as HHI or E with governance indicators to the most of MRIO analysis results. In the present work, we avoid the complete combination of governance metrics and indicators into a single aggregate quantitative value in order to see the advantages of the analysis of both aspects, avoiding a complex and difficult to interpret composite metric. However, the challenge of the further research is to find a manner to providing meaningful results without losing the clarity and the comparability of the results.

4. Conclusions

Our research quantifies the diversification of supply and the

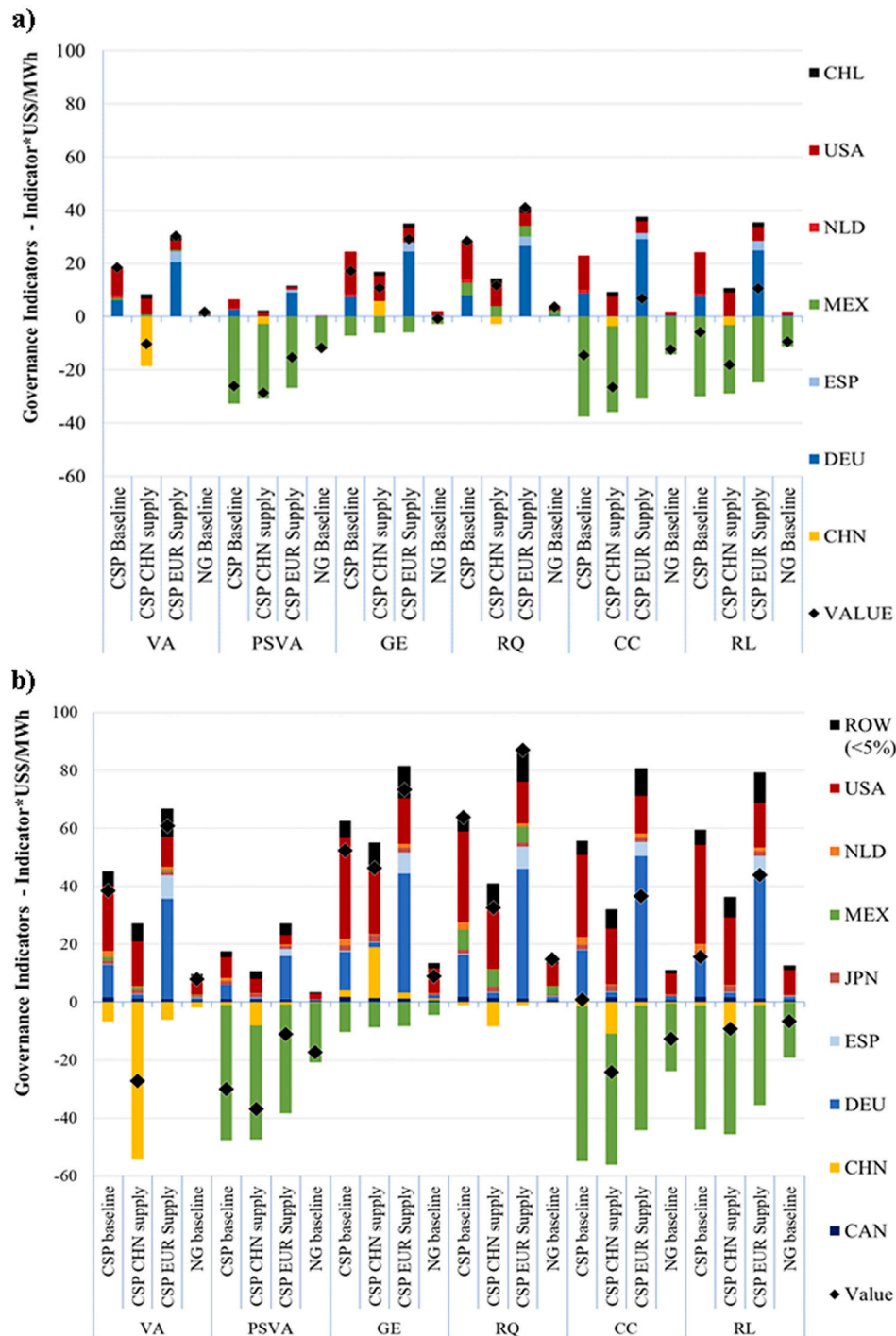


Fig. 6. Governance analysis results per study case, indicator and country; a) Direct Supply b) Total value chain supply results per study case, indicator and country. Included those countries whose contribution is greater than the 5% of the contribution to any of the indicators. The rest of the countries or regions have a contribution lower than 5% and are included in ROW.

governance levels along the value chain of two alternative energy investments in Mexico (NGCC and a CSP power plants), by using a set of indicators which allow to point out potential geopolitical risks. The results showed that the NGCC supply chain has a lower level of supplier diversification than that of CSP and a generally higher level of geopolitical risk. This is because NGCC suppliers along the value chain score worse in most of the indicators. This implies that the imports required to produce each MWh 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 NGCC. In consequence, our results suggest

that CSP deployment in Mexico would not only increase the renewable power production reducing the carbon emissions of the energy sector, but could also have a lower associated geopolitical supply risk. However, we have also show the important detrimental role that Mexico's low governance score plays in the total CSP related results. It does not necessarily mean that importing from abroad is better than domestic supply, but it calls for CSP support policies that include mitigation measures to address the identified risks.

The sensitivity analysis conducted for the CSP scenario that considers two alternative set of providers for some key components of the solar

plants revealed substantial differences. While CSP plant with European supply reaches quite high levels of governance, Chinese value chain supply present the lowest values among the CSP scenarios and also worse results than NGCC for some of the governance indicators. In consequence, the method proposed have allowed the identification of hidden geopolitical risks that would otherwise have gone unnoticed.

Methodologically, our main contribution is the extension of the MRIO method to consider geopolitical aspects measured by the governance and diversification along the supply chain. Some methodological limitations have been identified, though. The main one is associated to the static nature of the input-output analysis. Another important limitation is the implicit simplification that assumes that a high diversity of suppliers always means low vulnerability. Notwithstanding these limitations, the proposed method can be used to support the decision making process of both public sector policy makers and private sector investors in deciding between alternatives identifying the geopolitical weakness along the value chain. Furthermore, this method may also be used by regulators to put in place the necessary measures to mitigate the identified risks.

Declaration of Competing Interest

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

Additional Information. Supplementary data

Information on WGIs (Part A), technical and detailed cost data (Part B), and countries direct contribution to each scenario (Part C). Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eiar.2021.106708>.

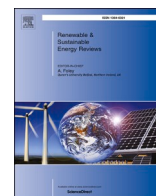
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2. RESULT 2: ASSESSING THE SUSTAINABILITY IMPACTS OF CONCENTRATED SOLAR POWER DEPLOYMENT IN EUROPE IN THE CONTEXT OF GLOBAL VALUE CHAINS

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Assessing the sustainability impacts of concentrated solar power deployment in Europe in the context of global value chains

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ABSTRACT

In the context of the European Green Deal and the Recovery Plan for Europe, CSP can play its role, by providing dispatchable and flexible energy when other renewable technologies cannot. The aim of this paper is to identify the potential socioeconomic, social and environmental impacts associated to the future deployment of CSP projects in Spain, taking into account the global value chain. Based on an extended multiregional input-output model developed by the authors, this paper identifies the country and sector-origin of nine sustainability indicators for the two dominant CSP technologies (parabolic trough and central receiver). The research considers the deployment of a 200 MW CSP power plant in Spain to compare the sustainability impacts of these two technologies under three different scenarios regarding the country-origin of the main components. The results show that central receivers have more positive economic impacts, both in terms of value added and employment creation, and lower negative environmental and social impacts than the parabolic trough alternative. The economic and environmental impacts of the CSP deployed in Spain depend on the origin of components, with the highest negative environmental impacts occurring when the components come from China and the lowest when they come from Germany. The same occurs for the social impacts and supply risks, which are lower when Germany supplies the main components. The scenario in which Spain supplies all the components performs better than the Chinese supply scenario in terms of social risks, whereas no major differences among them were found on supply risks.

Abbreviations: CC, Control of Corruption; CN, China; CR, Central receiver technology; CR_S1, Central receiver CSP plant under S1 scenario supply of components; CR_S2, Central receiver CSP plant under S2 scenario supply of components; CR_S3, Central receiver CSP plant under S3 scenario supply of components; CSP, Concentrated solar Power; DE, Germany; DG_{WGIEX}, Combined governance and diversity indicator for the indicator *i* over the total production (*x*) or the impact (silver extraction); DNI, Direct Normal Irradiation; E, Entropy; EMRIO, Extended multiregional input-output; ES, Spain; EU, European Union; EUR, Euros; F, Total sustainability impact vector (kg. of CO₂, employees, etc.); *f*, Impact vector (e.g. employees/EUR or kg of pollutants/EUR); FISA, Framework for Integrated Sustainability Assessment; FTE, Full-time equivalent; g CO₂ eq, Gram of carbon dioxide equivalent; GE, Government Effectiveness; Gg, Gigagrammes; GHG, Greenhouse gases; GVCs, Global value chains; GW, Gigawatts; HTF, Heat transfer fluid; ICIO-OECD, OECD Inter-Country Input-Output; IOA, Input-Output analysis; IOTs, input-output tables; kg. of CO₂, Kilogram of carbon dioxide equivalent; kWh, Kilowatt-hour; l, Litre; M.EUR, Million euros; M.WH, Million of working hours; m², Square meter; Mg, Megagram; mg, Miligram; Mm³, Millions of cubic meters; MRIO, Multiregional Input-Output analysis; MRIOTs, Multiregional Input-Output Tables; Mt, Megatons; MW, Megawatt; n.e.c., Not elsewhere classified; NECP, Spanish National Energy and Climate Integrated Plan; O&M, Operation and Maintenance; OECD, Organisation for Economic Cooperation and Development; PEF, Product environmental footprint; PSNV, Political Stability and No violence; PT, Parabolic trough; PT_S1, Parabolic through CSP plant under S1 scenario supply of components; PT_S2, Parabolic through CSP plant under S2 scenario supply of components; PT_S3, Parabolic through CSP plant under S3 scenario supply of components; PV, Photovoltaics; *P_{SC}*, Share of contribution of each supplier (countries or regions) of the sample to the total production or the total impact; R&D, Research and Development; RES, Renewable energy sources; REU, Rest of Europe; RL, Rule of Law; ROW, Rest of the World; RQ, Regulatory Quality; S1, Parabolic trough under S1 scenario supply of components; S2, Parabolic trough under S2 scenario supply of components; S3, Parabolic trough under S3 scenario supply of components; SAM, System Advisor Model; SDG, Sustainable Development Goals; SHDB, Social Hotspot Database; SI, Supplementary information; VA, Voice and Accountability; WGI, Worldwide Governance Indicators; WGI_{ic}, Governance value of each indicator for the six indicators analysed (*i* = VA, PSVA, GE, RQ, RL and CC) for the country or region *c*; WH, Working hours; WL, Rest of Latin America; *x*, total production; *y*, and the demand; *y_{CSP}*, Cost vector for each stage (investment or O&M); (*I*-A)⁻¹, Leontief inverse matrix.

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1. Introduction

Challenging times due to the coronavirus crisis are faced by countries all over the world, including those in the European Union (EU). The economic recession brought obvious negative economic impacts, particularly in terms of employment destruction and a subsequent increase in poverty [1], especially in countries where the pandemic hit harder, such as Spain and Italy [2]. Stimuli have been deployed to overcome the situation with the Recovery Plan for Europe [3]. Meanwhile, the European Green Deal plans to fight against climate change aspiring to be a neutral continent by 2050, through investing in environmentally-friendly technologies and decarbonizing the energy sector [4]. The EU targets for the energy transition require an increasing deployment of renewable energy sources (RES). This deployment can be understood as green investments that reduce greenhouse gases (GHG) emissions. Both the Recovery Plan and the Green Deal seem to be consistent with renewables deployment, since they have intrinsic and inevitable impacts in the economy, society, and the environment.

It is worth considering whether RES may play an important role to overcome short, medium and long-term issues that are defining the European reality nowadays considering renewable technologies constraints in terms of dispatchability that affects the energy systems stability. Many energy scenarios are built including storage options, hydrogen and conventional sources with carbon capture, storage and use [5,6], which complement fast and massive RES deployment as the solution to climate change and employment in the short term. In this sense, the deployment of Concentrating Solar Power with storage (CSP) is a plausible alternative due to its virtues related to dispatchability and flexibility, not found with other RES [7]. By providing this flexibility, CSP can support the penetration of higher shares of variable renewable technologies in the European energy system [8]. This technology still shows higher generation costs compared to other renewable alternatives [9]. However, remarkable breakthroughs in the past years may bring this technology back to the current scenario [10,11], complementing existing solar photovoltaics (PV) or wind, by storing thermal power during daylight and providing electricity at night and flattening the duck curve [12]. Besides, when comparing the cost of dispatchable CSP and PV with storage, distinct niches for both technologies remain: PV plus batteries for short storage durations and CSP plus thermal storage for longer ones [13], which confirms that CSP can have a niche in the future European electricity mix [14]. In fact, the European CSP industry has a leading role in the CSP sector both in terms of capacity installed in Europe and market share in other regions [15].

CSP technology remains attractive in regions endowed with sufficient direct normal irradiance (DNI) such as those near or included in the Sun Belt [16]. In Europe, countries such as Italy, Greece or Spain are potential CSP electricity producers. Indeed, Spain has been a referent in this technology [17] with more than 2 GW deployed in the country during the last two decades and a 37.6% of the overall CSP deployment worldwide [18]. Although the Spanish CSP industry has declined in the last years [19], the current Spanish National Energy and Climate Integrated Plan (NECP) envisages 5 GW of new CSP capacity with storage in the next decade [20].

Considering that CSP could be promoted in Europe, additional installed capacity will have positive or negative impacts on the economy, society and the environment, or trigger higher or lower energy supply dependence from non-European economies. Components will be produced, intermediate inputs (both domestic and imported) will be required, commodities will be extracted and personnel will be necessary to undertake these activities. In a world where the production process is determined by the so-called global value chains (GVCs), identifying where (which countries and sectors) impacts (value added, employment, GHG emissions, etc.) are being generated can be useful to design appropriate environmental, energy and industrial policies. For example, the penetration of China as a potential supplier for the CSP industry [19] may displace part of the economic benefits outside Europe.

In general, deploying power plants is expected to generate employment and economic growth across many sectors and countries. It would also imply abating GHG emissions once the new facilities are fully deployed. However, the manufacturing, construction, and installation stages are likely to impact the environment and society in many respects. All along the production process up to the final installation, greenhouse gases will be emitted, water and mineral resources will be consumed, and the risk of negative social impacts could be increased. Due to the existence of GVCs, it is likely that unfair wages would be paid somewhere, and children would be exploited in some economic activities. These positive and negative environmental and social risks along the value chain should be accounted for when considering different energy technology alternatives. Thus, the analysis of the sustainability impacts of projects needs to rely on a methodology which considers the different dimensions of sustainability [21].

In this sense, Input-Output analysis (IOA), and the global version, Multiregional Input-Output analysis (MRIO) are able to capture the direct and indirect impacts associated to GVCs. These tools have become widely-used methodologies to measure the total, direct and indirect, impacts of energy investments [22,23]. Most IOA studies on RES investments have focused on employment [24–26]. Research on wider sustainability impacts of renewables and decarbonisation policies can be found in the literature [27–30]. In the case of CSP, IOA has also been used to assess the impacts on employment [31], other socioeconomic and environmental effects [32], and also the endogenous geopolitical risks all along the value chain [33]. An extended multiregional input-output (EMRIO) based assessment (named Framework for Integrated Sustainability Assessment (FISA)) that covers the three dimensions of sustainability was proposed by Ref. [34] for the analysis of CSP deployment in Mexico. Also in this line, the recent work [35] is focused on the assessment of employment and carbon intensities of CSP deployment considering China's National Development and Reform Commission (NDRC) and the International Energy Agency (IEA) projections under the MRIO based triple-bottom line approach.

Other papers have analysed the sustainability implications of CSP deployment using multi-criteria analysis for the comparison between renewable energy projects by including different criteria calculated individually and lately scored, and in some cases aggregated and weighted to build a final global score. Some authors undertaking CSP assessments use a short set of indicators representing the criteria considered [36,37], whereas others propose a wider approach with sustainability pillars, considering several methods and indicators to evaluate each criterion of sustainability [38]. These last ones carried out a deep review on the literature on indicators and classified those in five pillars, covering a wide-range of indicators: technical, economic, social, environmental, and risk.

This paper contributes to the scientific evidence of the sustainability implications of CSP by assessing the potential socioeconomic, social and environmental sustainability impacts while also addressing the supply risks implications associated to the future deployment of CSP projects in Spain, taking into account the CSP global value chain. For that, the research departs from the FISA framework [34], and enhance it to also consider supply risks along the value chain. Then, the analytical framework to CSP deployment in Spain is applied considering the two most popular CSP technological designs, parabolic through (PT) and central receiver (CR)¹, which jointly account for over 95% of total installed CSP capacity worldwide. Furthermore, considering the current market of component manufacturing, different alternative scenarios of country-origin for the supply of key components are assessed (Pure Spanish Investment, European Alliance with Germany, and Chinese supply). These scenarios are compatible with the projections and future trends of CSP in the world [39].

¹ An explanation of both CSP technologies used for scenario assessment is included in the Supplementary Information (SI), Part A.

The paper is structured as follows: Section 2 describes the methodology. The main results are provided and discussed in Section 3. Section 4 concludes.

2. Materials and methods

2.1. EMRIO model

The methodology followed in this work is based on input-output analysis (IOA) [40]. It is based on symmetrical tables called input-output tables² (IOTs), which consist of the inputs required to produce a unit of output in each economic sector. The IOTs comprise two main components, the inter-industry flows (or transaction matrix), which describes the flows from a sector to the rest of sectors, and the final demand. Intermediate goods and services are those which are further processed by other sectors. Therefore, total production (x) can be expressed as a function of demand as follows:

$$x = (I - A)^{-1}y \quad (1)$$

Where $(I - A)^{-1}$ is the Leontief inverse matrix, or the multiplier matrix, that expresses the total production (direct and indirect) of each sector required to satisfy the final demand and y is the final demand vector. The multiplier effect is defined as the ratio between the total production (x) and the demand (y) and can be seen as the impact that an increase in final demand has on total production. When various regions or countries around the world are considered, the change in the demand of goods and services produced in a country from an investment done in another country can be estimated by using Multiregional Input-Output Tables (MRIOTs) [41]. Considering this IOA model, if the final demand vector y provided by the MRIOT that describes the final demand of a country is replaced by an investment vector, it is possible to analyze the economic impacts derived from a change in the final demand caused by the specific investment, such as a new infrastructure deployment (CSP power plants in our case). By combining MRIOT's information with regional and/or sectorial data (employment, greenhouse gases emissions, etc.), the analysis enables the estimation of impacts of an investment in any sector or industry that are directly and indirectly stimulated, as well as showing the leakage effects between sectors. This extension is achieved by including an extension vector (socioeconomic, environmental, etc.) which expresses the socioeconomic or environmental impact per monetary unit produced, for example, the kg. of CO₂ emitted by a specific sector and year per unit of output produced by such specific sector. The extension is calculated as follows:

$$F = f \bullet (I - A)^{-1} \bullet y_{CSP} \quad (2)$$

Where F represents the total sustainability impact (kg. of CO₂, employees, etc.), $\hat{f}$ is the impact vector (e.g. employees/EUR or kg of pollutants/EUR), and y_{CSP} is the investment vector that includes the costs of investment and operation and maintenance (O&M) stages of the CSP plant deployment. Table 1 summarizes the type of results that can be obtained with this method.

EXIOBASE3 [42] has been used as the MRIOT. Therefore, it is assumed the productive structure pattern has remained unchanged from 2011 onwards. This is one of the main limitations of this methodology. In the long-term (horizon year 2030 and 2050), the production function may vary due to technological change. Hence, this must be understood as a counterfactual exercise that addresses the sustainability impacts

that would occur if the CSP plants were deployed today, rather than a forecasting simulation.

Another limitation of the model is that the country and sector aggregation of the IOTs might not be as representative of the CSP industry as desired. This is specially seen in the case of employment, due to lack of data availability. Differences between the results of the input-output approach and the estimations of the industry regarding the direct employment on CSP in the literature appear to be remarkable [43]. Industry estimations only consider the direct employment at the plant level and in the manufacturing of components. Direct employment calculated through input-output analysis provides, on average, higher figures than the industry ones. This happens because sectors aggregation in the IOTs. As examples, the heliostats production corresponds to "glass products" sector; the steam turbine is allocated in the sector "machinery and equipment", etc. Thus, the sectors that are initially involved might not be as representative of this technology as desirable. Nevertheless, indirect effects are not negligible at all and must be considered.

As a solution regarding the specific case of employment, a hybrid approach is followed by using the industry figures for direct employment (using data from the literature and from consultations with industry, firm COBRA³) recalculating the indirect employment using the ratio indirect/direct or employment multipliers obtained in the input-output analysis [44]. Total sustainability effects originated by the reinvestment into the economy of the wages earned by the labour in the investment (installation/construction) and operation of the power plant have not been considered. In other words, the indicators presented in this paper do not capture the induced effects that arise as an additional stimulus of households' consumption.

Supply risks analysis of the GVCs in terms of dependence and governance levels is conducted departing from the results of the EMRIO analysis. The rationale of the assessment is that, for investors, decision makers and regulators, the risks associated to a highly diversified portfolio of suppliers from countries with high levels of governance could be lower and then preferable over other alternatives. The approach has already been developed by the authors and has recently been published [33]. For the methodological details refer to this paper. In the present study, the dependence and the level of governance along the supply chain are assessed considering the total demand as well as silver extraction, which will be a key raw material for the deployment of the CSP technologies in the next years.

Regarding the dependence issue, the higher the number of suppliers along the value chain, the lower the dependence risk. Thus, for the dependence analysis, the diversity metric known as Entropy (E) is used. The entropy metric has been used and studied as an indicator of diversity in several disciplines, including economics [45], environmental studies [46] and other contributions in the scientific literature [47,48]. The entropy is calculated according to:

Table 1

Type of results that are obtained from the IOA, their formulation and meaning.

Impact	Formulation	Meaning
Direct impact	$(\hat{f} \bullet y_{CSP})$	Final demand of goods and services due to the CSP power plant, distinguishing between domestic direct effects and non-domestic direct effects.
Indirect impact	$(F - \hat{f} \bullet y_{CSP})$	Intermediate outcomes that will occur in order to meet changes in the final demand (distinguishing between domestic and non-domestic indirect effects).
Multiplier effect	$(\frac{F}{\hat{f} \bullet y_{CSP}})$	Change in the total impact as a result of changes in the final demand for goods or services described.

² IOTs can be interpreted considering columns and rows. Columns show the monetary value of products or services that a sector needs from other sectors (inputs) to obtain its total production; whereas rows display the distribution in monetary values of the production of one sector over the rest of the sectors (outputs) [79].

³ In the MUSTEC project, industry partners provided primary data.

$$E_{\text{total production/impact}} = - \sum_{C=1}^N P_{xc} \cdot \log P_{xc} \quad (3)$$

Where P_{xc} is the share of the contribution by each supplier (countries or regions) of the sample to the total production or the total impact. This metric can be applied to an economic indicator (output, in monetary units) or a material indicator (e.g, silver extraction, Mg). One of the advantages of using this metric is that it can be compared with a maximum value, E_{max} , given by the number of countries in the MRIOT.

Not only is the diversification of suppliers relevant, but also issues such as practices, behaviors, customs regimes and institutions in those countries (as they will play a role in supply). In order to characterize a supplier in terms of governance, the six-composite Worldwide Governance Indicators⁴ [49,50] are used. These criteria are: Voice and Accountability (VA), Political Stability and No violence (PSNV), Government Effectiveness (GE), Regulatory Quality (RQ), Rule of Law (RL), and Control of Corruption (CC).

By applying equation (4), the combined governance and diversity indicator of the total output for each of the six governance criteria is obtained (DG_{WGIix}). Thus, a component is added for measuring the level of governance along the value chain by weighting the contribution of the countries/regions as suppliers in the Entropy equation, which leads to an indicator which combines the diversity metric and the level of governance. Then, the lowest risks would be associated to higher levels of diversity and better levels of governance.

$$DG_{WGIix} = - \sum_{C=1}^N P_{xc} \cdot WGI_{ic} \cdot \log P_{xc} \quad (4)$$

Where WGI_{ic} is the governance value of each indicator for the six indicators analysed ($i = \text{VA, PSVA, GE, RQ, RL and CC}$) for the country or region c .

2.2. Data sources and methods of characterization

The three main data components at the core of the analytical framework used in this work are a multi-regional input-output table (MRIOT), EXIOBASE3 in this case, the Social Hotspot Database (SHDB), and the CSP cost specific data from the MUSTEC project [44]. FISA uses the investment and operation and maintenance costs of the project to obtain the total production of goods and services and links these results with environmental and socioeconomic extension vectors and social risk data per country and sector to obtain economic, environmental and social sustainability indicators. Additionally, in this work, a combined indicator capable of considering the diversification and the level of governance of the suppliers along the value chain has been included in the sustainability assessment as a measure of the supply risk [33]. Thus, results are presented in terms of nine socioeconomic, environmental, social and supply risks indicators (Table 2). These indicators are among the ones most selected in the sustainable development literature [38, 51].

⁴ WGI criteria indicators are briefly describes as follows: Voice and Accountability (VA) reflects perceptions on citizens' access to participate in selecting government, to freely expressing and association; Political Stability and Violence Absence (PSNV) measures perceptions of the likelihood of political instability and/or politically-motivated violence; Government Effectiveness (GE) reflects perceptions of the quality of public services, civil service and the level of independence on policy formulation and implementation, and the credibility of the government's commitments; Regulatory Quality (RQ) reflects perceptions of the ability of the government to formulate and implement policies and regulations; Rule of Law (RL) reflects perceptions on agents' confidence in and abide by the rules of society (contract enforcement, property rights, police and courts practices); Control of Corruption (CC) reflects perceptions on how the public power is exercised for private gain.

For a deeper understanding of the databases used in this research, a detailed explanation is provided in the supplementary information Part B (SI).

Among the environmental indicators, GHG emissions and water consumption have been chosen as key criteria for the sustainability assessment and are deemed suitable for the context of the analysis (policies for decarbonisation in a country with areas in risk of desertification). Silver extraction has been selected as an indicator of sustainability since it is considered a key material for the deployment of solar technologies [53]. Silver is required by both solar technologies, PV and CSP, so the production and availability of this mineral plays a key role on their deployment. The other way around, the deployment of solar technologies has an effect on the production and market of silver around the world [54,55]. This fact, together with the demand by the rest of the sectors and activities [56] (such as other industry, photography, jewelry fabrication, silverware, physical investment, etc.) makes silver a mineral worth focusing on in terms of supply risk for CSP deployment.

Related to social risks, it seems reasonable to assume that a high level of development and low social risks in a country are correlated. The analysis of GVCs helps to address the risks associated to investments in developed countries with associated high social risks. The social risks indicators have been selected assuming the alignment of the European policies with the Sustainable Development Goals (SDG) and, in particular, with SDG8 (fostering decent work along the world).

Fig. 1 synthesizes the adapted FISA⁵ application in this paper. This methodological framework can be applied to derive specific recommendations aimed at minimizing the adverse social, environmental and economic effects along the whole project supply chain as well as to address potential supply risks, which could suggest measures to mitigate them and support the development of related regulation and mechanisms for CSP investments.

In spite of the high quality of databases and other sources of data being used, some assumptions have been made and improvements on data have been carried out in order to achieve a higher representativeness of the results. A detailed explanation on data sources and methodological details on the treatment of data are provided in the SI-Part B. Anyway, some methodological aspects should be highlighted. First, for the specific case of the molten salts supplied by Chile, the employment factor for this country has been used based on data from ICIO-OECD (OECD, 2018), as this country is not individually included in EXIOBASE3. Second, for employment creation, a hybrid approach has been adopted by using the primary data from industry (Personal communication, MUSTEC consortium partner) and recalculating the indirect

Table 2

Socioeconomic, environmental social and supply risk indicators covered in the present research. FTE: full-time equivalent ([52]).

Impact	Database	Indicator	Units
Socioeconomic	EXIOBASE3	Value added	M.EUR
		Employment	Full-time equivalent (FTE)
Environmental	EXIOBASE3	Greenhouse gases emissions (GHG emissions)	Gg CO ₂ eq
		Water consumption	Mm ³ of blue and green water
Social	SHDB	Silver extraction	Mg of silver
		Sweatfree wage	Medium risk hours
Supply risks	WGI	Child labour	Medium risk hours
		Risk on supply of total goods and services	Non-dimensional
		Risk on supply of silver	Non-dimensional

⁵ This has previously been applied in the EU-funded MUSTEC project. <http://www.mustec.eu/>.

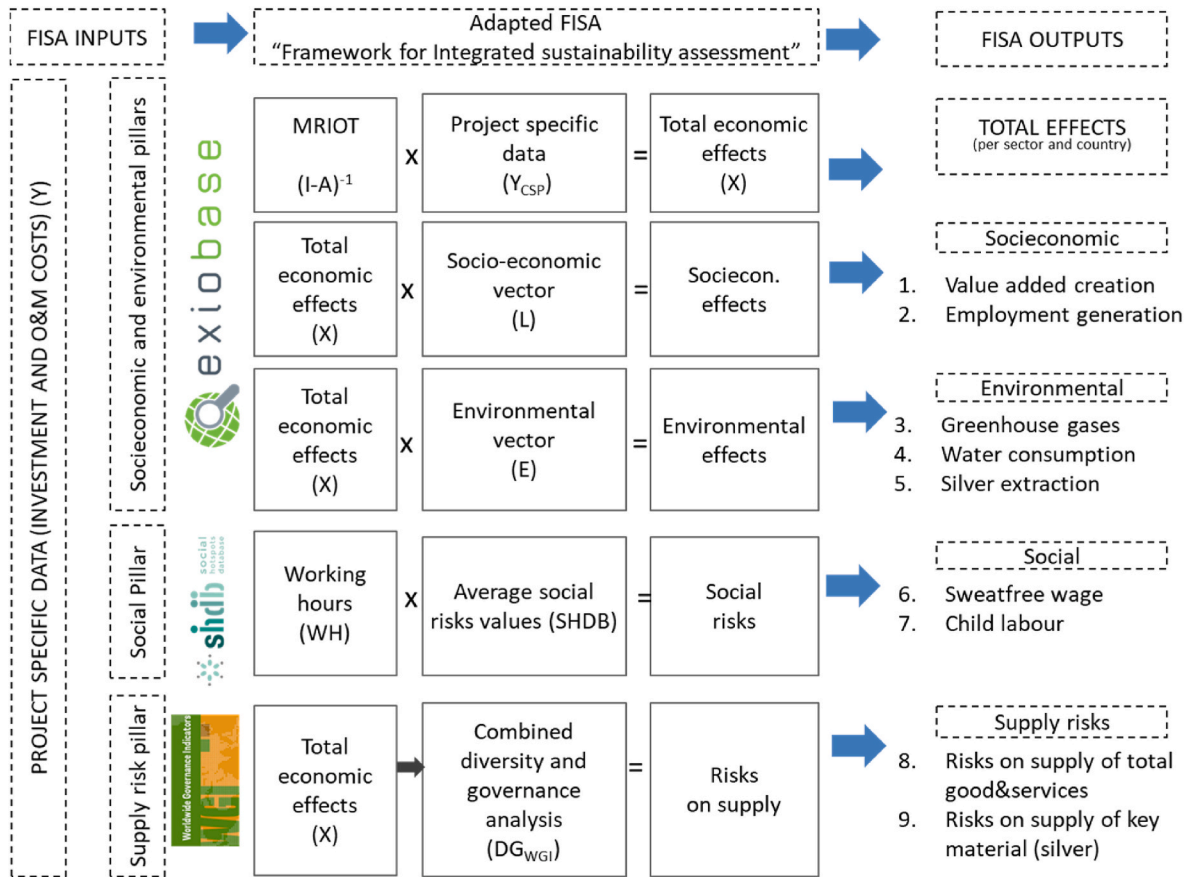


Fig. 1. Adapted Framework for Integrated sustainability assessment (FISA).

employment using the employment multipliers obtained in the IOA. Third, two characterization methods have been used for the environmental impacts: the carbon emissions indicator is calculated using the factors of the PEF method [57] for the main greenhouse gases emissions whereas, for the characterization of the water scarcity stress, the AWARE method [58] has been applied. Fourth, the SHDB version used is an adapted version in concordance with EXIOBASE, since it was originally built based on other MRIOT.

2.2.1. Scenarios assessed and cost data

The deployment of a 200 MW CSP plant (dry cooling technology) in Southern Spain has been chosen as a representative case for the analysis. Two CSP technologies have been considered: a parabolic trough (PT) power plant with synthetic oil as heat transfer fluid (HTF) and thermal storage using molten nitrate salts, and a central receiver (CR) power plant using molten salts both as HTF and as thermal storage medium. Technical data (i.e., technological characteristics, lifespan, etc.) are based on a prototype CSP plant installed in the South of Spain, and meteorological conditions for Seville, with a DNI of 2353 kWh/m²/year.

The costs have been obtained from the System Advisor Model (SAM) [59] developed by NREL. For the cost inputs, own data with reference costs to 2018 has been used and, when not available for some main equipment, the SAM's default costs were used (for details on the cost data, see Ref. [60]). Then, the Industrial Producer Price Index provided by Eurostat for the period (2011–2018) were used and the costs were deflated to 2011 prices. The final share of investment cost data is included in the SI, Part C. The disaggregation of O&M costs regarding the CR technology come from Ref. [34]. In the case of PT, data were obtained from Ref. [61].

Regarding the country-origin of CSP plant components, three scenarios have been proposed:

- Pure Spanish Investment (S1): all final components, with the exception of the molten salts that come from Chile and the thermal oil that comes from Germany, are produced in Spain, as well as the goods and services needed for construction, installation and O&M.
- Alliance with Germany (S2): under a potential cooperation agreement between Spain and Germany, firms from Germany would supply some of the components of the plant: the mirrors and the steam turbine for the PT power plant; and the mirrors, the frames and support structures, the drive mechanisms and track systems, the steam turbine and the heat exchangers for the CR power plant.
- China as supplier (S3): assuming China is a relevant role player in the future of CSP, in this scenario this country supplies components related to the solar field, with an estimated cost reduction of 20%. In the case of PT technology, China would supply the receiver tubes, the drive mechanisms track systems, and the steam turbine. In the case of the CR, China would supply the drive mechanisms and the steam turbine. The installation process and related civil works are assumed to be undertaken by both Spanish and Chinese workers (assuming 80% lower labour costs for the latter).

Cost specific data must be transformed into a vector that fits the EXIOBASE3 MRIOT, by allocating the components of costs to the sectors (and countries or regions). This sectoral breakdown allocation is based on [62], the International Standard Industrial Classification [34,63]. Thereby, a final vector has been created for both technologies under the three scenarios. The complete set of data used in this assessment is publicly available [60].

3. Results and discussion

The results of the FISA framework are displayed and discussed in this

section. First, the results per sustainability dimension are provided allowing the comparison between technological alternatives of CSP (PT and CR) and the scenarios considered (S1, S2 and S3) in terms of each indicator and also the contribution per regions of interest. Second, a synthesis of sustainability impacts is undertaken and a deeper discussion is conducted.

3.1. Socioeconomic sustainability impacts results

3.1.1. Value added creation

Table 3 shows the results of our calculations on the value added creation (direct and indirect) for the whole project. Findings per CSP technology indicate that CR technology creates more value added. Concerning the scenarios, S3 (supplies from China) lead to the lowest value added, with S1 and S2 having similar impacts. From a European perspective, and considering the value added that is originated inside the EU, the CR_S2 can be considered as the best alternative, with 82.7% (825 out of 984 M.EUR) of all the value added generated remaining inside the EU. As expected, investing in a PT plant with Chinese components results in the lowest European value added creation.

3.1.2. Employment creation

Similarly to the value added effects, the CR technology leads to better results regarding the employment effects (Table 4). However, in contrast to the value added effects, those employment effects are highest in S3 and lowest in S2. Again, the regional differences are substantial.

The benefits for Germany to engage in a CSP cooperation agreement with Spain are highest in the case of CR plants and amount to 10.3 FTE/MW. For Spain, employment generation ranges from 26.7 FTE/MW in the case of the Chinese investments in a PT plant (S3) up to 42.7 FTE/MW in the case of a pure Spanish CR plant (S1). From a European perspective, S3 would create a loss of domestic employment in the range of 5.3 FTE/MW for PT to 6.6 FTE/MW for CR. Germany leads to a slightly higher stimulus of European employment under cooperation (0.2 FTE/MW more than CR_S1, and no increase with PT_S1). However, it is less labour-intensive than Spain. Hence, the additional jobs created in Germany (9.5 FTE/MW) do not compensate the loss of Spanish employment (12.1 FTE/MW) when comparing S1 and S2 for CR (Fig. 2).

Labour costs on the operation and the installation of the CSP plant are provided by Ref. [44], whereas direct labour in the plant can be estimated with EXIOBASE. For the operational stage, the salary per worker in the Spanish production of electricity by solar thermal power can be used as a proxy, resulting in 1733 (PT) and 1933 (CR) additional FTE (8.67 and 9.67 FTE/MW respectively). Translated into permanent jobs, the results for PT (69 permanent jobs, 0.35 jobs/MW) and CR (77, 0.39 jobs/MW) are consistent with the industry estimations provided by the project developer, the firm COBRA (40 permanent jobs or 0.36 jobs/MW). For the installation of the CSP plant, S1 and S2 assume that

Table 3

Total, both direct and indirect, value added creation (Investment and O&M Stages) (M.EUR).

Region	PT_S1	PT_S2	PT_S3	CR_S1	CR_S2	CR_S3
ES	604	525	484	731	476	604
DE	40	119	38	22	288	18
REU	51	51	42	62	61	49
Total European	695	695	564	815	825	671
CN	10	10	108	12	12	120
WL	149	149	150	66	63	66
OECD	30	32	33	35	38	38
ROW	46	43	45	57	46	54
Total non-European	235	235	335	169	159	278
Total	930	930	899	984	984	949
of which Direct	462	467	442	451	477	420
of which Indirect	468	463	458	534	508	529

Note: Spain (ES), Germany (DE), China (CN), Rest of Latin America (WL), Rest of Europe (REU), OECD countries (OECD), Rest of the world (ROW).

Table 4

Total, both direct and indirect employment (FTE/MW).

Region	PT_S1	PT_S2	PT_S3	CR_S1	CR_S2	CR_S3
ES	32.3	28.2	26.7	42.7	30.6	35.8
DE	1.6	4.5	1.6	0.8	10.3	0.7
REU	2.1	2.1	1.7	2.8	3	2.3
Total European manufacturing	36	34.8	30	46.4	43.8	38.8
CN	1.8	2	19.2	2.5	2.7	27.1
WL	1.9	1.9	1.9	1.9	1.5	1.9
OECD	1.2	1.3	1.3	1.5	1.7	1.7
ROW	16.7	16.1	16.5	23	20	22.4
Total non-European manufacturing	21.8	21.2	37	29	26	49.3
Total manufacturing	57.8	56	67	75.4	69.8	88.1
of which Direct	20.4	19.5	21.1	26.8	25	28.6
of which Indirect	37.3	36.6	45.9	48.5	44.7	59.6
Direct installation and O&M (ES, European)	18.9	18.9	19.6	23.2	23.2	24.1
Total European	54.9	53.7	38.7	69.5	67	48.5
Total Spain (ES)	51.2	47.1	35.4	65.9	53.8	45.5
Total	76.7	74.9	86.6	98.5	92.9	112.1

Note: Spain (ES), Germany (DE), China (CN), Rest of Latin America (WL), Rest of Europe (REU), OECD countries (OECD), Rest of the world (ROW).

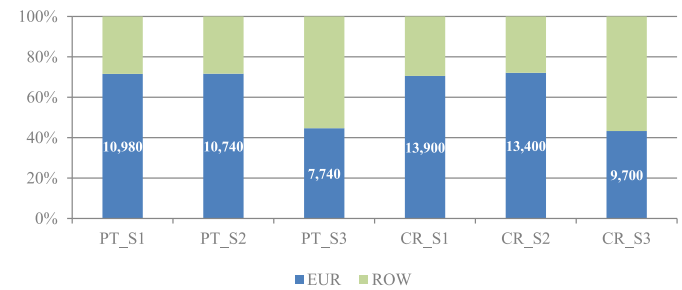


Fig. 2. Share of European and non-European (ROW) employment creation in the different scenarios. Numbers indicate the employees engaged.

the labour of the construction sector is Spanish; S3 assumes Chinese labour that is moved to the host country (Spain in this case). Hence, the salary per worker in the Spanish and Chinese construction sector is also estimated from the MRIOT to obtain the FTE. In this sense, the additional direct employment at this stage is 2044 (PT) and 2698 (CR) FTE in S1 and S2 (10.2 and 13.5 versus 13 FTE/MW reported by the company COBRA), and 2177 (PT) and 2874 (CR) FTE under S3 (10.9 and 14.4 FTE/MW, respectively).

For the CSP technologies, the most benefited sector in terms of value added and employment is *Manufacture of machinery and equipment n.e.c.* (abbreviation of “not elsewhere classified”), followed by *Other services activities* in Spain. The *Mining of chemical and fertilizer materials, production of salt, other mining and quarrying n.e.c* sector from the rest of Latin America (molten salts from Chile) is also important in terms of value added. The mining sector appears to be more capital than labour-intensive and does not have a remarkable impact in terms of employment. For the CR_S2, the German sectors of *manufacture of fabricated metal products except machinery and equipment* and *manufacture of electrical equipment and apparatus* also have an important share in terms of value added and employment. Results differ slightly when compared to the PT_S2 scenario: the *Mining of chemical and fertilizer materials, production of salt, other mining and quarrying n.e.c* sector from the rest of Latin America (molten salts from Chile) retains most of the value added created. Services act as a glue in the global value chains, creating value added and employment. This phenomenon (*servicification* of manufacturing [64]) can be seen in the Tertiary sector impacts.

In comparison with other technologies, CSP is among the most job-intensive renewable energy technologies and, therefore, its

possibilities to boost employment regeneration in Europe after the COVID-19 pandemics are high. Fig. 9 in the SI (Part D) shows some results from the literature on employment creation per installed capacity (MW) for different renewable energy technologies, including CSP. In spite of being difficult to compare due to the wide-ranging values, CSP values obtained in this research are within the range of published results.

3.2. Environmental impacts

3.2.1. GHG emissions

According to our calculations, total GHG emissions of CSP range from 15 to 28 g CO₂ eq/kWh, which are in line with the life cycle analysis literature (22–30 g CO₂ eq/kWh [65,66]). The input-output literature provides a broader range of results. Table 5 shows the results per technology and scenario. Regarding the CSP technologies, the CR is less carbon intensive compared to PT [67]. Concerning the scenarios, the highest emissions occur in S3 for both technologies, probably due to the high carbon intensity of Chinese productive sectors. Even in this case, emissions are well below those of the alternative fossil electricity generation technologies and in the range of the other renewable technologies [68]⁶. This can be understood as the CSP investments carbon footprint of Spain, while also reflecting the producer perspective (the origin of the emissions) compatible with the Paris Agreement reporting. Scenario S2 (components from Germany) will result in lower GHG emissions than if a fully Spanish investment is considered (S1), due to the lower carbon intensity of the German production sectors.

The deployment of this CSP power plant will increase European GHG emissions by around 162–238 Gg of CO₂eq as a result of the manufacturing of the components and the intermediate products required in the value chain that have their origin in Europe. These values represent between 28% and 55% of the total emissions produced in the value chain of this technology. However, the European participation in terms of value added (70–84%) and employment (43–72%) is higher, indicating the CO₂ decoupling from economic growth in Europe.

The sectors producing the largest GHG impacts are the *mining of*

Table 5

Total (both direct and indirect) GHG emissions in Gg of CO₂ eq (Investment and O&M Stages).

Region	PT_S1	PT_S2	PT_S3	CR_S1	CR_S2	CR_S3
ES	196.0	154.2	124.1	175.0	98.8	144.4
DE	19.9	50.4	19.5	10.0	67.2	9.1
REU	22.1	22.1	18.1	27.1	25.9	22.0
TotalEuropean	238.0	226.7	161.7	212.1	191.9	175.5
CN	26.1	26.3	250.7	33.2	31.0	261.3
WL	83.9	83.6	84.6	37.2	35.7	37.4
OECD	17.6	18.2	22.3	21.1	19.8	26.5
ROW	66.3	62.9	67.1	82.1	64.7	77.6
Total non-European manufacturing	193.9	191	424.7	173.6	151.2	402.8
Total manufacturing	431.9	417.7	586.4	385.7	343.1	578.3
of which Direct	163.9	156.0	129.0	66.7	59.5	66.8
of which Indirect	268.0	261.7	457.4	319.0	283.6	511.5
Total (kg/kWh)	0.021	0.020	0.028	0.015	0.013	0.022

Note: Spain (ES), Germany (DE), China (CN), Rest of Latin America (WL), Rest of Europe (REU), OECD countries (OECD), Rest of the world (ROW).

⁶ CSP has lower carbon emissions than crystalline silicon PV (with GHG emissions of around 45 g CO₂ eq/kWh [80]), higher emissions than those of wind energy (with GHG emissions of around 11 CO₂ eq/kWh [81]), and similar emissions than geothermal (33.6 g CO₂ eq/kWh [66]). GHG emissions associated to CSP investments and operation are much lower than those of fossil technologies [82].

chemical and fertilizer materials, production of salt, other mining and quarrying n.e.c sector in WL region, the Spanish secondary sector n.e.c. and the manufacturing of glass and glass products also in Spain. The electricity mix, as a source of CO₂ emissions, is also a relevant contributor of CO₂ emissions especially in China but also in Spain and Germany. This source of emissions will be reduced as these countries move towards a decarbonised energy transition.

3.2.2. Water consumption

As for water consumption (Table 6), embodied water results range from 0.7 to 1.7 l/kWh. This is mostly in line with values in the literature that range from 0.7 to 0.9 l/kWh [69]. CR is less intensive in water consumption than PT [70,71]. Concerning the different scenarios, the highest values also occur in S3 for both technologies, due to water consumption from Chinese components. As operational water consumption is reduced (since it is a dry cooling CSP plant), most of the impact is due to the water embodied in components. Chinese productive structure is water-intensive when compared to the other regions, which leads to the highest impacts of S3 for both technologies (see Table 6).

The water scarcity weighed results (last row in Table 6) stress the importance of the Spanish endowments as lower water scarcity results when Germany cooperates in a CSP plant due to the much lower water scarcity factors of Germany (see SI, Part B). A key finding of this research is that both the water-intensity of the economic sectors involved in the value chains as well as the water scarcity prevailing in each region where key components are manufactured are responsible for the overall results on water impacts. This result contrasts with the general findings of the LCA literature [69] that generally fail to consider the origin effect on indirect water consumption of some of the components.

Table 6

Total, both direct and indirect, water consumption in Mm³, and results of the water scarcity weighed in Mm³ of water deprived.

Region	PT_S1	PT_S2	PT_S3	CR_S1	CR_S2	CR_S3
WATER CONSUMPTION						
ES	3.5	2.9	2.6	3.8	2.3	3.0
DE	0.9	1.0	0.9	0.1	0.4	0.1
REU	0.8	0.8	0.7	0.9	0.9	0.8
TotalEuropean	5.2	4.7	4.2	4.9	3.5	3.9
CN	0.9	0.9	6.5	1.0	1.1	7.6
WL	0.8	0.7	2.2	0.8	0.7	2.0
OECD	1.2	1.2	3.8	1.4	1.2	3.5
ROW	9.7	9.1	12.9	11.4	8.9	13.3
Total non-European manufacturing	12.6	11.9	25.4	14.6	11.9	26.4
Total manufacturing of which	17.7	16.6	29.5	19.5	15.3	30.2
of which Direct	0.7	0.7	0.9	0.1	0.1	0.6
of which Indirect	17.0	15.9	28.6	19.4	15.2	29.7
Direct in the plant	6.2	6.2	6.2	2.6	2.6	2.6
Total (Mm³ water)	23.9	22.8	35.7	22.1	17.9	32.9
Total (l/kWh)	1.1	1.1	1.7	0.8	0.7	1.2
WATER STRESS						
ES	273	228	201	297	175	236
DE	1	1	1	0	1	0
REU	15	14	13	18	15	15
TotalEuropean	289	243	215	315	190	251
CN	37	38	276	44	45	321
WL	20	20	58	22	18	53
OECD	43	42	130	49	41	120
ROW	518	479	569	619	462	617
Total non-European manufacturing	618	579	1033	734	566	1111
Total manufacturing	908	823	1248	1050	757	1361
Direct in the plant	483	483	483	204	204	204
Total (Mm³ deprived water)	1390	1306	1731	1254	961	1565
Total (l deprived water/kWh)	66	62	82	47	36	59

Note: Spain (ES), Germany (DE), China (CN), Rest of Latin America (WL), Rest of Europe (REU), OECD countries (OECD), Rest of the world (ROW).

3.2.3. Silver extraction

The values of silver extraction range between 4.7 (PT_S2) and 8.1 (CR_S3) Mg (Table 7) or between 23.3 and 40.2 Mg of silver/GW. In terms of power production, the range of silver extraction values is between 0.22 and 0.387 mg/kWh. The values of silver required in CSP plants found in the literature [53] are 13.4 (PT) and 17 (CR) Mg of silver/GW, considering only the direct consumption. These are much lower than the direct need for PV (80 Mg/GW [72]). In our scenarios, the main contributor is the Latin America region in all cases. Highest values are found for CR technology, and within each technology, the scenarios S1 and S3 have the highest silver extraction demand per unit of power produced. As expected, the highest demand comes from outside Europe, with the sector of *Mining and extraction activities* from Latin America being the main contributor to the demand. Note that, in the CR_S2 scenario, much lower levels of extraction of silver are found, probably due to the higher recycling rates in manufacturing [54,55], which reduce the need for silver extraction. This fact is not as relevant in PT_S2, since the amount of glass (main sector causing the silver demand in the CSP plant) coming from Germany is notably lower.

3.3. Social impacts: sweatfree wage and child labour

Although direct investments are mostly made with European components and services, intermediate demands all along the global value chain coming from developing regions are likely to embody social risks. Most of the social risks regarding *Sweatfree wage* and *Child labour* are expected to occur outside the EU, especially in China and ROW (Table 8). CR_S2 performs better than any other alternative, showing the lowest risks in these two indicators. Focusing on the ROW region, in terms of Sweatfree wage, unfair wages are more likely to be seen in Africa, Rest of Asia and Pacific and the Middle East. Unfair wages in Russia can also be seen. In terms of Child labour, Africa, Rest of Asia and Pacific and Middle East remain the most affected regions. The analysed social risks appear mainly in the *Tertiary* and the *Primary* sectors in the ROW region.

3.4. Risk on supply

Considering only the entropy (E) metric, the highest diversity of the supply of goods and services along the value chain is found for the S3 scenarios and, thus, these would be the least dependent. On the contrary, the S1 are the scenarios with a lower diversity due to the high domestic demand from Spain and from Europe. In spite of a low diversity, this fact would be positive from a dependence point of view, since it would lead to a lower European dependence from a foreign

Table 7

Total (both direct and indirect) silver requirements measured in Mg of silver extraction (Investment and O&M Stages).

	PT_S1	PT_S2	PT_S3	CR_S1	CR_S2	CR_S3
ES	0.12	0.10	0.09	0.18	0.09	0.12
DE	0.00	0.00	0.00	0.00	0.00	0.00
REU	0.29	0.32	0.25	0.40	0.57	0.33
Total European	0.41	0.42	0.34	0.58	0.66	0.46
CN	0.00	0.00	0.00	0.00	0.00	0.00
WL	4.50	4.10	4.40	7.24	4.22	7.40
OECD	0.01	0.01	0.01	0.01	0.01	0.01
ROW	0.15	0.14	0.17	0.21	0.17	0.27
Total non-European manufacturing	4.66	4.25	4.58	7.46	4.4	7.68
Total	5.1	4.7	4.9	8.0	5.1	8.1
of which Direct	1.42	1.31	1.34	2.34	1.21	2.44
of which Indirect	3.64	3.37	3.58	5.70	3.85	5.69
Total (Mg of silver/GW)	25.3	23.3	24.6	40.2	25.3	40.7

Note: Spain (ES), Germany (DE), China (CN), Rest of Latin America (WL), Rest of Europe (REU), OECD countries (OECD), Rest of the world (ROW).

supply.

When applying the combined indicator of diversity and governance (DG_{WGLix}), it is possible to consider which are the key actors quantitatively (Fig. 3). Results show that the best scores are achieved in S2 scenarios for all the governance criteria due to the German contribution. S1 and S3 scenarios are quite similar for Control of Corruption (CC), Rule of Law (RL) and Regulatory quality (RQ), with S3 being slightly better than S1 in the CR scenarios for those criteria. This is due to the high diversity of the S3 scenarios, but also to the more distributed contribution from the OECD and ROW countries (positive for S3 in term of governance scores) and the contribution from Latin America countries (negative impact for S1). On the contrary, when focused on the Voice and accountability (VA) criterion, the low score for the indicator in China represents a notable penalty in the S3 scenarios.

The combined indicator of supply risk has also been applied to silver extraction along the value chain (Fig. 4). The best scores are reached in the scenarios S2 in all governance criteria, and specifically in the scenario CR_S2. Although the main silver extraction occurs in Latin America (WL), some countries with a low share play a relevant role in terms of contribution to diversity since their weight in the combined indicator increases with the number of different origins and a more distributed share. Specifically, the highest participation of Poland as a European producer of silver in the value chain in the S2 scenarios favors the good results. On the contrary, the contribution of Bulgaria has a negative impact for the criterion of Control of Corruption, Government Effectiveness and Rule of Law. The worst results are obtained in the scenarios S3, but closely follow by S1 results. In the S1 and S3, the shares of Poland and other European countries are slightly lower than those in the S2 scenarios, while the contribution from Latin America, Africa and Asia is modestly higher, since they are regions with countries which have worse scores in general. Among technologies, the PT scenarios reach similar values between scenarios for each criterion, while CR scenarios show more differences between them (notably for PSNV, RQ and VA).

3.5. Synthesis of sustainability impacts and key findings

The following tables summarize the sustainability impacts for the two CSP technologies (Table 9) and for the different scenarios (Table 10). Regarding the former, it can be observed that the central receiver technology leads to higher positive socioeconomic impacts (in terms of value added and employment) and lower negative environmental impacts (with the exception of silver extraction) and lower or equal social risks than parabolic trough. Regarding the risks of supply, central receiver also seems to entail lower risks than parabolic troughs. Therefore, the choice of central receiver can be justified both in terms of economic, environmental and social effects, i.e., there isn't a trade-off among those two impacts.

The picture is more complex with respect to the sustainability impacts in the different scenarios. It can be observed that S3 leads to much higher negative environmental effects than S1 and S2, whereas the economic effects are ambiguous (lower value added effects, but higher employment effects). In terms of social and supply risks, S3 shows higher risks than the other scenarios. Compared to S1, S2 has lower environmental effects, and lower social and supply risks, whereas the economic effects are greater in S1 (equal value added, but higher employment effects). These results suggest that S3 would be, overall, the least preferred scenario if the economic impacts (which are not higher than in the other two scenarios), the environmental impacts and social and supply risks (which are considerably worse) are taken into account. The comparison between S1 and S2 does not lead to a clear result: both higher (positive) economic impacts and lower (negative) environmental impacts and social and supply risks in S2 can be observed.

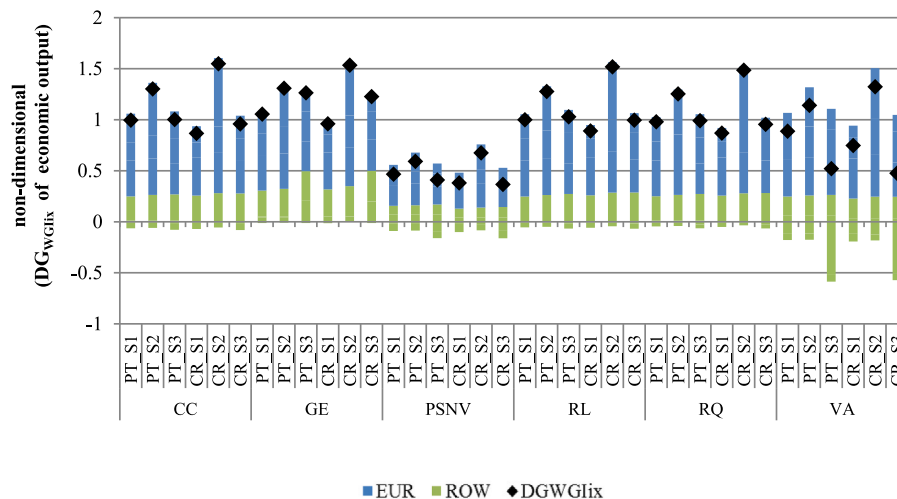
Cooperating with Germany to build a central receiver CSP plant (scenario CR_S2) seems to be the best option in environmental terms. German components are less carbon intensive than Spanish ones, and

Table 8

Social risks of the CSP investments in the different scenarios in terms of working hours (M.WH).

Region	PT_S1	PT_S2	PT_S3	CR_S1	CR_S2	CR_S3
SWEATFREE WAGE						
ES	1.12	1.00	0.95	1.56	1.07	1.32
DE	0.09	0.17	0.08	0.02	0.31	0.02
REU	0.42	0.41	0.36	0.54	0.47	0.44
Total European	1.63	1.59	1.39	2.12	1.85	1.78
CN	1.46	1.47	16.23	1.73	1.66	12.32
WL	0.06	0.06	0.06	0.03	0.03	0.03
OECD	0.56	0.57	0.57	0.64	0.61	0.63
ROW	50.72	47.59	47.10	58.66	46.60	52.18
Total non-European	52.8	49.69	63.96	61.06	48.9	65.16
Total manufacturing	56.06	52.86	66.74	65.30	52.60	68.73
of which Direct	0.74	0.73	3.70	0.97	0.88	1.19
of which Indirect	53.69	50.54	61.66	62.21	49.87	65.76
Total (WH/GWh)	2589.9	2439.6	3109.6	2369.9	1903.7	2511.0
CHILD LABOUR						
ES	0.00	0.00	0.00	0.00	0.00	0.00
DE	0.00	0.00	0.00	0.00	0.00	0.00
REU	1.63	1.58	1.36	2.06	1.81	1.65
European	1.6	1.6	1.4	2.1	1.8	1.6
CN	14.07	14.39	164.85	16.84	17.09	154.92
WL	0.55	0.55	0.55	0.27	0.25	0.26
OECD	6.89	7.44	7.60	7.48	8.51	7.93
ROW	100.03	94.07	97.13	116.67	91.26	106.74
Total non-European	121.54	116.45	270.13	141.26	117.11	269.85
Total manufacturing	123.18	118.03	271.49	143.31	118.92	271.50
of which Direct	0.50	0.50	42.35	0.20	0.20	34.27
of which Indirect	122.68	117.53	229.14	143.11	118.72	237.23
Total (WH/GWh)	5860.9	5615.8	12917.8	5375.4	4460.5	10183.5

Note: Spain (ES), Germany (DE), China (CN), Rest of Latin America (WL), Rest of Europe (REU), OECD countries (OECD), Rest of the world (ROW).

**Fig. 3.** Combined diversity and governance indicator for the analysis of the total output per each governance indicator, disaggregated per region (EUR and ROW), for the scenarios assessed.

also perform better when including the water scarcity weighting. Also, silver extraction is lowest in S2 scenarios, with a slightly better performance for PT technology than for CR in this indicator. From the German perspective, the cooperation project (S2) produces an increase in domestic GHG emissions of 50–67 Gg CO₂ eq (4–7 g CO₂ eq/kWh imported) and a domestic water consumption increase of 0.4–1 Mm³ eq (0.02–0.05 l/kWh imported). However, looking at the European Union as a whole, this cooperation has lower impacts on GHG emissions, water consumption and silver extraction needs than a pure Spanish investment. There is no additional silver extraction in Germany as this is a non-producer country, but likely plays a role as industrial recycler providing recovered silver. Also in the case of social impacts, the cooperation agreement with Germany to build a CSP power plant lowers the social impacts compared to a pure national Spanish investment, stressing once

more the benefits of a cooperative approach. In terms of value added creation, cooperating with Germany also captures the highest share of value added (82.7%, 825 out of 984 M.EUR remain inside the EU). However, in terms of employment, as Germany is less labour-intensive than Spain, a cooperative approach will result in a loss of domestic employment. Regarding the risks on supply, S2 scenarios show better results in all the governance criteria assessed, either considering the total demand of goods and services (total output) or only the silver extraction from the countries involved in the value chain. For the silver extraction, the advantage of S2 scenarios is remarkable in political stability and no violence (PSNV) as well as Regulatory quality (RQ), being especially relevant aspects for the well-functioning of the trade of silver providers and the manufacturers of key CSP components such as reflectors and receivers.

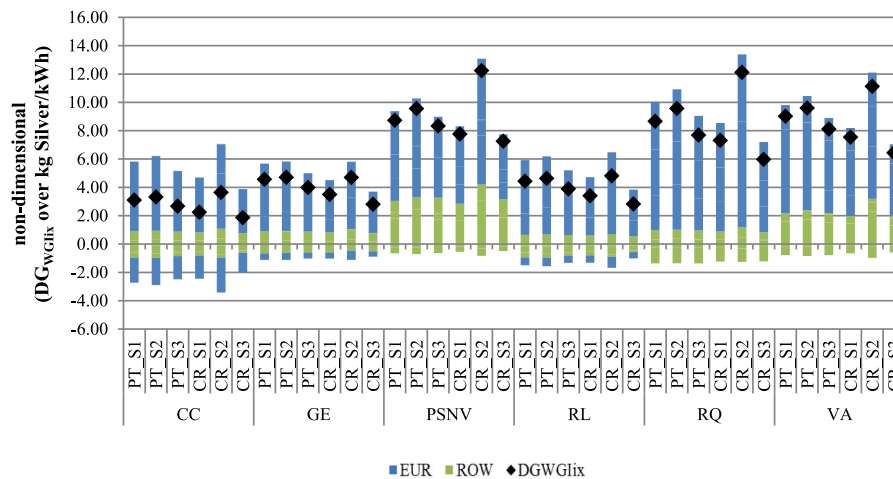


Fig. 4. Combined diversity and governance indicator of the silver extraction per unit of power produced for each governance criterion, disaggregated per region (EUR and ROW), for the scenarios assessed.

Table 9

Comparative sustainability impacts across technologies (parabolic trough and central receiver).

SUSTAINABILITY IMPACTS		PARABOLIC TROUGH ^a	CENTRAL RECEIVER
Economic	Value added	=	>
	Employment	=	>
Environmental	GHG emissions	=	<
	Water consumption	=	<
Social	Silver extraction	=	>
	Sweatfree wage	=	=
Supply risk	Child labour	=	<
	Risk on supply of total goods and services	=	<
	Risk on supply of silver	=	<

^a Reference category to which the impacts of the other CSP technology are compared.

Table 10

Comparative sustainability impacts across scenarios (S1, S2, S3).

SUSTAINABILITY IMPACTS		S1 ^a	S2	S3
Economic	Value added	=	=	<
	Employment	=	<	>
Environmental	GHG emissions	=	<	>
	Water consumption	=	<	>
Social	Silver extraction	=	<	=
	Sweatfree wage	=	<	>
Supply risk	Child labour	=	<	>
	Risk on supply of total goods and services	=	<	>
	Risk on supply of silver	=	<	>

^a Reference category to which the impacts of the other scenarios are compared.

Since environmental impacts are directly related to the production of goods and services, scenarios in which domestic content is higher will also have higher values in absolute terms. From the producer perspective, it is logical to think that there is a trade-off between economic growth or employment, and environmental impacts. The possible deployment of this type of power plants in Europe has been quantified using a model-based assessment [73]. According to their results, CSP can take up 7–8% of the total RES installed in Europe up to 2050. This means a cumulative installation in the range of 39–100 GW. Table 11 shows the relative importance of the impacts of the deployment of these cumulative installed capacities. In terms of employment, these investments will result in 50,310–231,667 jobs each year, which represent a 0.34–1.55%

of all unemployed in Europe (15 million unemployed people in Europe (Eurostat, 2021)). As most of the European jobs will be created in Spain, where the unemployment rate is very high, the relative importance of these new jobs is a bit higher. In terms of value added, the additional investments until 2050 represent 4–14 billion Euro, that is, between 0.03 and 0.11% of European GDP. Although these socioeconomic benefits appear to be low, CSP cooperative deployment will support a higher penetration of variable renewables such as wind and PV, which further boosts value added and job creation in Europe. The GHG emissions (1–4 Mt CO₂ eq/year) represent only 0.02–0.09% of total emissions in Europe annually. Similar relative values are found for water impacts. The need for silver extracted within Europe is negligible. The expected socioeconomic benefits driven by the necessary investments in CSP explained above appear to offset the small increase in the environmental impacts, even more considering the displacement of fossil technologies caused by the deployment of renewables in those projected scenarios.

The key findings of the sustainability assessment performed can be summarized in the following six bullet points:

- CSP deployment will create value added and employment that will be mostly retained in Europe: the deployment of a 200 MW CSP power plant would generate value added in a range between 900 and 950 M.EUR, of which 70–84% would remain in Europe. Employment creation has been estimated in 75–112 FTE/MW, of which 39–70 FTE/MW would be retained in Europe (43–72%). The lowest figures in that range correspond to a scenario of high penetration of the Chinese CSP industry in the European market.
- CSP electricity has a low carbon and water footprint and silver extraction demand: the electricity generated in this CSP plant would generate between 14 and 28 g CO₂ eq per kWh. The highest figure corresponds to a scenario of high penetration of the Chinese CSP industry. Only 28–55% of those emissions would be produced in Europe. Water consumption of the CSP power plant ranges from 0.7 to 1.1 l/kWh. It is mainly due to the water embodied in components and not so much related to the operational water consumption, which is quite limited. Silver extraction demanded by CSP, which is relevant from a dependence perspective, ranges between 0.222 and 0.387 mg/kWh and mainly comes from outside Europe.
- CSP power plants originate some social risks in their value chain: most of the social risks regarding fair wages and child labour are expected to occur outside the European Union, especially in China and Africa, Rest of Asia and Pacific, and the Middle East, and in sectors not directly stimulated by the investments. Hence it is of outmost importance to encourage the social responsibility along the

Table 11

Estimation of European impacts in relative terms for the scenarios (scenarios with low and high values of each impact).

Sustainability impact	Scenario		Total impact in Europe of 200 MW	Total impact in Europe per MW	Cumulative CSP deployment	Total Impact for the cumulative CSP deployment	Annual impact	Overall European impact	Source	Relative impact
GHG emissions			Gg CO _{2eq.}	Gg CO _{2 eq} /MW	MW	Tg CO _{2 eq}	Tg CO _{2 eq}	Total GHG emissions Tg CO _{2 eq}		
	Low	PT_S3	162	0.81	39,000	32	1	4237	[74]	0.02%
	High	PT_S1	238	1.19	100,000	119	4			0.09%
Water consumption			Mm ³	Mm ³ /MW	MW	billion m ³	billion m ³	Total water consumption in billion m ³		
	Low	CR_S2	6.1	0.03	39,000	1	0.04	243	[75]	0.02%
	High	PT_S1	11.4	0.06	100,000	6	0.19			0.08%
Silver extraction			Mg	Mg/MW	MW	Mg	Mg	Gg of silver extracted		
	Low	PT_S2	0.34	0.0017	39,000	66.3	2.2	21177.08	[55]	0.00001%
	High	CR_S3	0.66	0.0033	100,000	330	11			0.00006%
Value added			M.Euro	M.Euro/MW	MW	billion Euro	billion Euro	GDP billion euro		
	Low	PT_S3	564	2.82	39,000	110	4	12,985	[76]	0.03%
	High	CR_S2	825	4.13	100,000	412	14			0.11%
Employment				FTE/MW	MW	FTE	FTE	Unemployed people		
	Low	PT_S3		38.7	39,000	1,509,300	50,310	14,916,000	[77]	0.34%
	High	CR_S1		69.5	100,000	6,950,000	231,667			1.55%

value chain of all the components of these plants in order to minimize the occurrence of such risks.

- The penetration of the Chinese CSP industry in the European market will worsen the sustainability of CSP plants: the scenarios that consider a higher penetration of the Chinese CSP industry in the European market would reduce the generation of value added at both the European and but global levels. Although these scenarios increase total job creation, this increase only occurs in China and comes at the expense of a decrease in European employment. The participation of the Chinese industry in the power plants also increases the carbon and water footprints, the risk of unfair wages and child labour, and rises the need for silver extraction and, therefore, the risk of supply (lower diversity and with a lower governance quality). These negative impacts could be minimized if China moved to a fair, inclusive and low-carbon energy transition.
- A cooperative approach for CSP deployment (especially in the case of central receiver technology) seems to perform better than a pure Spanish investment regarding the sustainability indicators analysed: under the assumptions used in this assessment, a cooperative approach in which Germany manufactures some key components of the CSP plants becomes the most appealing option as it retains wealth inside the European Union, minimizes the Carbon and Water footprints and the indicator of Silver Extraction, reduces the risks of incurring unfair wages and child labour that may occur all along the supply chains (mostly outside the European Union) and decreases the risk of supply.
- There are tradeoffs between the socioeconomic benefits and the environmental and social impacts driven by the CSP investments: However, the analysis of the relative share of these benefits and impacts has shown that the expected socio-economic benefits driven by the necessary investments in CSP offset the small increases in environmental and social impacts.

3.6. Main limitations and assumptions

Methodologically, there are three main limitations. The first one is related to the MRIO tables (MRIOT). On the one hand, the long-time lag in updating the MRIOT (year 2011 data in EXIOBASE3) does not allow the analysis of individual changes in the indirect demand. However, the environmental impact associated to Chinese sector in S3 scenarios due to the higher water and carbon intensity may be tackled and smoothed in the future. In this regard, a brief analysis of the change in coefficients

according to the later releases of the satellite accounts of EXIOBASE is included in the SI (Part E). On the other hand, the sectoral aggregation of MRIOT limits the fine-tune breakdown allocation of inputs needed for deployment and may not be as representative of the specific input as desired. Second, the supply risk assessment is based on the conceptualization of higher diversity and governance scores. This always involves lower risk, but some influences and exogenous relationships between countries are not captured by the method. Further research on the supply risks associated to the GVCs of the CSP and renewables deployment focused on materials requirements and resources constraints should be addressed. And, third, the sustainability assessment over the three classical dimensions only includes some selected indicators, but excludes other impacts such as land use or the effects of market prices.

As for the assumptions about the scenarios, representative examples of CSP have been assessed by including the two most popular technologies and three plausible country-origin scenarios for the current market, but only one host country is considered. However, the choice of this country (Spain) is easy to justify. Apart from the moderate DNI levels, and the long experience with CSP of the Spanish industry and R&D, the Spanish government has given the signal that it will support the uptake of CSP by fixing a minimum volume of 220 MW in the next renewable energy auction, which will be conducted on October 25th, 2022 [78]. This reinforces the representativeness of Spain as a host country for potential CSP deployment in Europe. Costs assumptions in each scenario are quite influential on the results. Therefore, the difference in deployment costs between the Chinese scenario and the two other scenarios is taken into account by assuming 20% lower costs of the Chinese components. However, a dilemma would arise if these costs became much lower, and even a scenario with lower local benefits (e.g. with higher environmental impacts) could be justified, suggesting S3 as a better option.

4. Conclusions

This paper provides an assessment of the sustainability impacts associated to the potential future deployment of CSP projects, considering different CSP technologies and scenarios regarding the origin of the components. The results show that central receivers have more positive economic impacts, both in terms of value added and employment creation, and lower negative environmental impacts than the parabolic trough alternative regarding carbon emissions and water consumption, but slightly higher requirements for silver extraction.

Social and supply risks are also lower. On the other hand, the economic and environmental impacts of the CSP deployed in Spain depend on the origin of the components, with the highest negative environmental impacts and social and supply risks occurring when the components come from China and the lowest impacts when they come from Germany. The most positive economic impacts in terms of value added creation tend to occur when the components are manufactured in Spain and Germany and, with respect to employment creation, when they are manufactured in China. CSP deployment in Spain would create value added and employment that would be mostly retained in Europe.

As a dispatchable renewable energy technology, CSP provides clean power on demand. The positive economic benefits of CSP provide an additional reason to such flexibility to support this technology. As suggested by the results of the scenarios, which take into account the origin of the different components of the CSP project, the positive sustainability effects at the EU level and at the level of one Member State (Spain) justify intensifying measures to encourage the uptake of this technology. More specifically, auctions should be designed to encourage that this technology is awarded and receives support, for example, through contingents, i.e., CSP-specific auctions. In this context, the 220 MW of auction volume to be awarded in Spain in 2022 as a starting point to reach the 5 GW expected until 2030 is a good step in this direction, although probably a too timid one. Considering our results, such volumes should increase in the future in order to have a meaningful penetration of this technology, which will be much needed with an increasing penetration of variable renewable energy sources, in a country which may considerably benefit from its positive economic impacts, particularly the employment effects, given its relatively high unemployment rate.

The different results per technology suggest that, in general, supporting central receivers as the CSP alternative brings additional benefits in terms of, both, higher economic impacts and lower environmental effects. The higher needs of silver extraction of central receivers lead to higher risks on supply of this key material for this technology except in the case of the European cooperation approach, since the lower diversity is compensated by a better quality of governance. In other words, central receivers may have added local benefits, which suggests that their deployment should be prioritized by, for example, including a premium in the merit order in CSP auctions for this technology. Those benefits would be maximized under the European cooperation alliances in which German firms manufacture the key components.

Our findings suggest focusing energy policy strategies on reinforcing the local and European CSP industry through cooperation mechanisms that would ensure contributing to energy security, dispatchability and flexibility in the European electricity mix, while promoting employment and economic growth, and, thus, a more sustainable energy system.

Credit author statement

Ana R. Gamarra: Methodology, Data curation, Formal analysis, Investigation, Writing- Original draft preparation. Santacruz Banacloche: Conceptualization, Methodology, Investigation, Data curation, Resources, Writing- Original draft preparation. Yolanda Lechón: Conceptualization, Writing - Review & Editing, Supervision. Pablo del Río: Writing- Reviewing and Editing.

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Declaration of competing interest

The authors declare that they have no known competing financial

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Data availability

I have shared a link to the data and original sources in the manuscript (<https://zenodo.org/record/3964021#.Yzczj3bP02w>)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rser.2022.113004>.

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3. RESULT 3: METALS' SUPPLY CHAIN RISK ANALYSIS OF RENEWABLE ENERGY INVESTMENTS. A METHODOLOGICAL PROPOSAL AND A CASE STUDY OF SOLAR POWER PLANTS IN SPAIN

Metals' supply chain risk analysis of renewable energy investments. A methodological proposal and a case study of solar power plants in Spain

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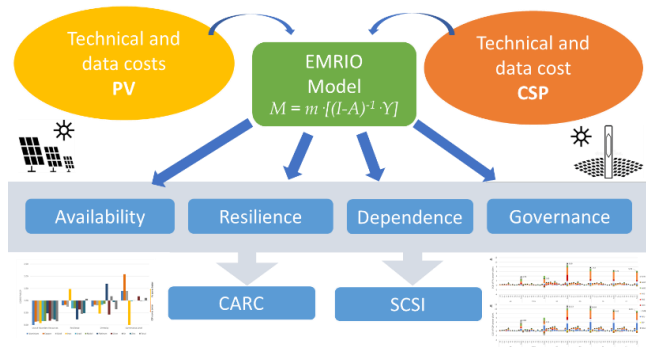
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Abstract

The material supply chain plays a crucial role in the European renewable energy deployment to support the transition to a more sustainable and decarbonized economy. This paper is focused on the assessment of the potential risks and strengths along the supply chain of a set of metals associated to two alternatives of 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 ten different metals along the value chain. First, different metrics and indicators for the analysis of the supply chain are explored. Second, a framework of analysis to cover the main components of the supply chain risks and strengths is proposed. Then, we compare the results from two perspectives: analysis of individual components of the supply risks criterion, and a combined index that represents the strength of the value chain. The results show, in general, a better performance of the concentrated solar power supply chain of metals in the indicators of availability of resources and diversity of suppliers but slightly worse scores in the resilience and governance component. The index reflects an overall better performance of concentrated solar power. Among metals, Platinum, Silver and Tin play the main role in the analysed risks. European deployment of renewables should be accompanied by measures to secure supply such as cooperation agreements and should also foster the recovery of secondary material maximizing intra-European resilience.

Graphical abstract



Keywords: Supply chain risks; raw material supply; Renewable energy; Multi-regional Input-Output.

Abbreviations list and notation in equations

Abbreviations		Notation in equations	
$(I-A)^{-1}$	Leontief inverse	ADP_m	Abiotic Depletion Potential of the metal m
A	Technical coefficients matrix based of the MRIOT	m	Each metal ($m = \text{Al, Cu, Au, Fe, Pb, Ni, Pt, Ag, Sn, Zn}$)
ADP	Abiotic Depletion Potential	DR_m	Annual production or extraction rate of resource m (kg/yr)
Ag	Silver	R_m	Ultimate reserve of the reference mineral m (kg)
Al	Aluminium	DR_{ref}	Annual production or extraction rate of the Sb (kg/yr).
Au	Gold	R_{ref}	Ultimate reserve of the reference mineral Sb (kg)
CC	Control of Corruption	$ERPR_m$	Intra-European recycling potential rate of the metal m extracted as consequence of the investment
CE	Circular Economy	M_m	Mass of each of the extracted metal as consequence of the investment using EMRIO
CSP	Concentrated Solar Power	M_t	Total of the quantified mass of extracted metal as consequence of the investment using EMRIO
Cu	Copper	$EOLRIR_m$	End-of-life recycling input rates in Europe of the metal m
EMRIO	Extended Multi-regional Input-output	$ERPR$	Total Intra-European recycling potential rate of the assessed metals extracted as consequence of the investment
EU	European Union	E_m	Entropy of the extraction of the metal m along the supply chain
Fe	Iron	c	Countries or regions included in the MRIOT
GE	Government effectiveness	E_m	Share of contribution of each countries or regions c to the extraction of required of each considered metal m
GRI	Global Resources Index	E_{mmax}	Maximun value of Entropy considering the number of countries or regions c of the extraction of the metal m along the supply chain chain
GWh	Gigawatts-hour	E_t	Sum of Entropy of the extraction of assessed metals along the supply chain chain
kg of Sb eq.	kilograms of Antimony equivalent	i	Governance criterion ($i = \text{VA, PSVA, GE, RQ, RL, CC}$)

HHI	Herfindahl-Hirschman Index		
LCA	Life cycle analysis	E_{tmax}	Maximum value of Entropy of the total extraction of the assessed metals along the supply chain
MFA	Material Flow Analysis	$G_{WGI_{m,i}}$	Governance index of the total extraction of each material m per governance criteria i
MRIO	Multi-regional Input-output	$M_{m,c}$	Mass of each of the extracted metal in the country c as consequence of the investment using EMRIO
MW	Megawatts	$WGI_{i,c}$	Governance value of each indicator ($i = VA, PSVA, GE, RQ, RL, CC$)
Ni	Nickel	RP_m	Ratio Reserves-Production of the metal cam
Pb	Lead	$eRPR_{m,c}$	Reserve-production ratio
PSVA	Political stability and violence absence	$eR_{m,c}$	Reserve of the reference metal m in the country c (kg)
Pt	Platinum	$DR_{m,c}$	Extraction rate of resource m by the country c (kg/yr)
PV	Photovoltaics	$eR_{m,global}$	Reserve of the metal m globally (kg)
RL	Rule of Law	$DR_{m,global}$	Extraction rate of resource m globally (kg/yr)
RQ	Regulatory Quality	WGI_{iEUR}	Average of values of the governance criteria indicator i of the European countries
Sb	Antimony	$SCSI_{m,i}$	Supply Chain Strength Indicator of the supply chain of extraction of the metal m for the indicator i
Sn	Tin	$SCSI_{t,i}$	Supply Chain Strength Indicator of the supply chain of extraction of the sum of assessed metals for the indicator i
SR	Supply Risk		
VA	Voice and accountability		
WGI	Worldwide Governance Indicators		
Zn	Zinc		

1 Introduction

The Green Deal Industrial plan to make Europe the home of clean tech and industrial innovation on the road to net zero has been in the spotlight in the recent World Economic Forum Annual Meeting 2023 in Davos (von der Leyen, 2023). 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 threaten the urgent need for a fast European energy transition towards carbon neutrality due to an increasing demand around the world in the present and foreseen future (OECD, 2018). Many of the decarbonization strategies will rely on the availability of several raw materials, many of them classified as critical due to economic importance and supply risks criteria (IEA, 2021; Rietveld et al., 2022). Electricity networks deployment needs a huge amount of copper and aluminium, with copper being a cornerstone for all electricity-related technologies. 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 vehicles motors (IEA, 2021). 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 recent crisis of resources of certain minerals and metals needed for the deployment of renewable energies is even more important considering the need to deal with the current energy crisis in Europe, boosted by the Russia-Ukraine conflict. Raw materials are strategically crucial for European economy, job creation (Llorente-González and Vence, 2018) and social transition to green, digital and sustainable society (IndustriAll Europe Executive Committee, 2021), but also for energy system security. The European Union (EU) could be in a favourable position to benefit from this process, reducing its dependency on external supply and enhancing its energy security, with the inherent geopolitical dividends this would bring (Rangel Hernández, 2022). However, the concentration of these resources in a few countries (mainly in non-EU countries), the prone to value chain shocks causing supply disruptions as seen in the recent world history (COVID pandemic crisis (Willy C., 2020), semiconductors crisis (Aboagye et al., 2022; Schuh and Schnellbacher, 2022) , or the Maritime's channel bottlenecks , among others). Furthermore, the current low rates of recycling and substitution of some scarce materials, reveal the potential weakness of the supply chain of key materials for renewables deployment in Europe.

The methods to approach the assessment of energy security have been widely studied in the social science field. There is a broad body of literature which reviews and redefines the concept of energy security and the dimensions involved. Azzuni et al (Azzuni and Breyer, 2018) found 66 different definitions for this concept, in 104 literature sources. Some of these include large lists of physical, economic, social and environmental dimensions and components, proposing complex and long sets of indicators (Jansen and Seebregts, 2010; Narula and Reddy, 2016; Sovacool, 2011; Sovacool and Mukherjee, 2011; Vivoda, 2009). Particularly relevant is the work of (Cherp and Jewell, 2014), who purely define energy security as "*low vulnerability of the vital energy systems*". Considering the previous literature and this later definition, there would be three main orthogonal dimensions in the basement of the energy security concept: availability of resources, dependence on the supply and resilience of the supply chain. In the confluence of these three, the vulnerability would tend to zero.

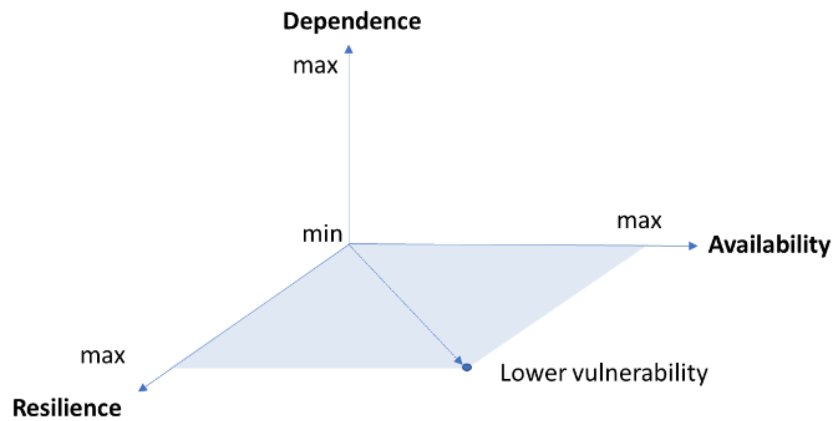


Figure 1. Three orthogonal dimensions of energy security to minimise vulnerability of the energy systems supply chain. Own elaboration.

The three aspects are closely linked with the *Circularity* concept and the circular economy philosophy (CE) since a higher efficiency of materials use can increase the availability, reduce the dependence and increase the resilience of the supply chain. Several metrics and indicators have been proposed for these three key aspects (availability, dependence, resilience) of supply risks of materials along the value chain. As for availability and demand of minerals, most of them are based on Material Flows Analysis (MFA) and Life Cycle Analysis (LCA) studies. These methods provide highly detailed figures of the involved flows, but have some disadvantages. Among these are the time-consuming data collection, the need of establishing system boundaries (with the associated limitations such as the cut-off and certain level of truncation) and the poor regionalization of the resources production existing in the LCA databases.

The Extended Multi-regional Input-Output (EMRIO) method is specially suitable for the analysis of the supply chain as it allows identifying the 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 (Gamarra et al., 2022b; Yamamoto et al., 2022). In environmental analysis, this model has been used for the quantification of material requirements involved in the deployment of energy policies as part of sustainability impact assessment (Banaclache et al., 2020a; A. R. Gamarra et al., 2023), and for the accounting of the abiotic depletion potential (ADP) involved in the value chain (Beylot et al., 2020; Castellani et al., 2019). In addition, hybrid approaches LCA-EMRIO have also been used for the specific analysis of some specific minerals (Gamarra et al., 2022a; Hertwich et al., 2015).

(Alonso et al., 2007) proposed two mechanisms that would result in a situation of materials scarcity: physical constraints, the amount and quality of a resource that is physically determined and ultimately limits resource availability; and institutional inefficiency, 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 point of view of the material flows vulnerability, (Adibi et al., 2017) identified four groups of indicators in the literature. The Global Resources Index (GRI) that combines ADP, recycling and governance metrics is one example. However, GRI is not able 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 (Blengini et al., 2017) includes dependence by incorporating a metric of concentration of supply. This last one, has been recently applied to the analysis of Photovoltaics (PV) and wind power production (Talens Peiró et al., 2022), reflecting weakness and risks associated to both power technologies.

In this paper we aim to propose a way to address the assessment of the risk and strengths along the supply chain of a set of metals and metalloids (hereinafter called metals) exemplified on the case study of solar technology deployment in Spain: Concentrated solar Power (CSP) and PV. The innovative proposed new methodological framework aims to measure the risk or strength of the energy investment supply chain by covering the three dimensions by measuring four components: availability, resilience, dependence and governance. Additionally, the proposed method is intended to be combined with existing EMRIO sustainability assessment methods to maximize the potential for supporting decision-making processes on renewable technology deployment alternatives.

First, we present the individual indicators and metrics as part of the methodological argumentation in section 2. 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, of comparative analysis by individual component and of 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 on the methodological aspects and the results of the case studies are presented.

2 Methodology

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 has been

successfully applied in material footprint assessments of global value chains (Cabernard et al., 2019) and future low-carbon economy scenarios (de Koning et al., 2018). The use of proper data sources allows expanding the system boundaries globally to include a wide range of direct and indirect impacts, and it is possible to track the specific origin of supply. Departing from the investment and operation and maintenance (O&M) costs data, the methodology allows the quantification of the material extraction of selected metals and minerals in each country and in each sector involved along the value chain. 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 introductory section (availability, dependence and resilience). The complete framework is depicted in the Figure 2.

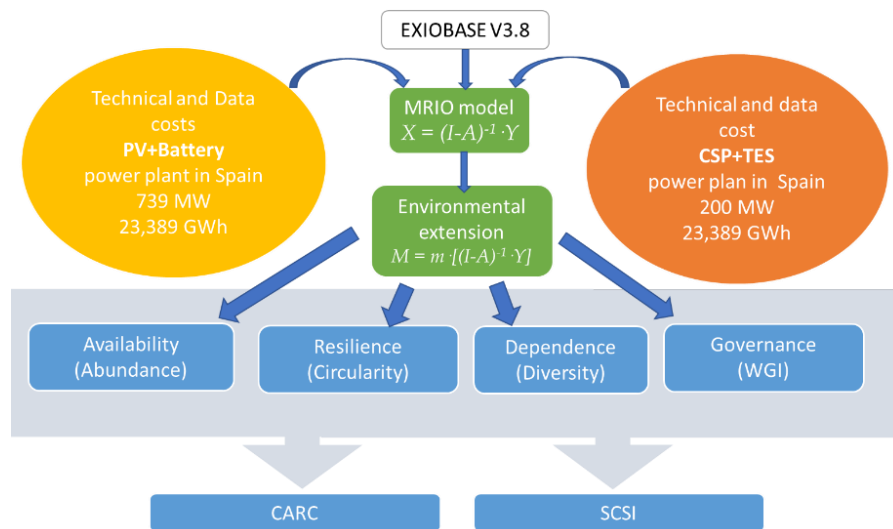


Figure 2. Methodological scheme. MRIO: Multi-regional input-output; X : output; Y : costs vector; A : MRIOT; M : amount of domestic extraction used (mass) of each raw material (metal in our case); m : environmental vector of domestic extraction (mass) of each raw material (amount of metal in our case 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.

On the top of the figure, the matrix algebra calculations of the Multi-regional Input-Output (MRIO) provides the total (direct and indirect) economic effects (X) associated to any investment. The model is extended (EMRIO) by using specific satellite accounts (m , extension vector) consisting of the country and sector coefficients for the Domestic extraction of each material per sector economic output. As main data source for the EMRIO assessment, the Multi-regional Input-Output Table (MRIOT) Exiobase v3.8. corresponding to the 2018 year was used (the corresponding technical coefficients matrix are noted as A in Figure 2, within the known as Leontief inverse $(I-A)^{-1}$ being the core of the EMRIO model (Miller and Blair, 2009)). 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.

2.1 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 (Berger et al., 2020), 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 et al., 2002). Other methods found in the LCA literature are LIME2-midpoint (Itsubo and Inaba, 2017) and EDIP (Wenzel, Henrik, Michael Z. Hauschild, 1997). In this work, the most recent values of ADP ultimate reserves are used (van Oers et al., 2020). 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 (Equation 1).

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

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

2.2 Resilience

The resilience of the supply chain to provide each resource can be increased by CE practices as they reduce the dependence of located resources and contribute to the diversify 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 (Kennedy and Linnenluecke, 2022). (Cherrafi et al., 2022) uses the example of the global pandemic disruption of the flow and pricing of raw materials and finished products in order to illustrate how the CE is able to increase the resilience of the supply chain,

since it increases stocks and availability, can help to buffer volatility of prices and reduce foreign dependence.

As for measurement of circularity, (Corona et al., 2019) and (Walzberg et al., 2021) reviewed the methodological developments regarding circularity metrics for products and services to identify the foundations of circularity metrics and applications used up 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 simplicity of some metrics, we include an indicator of circularity of the materials provided by (EC-DG GROW, 2021) and known as End-of-life recycling input rates in Europe ($EOLRIR_m$). It reflects the use of secondary raw materials. As the analysed case studies are power plants to be deployed in Spain, the European rate is useful for the assessment. Investments in other regions would need appropriate rates. The proposed rate is used to monitor progress towards a CE on the thematic area of “secondary raw materials” of CE strategies of the European Commission. The indicator measures, for a given raw material, how much of its input into the production system 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, few data are available at European and international level on the amount of secondary raw materials produced. Available data sources for the calculation of the $EOLRIR_m$ are: Material System Analysis data for the EU, currently carried out for a limited number of materials; International reports and Industry data and scientific publications. Appendix 1 (Table A) 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.

$$ERPR_m = \left(M_m / M_t \right) \cdot EOLRIR_m \quad (\text{Eq. 2})$$

$$ERPR = \sum_m^n ERPR_m \quad (\text{Eq. 3})$$

Where $ERPR_m$ is the intra-European recycling potential rate of the metal m extracted as consequence of the investment, and M_m/M_t is the share of the mass of each of the extracted metal 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).

2.3 Dependence

Dependence is included in the methodological framework by measuring the diversity of supply in terms of 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 has been used as an indicator of diversity in several disciplines, from physics to ecology, and more recently in economics in publications of European Central Bank (Corsetti et al., 2019), scientific literature (Gamarra et al., 2022b; Teza et al., 2021, 2018), and environmental studies (Többen et al., 2018). The more diverse (higher value of E_m) is the value chain, the less dependent 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:

$$E_m = -\sum_{c=1}^N S_{m,c} \cdot \log S_{m,c} \quad (\text{Eq. 4})$$

Where $S_{m,c}$ is the share of contribution of each countries or regions 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} , being the maximum value of diversity for a sample (given by the number of exporter countries or regions of the metal m in the MRIOT). The ratio E_m/E_{mmax} of each material represent 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 the total entropy (E_t/E_{tmax}).

2.4 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 to the pure level of diversity. Not only the number and share of suppliers is relevant in the dependence relationship between exporters and importers, but also geopolitical risks can be of concern. In order to weight the quality of the different origins of the supply in terms of endogenous geopolitical risk, a combined metric using criteria of governance level in each region or country is proposed. 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 (Kaufmann et al., 2011; Kaufmann and Kraay, 2018). The six criteria are: 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 been already used in the formulation of previous indicators of the risk of supply of materials to incorporate the endogenous geopolitical risks associated to their origin (Adibi et al., 2017; Talens Peiró et al., 2022) and the risk along the value chain of total goods and services (Gamarra et al., 2022b).

By applying equation 5, the governance index of the total extraction of each material per each of the six governance criteria is obtained (G_{WGLim}). 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.

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

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 Mg of each metal per GWh produced, resulting a value of governance weighted demand of metals/GWh, what allows the comparison among technologies.

2.5 Comparative analysis of individual risk components (CARC)

The comparative analysis of individual criteria provides a global picture of the value chain risks associated to each investment. Table 1 show 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_{WGlim}
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2.6 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 (Sun, 2022) and have used combined indices focused on different aspects (Choudhary et al., 2022). For example, the European Commission (EC)'s supply risk assessment measures the supply risks using the product of supply concentration, import reliance, governance performance, trade adjusted parameter, and substitution index (Blengini et al., 2017; Talens Peiró et al., 2022). The Geopolrisk tool¹ applies a different approach in a combined index that uses LCA (Cyvi Group-ISM-University of Bordeaux, 2021) and provides a value for the geopolitical supply risk. The tool is based on the development of characterization factors for the midpoint indicator 'Supply Risk Potential' that combine concentration of the supply, imports and prices.

Other examples are those focused on resource criticality measurement such as the one developed for the Chinese context by (Yan et al., 2021) that analysed three types of supply risks, i.e., sustainability risk, reliance risk, and tolerance risk, in identifying 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 to other markets. Later, the U.S. framework was further developed by (Graedel et al., 2015) 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 renewables, e.g.) whose trade flows are not being characterized at global scale and are based on MFA an 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 (Watari et al., 2020).

The Supply Chain Strength Indicator (SCSI) proposed here incorporates the four elements Availability-Resilience-Dependence-Governance (A-R-D-G) combined to measure the three orthogonal dimensions of security of energy supply traditionally discussed in the literature: dependence, availability and resilience. Additionally, governance is introduced as an additional component to each dimension that qualifies the geopolitical risks associated to the supply chain. SCSI is calculated using equation 8. First term measures dependence by a governance weighted

¹ Available at: <https://geopolrisk.org/>

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 (A. R. Gamarra et al., 2023).

The second term measures availability. In order 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 in years of physical availability of resource until reaching the total depletion of the resource.

$$RP_m = \frac{R_m}{DR_m} \quad (\text{Eq. 6})$$

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, technological constraints among others). To overcome this limitation, the U.S. Geological Survey (USGS, 2020) uses the definition of *reserve* that allows quantifying the part of the ultimate reserve which could be economically extracted or produced at the time of determination. Therefore, provided that the location of the reserves is known, the abundance of each metal in each country or region can be estimated (eRP_{mc}). We have used the data presented in the statistics of (USGS, 2020) and the works carried out by (Bach et al., 2019; Reichl and Schatz, 2022; Teseletso and Adachi, 2021). The production by metal and country is also obtained from (USGS, 2020) and (Reichl and Schatz, 2022). 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 economic reserve-production ratio ($eRPR_{mc}$).

$$eRPR_{m,c} = \frac{\frac{eR_{m,c}}{DR_{m,c}}}{\frac{eR_{mglobal}}{DR_{mglobal}}} \quad (\text{Eq. 7})$$

Then, the second term of the SCSI consists on the economical 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 measures 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.

$$SCSI_{m,i} = \left[- \sum_{c=1}^N S_{m,c} \cdot WGI_{i,c} \cdot \log S_{m,c} \right] + \left[- \sum_{c=1}^N eRPR_{m,c} \cdot S_{m,c} \cdot WGI_{i,c} \cdot \log eRPR_{m,c} \right] + \left[- \sum_{c=1}^N S_{m,c} \cdot EOLRIRm \cdot WGI_{i, EUR} \cdot \log S_{m,c} \right] \quad (Eq. 8)$$

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

The result of the addition of the three terms is a non-dimensional indicator for each metal and the total ($SCSI_{t,i}$) per and 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 which positive scores of governances and lower risks. The size of the value depends on the governance scores and the diversity of the supply, of the reserve availability (economic reserve production ratio for each metal and country), and of the supply weighted by the 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.

2.7 Case studies

The methodological approach presented before has been 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 MUSTEC² project. In order to make the case studies of CSP and PV power plants comparable in terms of dispatchability and flexibility conditions, a storage system able to provide the same electricity production during the lifespan of the plants was considered in each plant. The storage system of the CSP plant is able to provide 11 hours of storage thanks to a Thermal Energy Storage (TES) system. A battery system able to provide the same amount of energy has been considered for the PV case study.

The data costs of a parabolic trough CSP plant and PV power plant were obtained from (Banaclache et al., 2020b). The authors used the latest cost assumptions found in recent literature of investment and O&M costs (Schöniger and Resch, 2019). They also used the System Advisor Model (SAM)³ to disaggregate these costs into the different components and costs categories. The study considers a plausible scenario of Spanish-German cooperation where the

² <https://mustec.eu/>

³ <https://sam.nrel.gov/concentrating-solar-power.html>

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 (Feldman et al., 2016; Fu et al., 2018) combined with photovoltaics O&M cost data disaggregation from (Markaki et al., 2013). The vector of costs (Y in the Figure 2) is built based on the regionalized cost data for each alternative of solar power plant assessed. Detailed data can be found in (Banacloche et al., 2020b).

3 Results

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 done 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.

	Al	Cu	Au	Fe	Pb	Ni	Pt	Ag	Sn	Zn	Total
ADP (kg Sb eq./MWh)											
PV	2.3E-08	2.4E-04	2.8E+00	1.3E-08	5.0E-06	5.5E-07	3.3E-02	1.2E-02	3.1E-05	2.6E-06	2.8E+00
CSP	3.8E-12	3.2E-05	4.1E-01	9.8E-10	8.1E-07	8.9E-08	1.6E-02	2.0E-03	7.6E-06	5.9E-07	4.3E-01
1/ADP (MWh/kg Sb eq.)											
PV	4.3E+07	4.2E+03	3.6E-01	7.6E+07	2.0E+05	1.8E+06	3.1E+01	8.5E+01	3.2E+04	3.8E+05	3.5E-01
CSP	2.6E+11	3.2E+04	2.4E+00	1.0E+09	1.2E+06	1.1E+07	6.4E+01	4.9E+02	1.3E+05	1.7E+06	2.3E+00

The regional and sectoral analysis of the contribution revealed that the *Mining of iron* in China and *Mining of copper ores and concentrates* in the region of Rest of Latin America (WWL⁴) 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 B. 1 in the appendix shows the regional share of the cumulated 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 in (Mahmud et al., 2018), where the impacts to resource use by the solar-PV system with batteries are ten times as high as the

⁴ The region WWL clusters the Latin América and Caribe excluding Mexico and Brazil (countries individually included in the regionalization of the MRIOT used - Exiobase).

ones for the solar-thermal by unit of electricity. PV is revealed as more intense than CSP in the extraction of scarce materials, being the difference especially relevant for gold, silver and platinum. This last one metal and the belonging group (PGM) is included in the last list of Critical raw materials (CRM) developed by the European Commission (European Commission, 2020).

3.2 Resilience: circularity

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

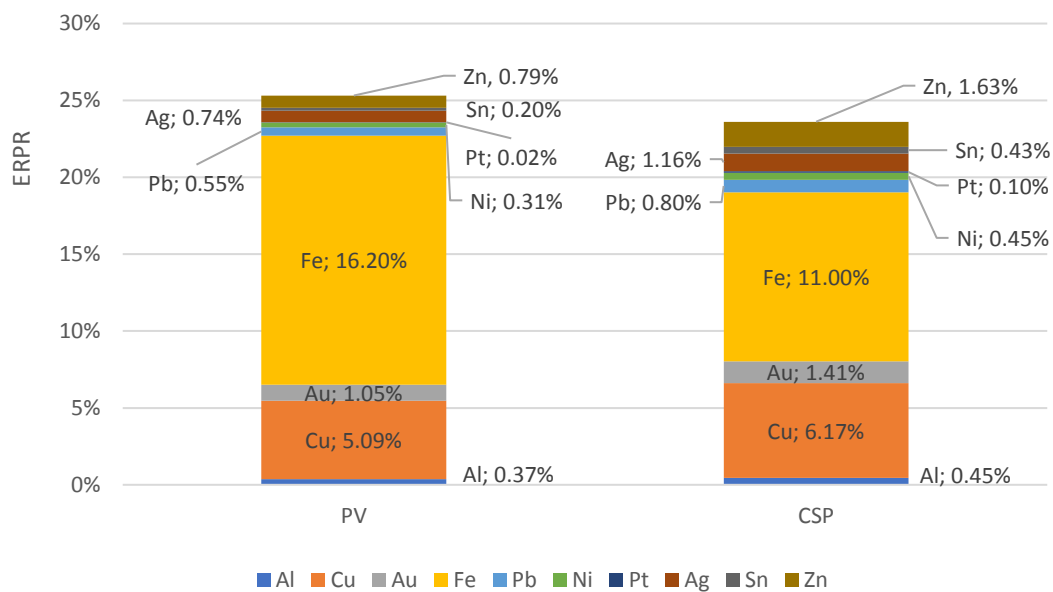


Figure 3. European recycling potential rate of the metals extracted along the supply chain of both solar power plants per metal (ERPR).

3.3 Dependence: diversity of the supply

From the dependence side, the concentration of the origin of the supply of raw materials and components leads to dominant roles of few suppliers driving unequal trade relationships and increasing the dependence on them. On the contrary, the higher the number of suppliers along the value chain and the more distributed the contribution from each one, the lower the dependence and supply risk. The share of material extracted in each region or country associated to the supply chain of each solar power plant assessed is graphically depicted in the Figure B. 1 of the Appendix B.

The values of E_m/E_{mmax} (Figure 4) show that CSP supply chain is more diverse than the PV supply chain for all the metals assessed, except for Platinum and Tin, for which while CSP value of E_m/E_{mmax} is 18% and 46%, PV achieves 30% and 53% respectively. There are not great differences between 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.

Recent works applied a similar approach for the analysis of this aspect of dependence using EMRIO and considering total economic trade of good and services demanded by CSP and Natural Gas power plants deployment (Gamarra et al., 2022b).

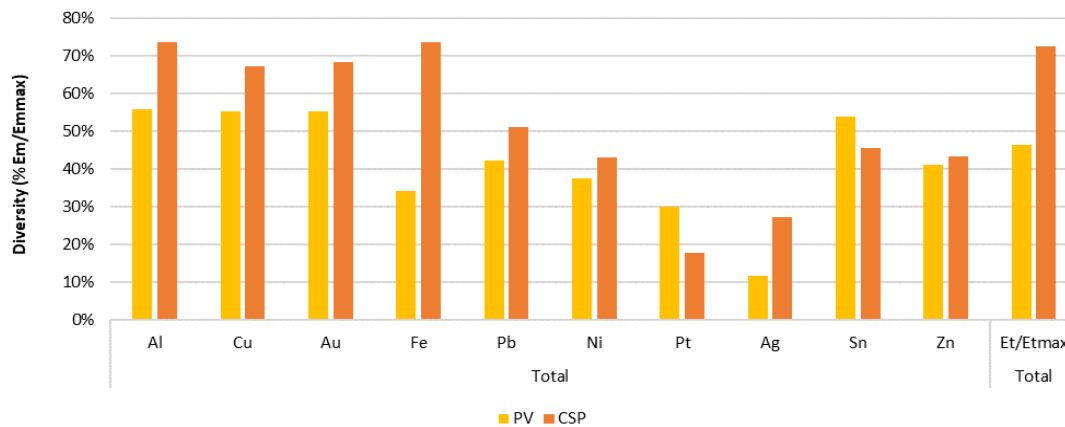


Figure 4. Diversity indicator (E_m) of the supply chain associated to each solar power plant deployment, per metal.

3.4 Governance: six-composite indicator

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

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 worthy to note that CSP value chain present all the indicators in the positive side of the axis, while some of the PV value chain indicators have negative values of governance. Iron (in yellow in Figure 5) and copper (in orange in Figure 5) are the most important metals in the analysis of governance. A cumulative total value is included in the figure to show the final balance. The PV value chain obtains a higher score in the total value due to the great positive contribution in the Government effectiveness (GE) of Iron and copper, followed by the also 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 to the Chinese origin. The contribution from Australia plays

a role in the positive side of both graphs. Figure B.2 of the appendix show 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). In 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.

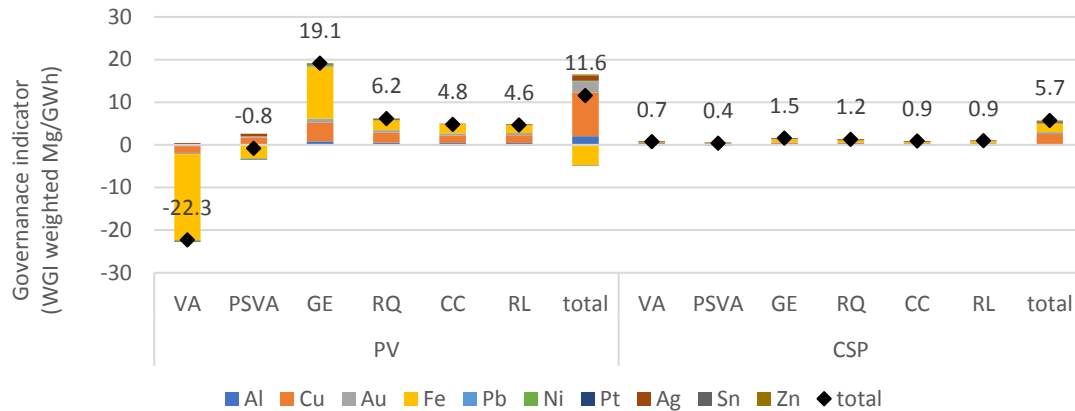


Figure 5. Governance indicator G_{WGI} of the supply chain in each scenario (PV on the right, CSP on the left) by metal (colours), per governance indicator per electricity produced.

For the comparative analysis in the case of the governance indicator, in order to remove the negative numbers in the G_{WGI} 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^*_{WGI} 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 analysed 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 to 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 performs better that PV in most metals. However, PV value chain performs much better in one of them (Iron), resulting in a total result in favour 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 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. PV value chain obtains better scores for all the metal 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 of materials by the PV value chain per MWh amplifies the range of positive and negative values of the indicator.

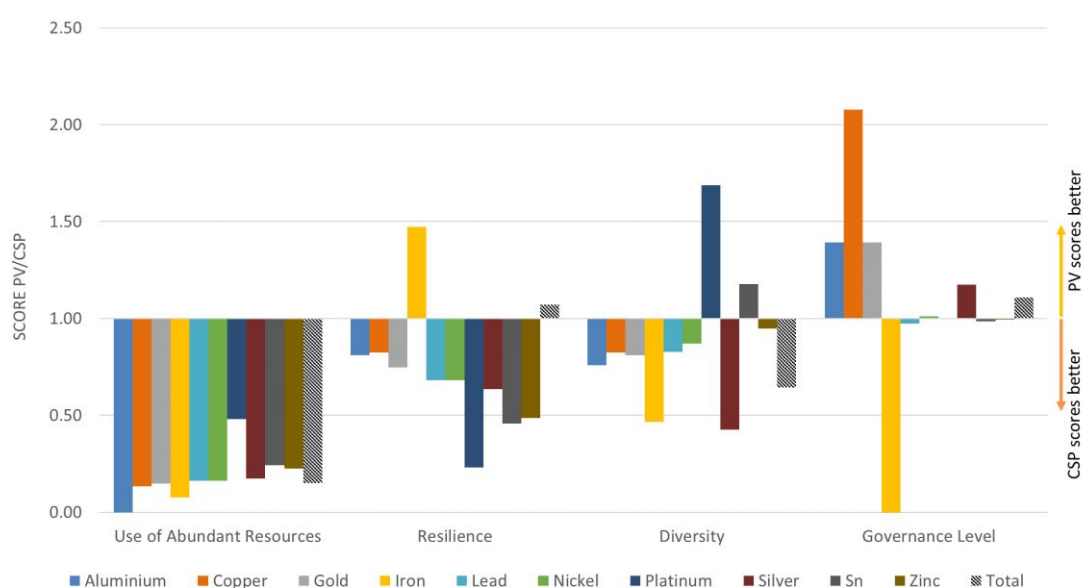


Figure 6. Risks' component comparative analysis (CARC) results. Values over 1 means a better score (lower risk) of PV for the criterion. Values below 1 means a better score (lower risk) of CSP value chain for the criterion.

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

3.6 Supply Chain Strength Index: SCSi

Results on the SCSi of the supply chain of PV and CSP case studies are showed in Figure 7. At first glance, the PV supply chain has a lower contribution on the negative side of the graph (Figure 7), which means that this chain would have more strengths than the CSP supply chain. However, focusing on the total value for all metals, PV performs worse in the scores of the SCSi for all governance criteria. Results on the contributions per country and metal brings more detailed differences (see Figure B. 3 in Appendix 3).

The indicator reflects larger diversity of supply origins in the CSP supply chain. In the PV analysis, the contributions from Australia (orange), WWL (green), China (dark red) clearly dominate the result, followed by North America (noted as USA&CAN, being Canada the main responsible, and finally, RoW (grey) being Indonesia the main contributor. In the CSP value chain, the result is affected by a wider variety of countries. The participation of European countries such as Poland, Finland or Sweden is higher in the CSP value chain, therefore, the contribution of REU region to the strengthens of the value chain is relevant. Also, the participation of other countries such as Rest of Africa region (WWF, brown) and Russia (light red) provide the main negatives.

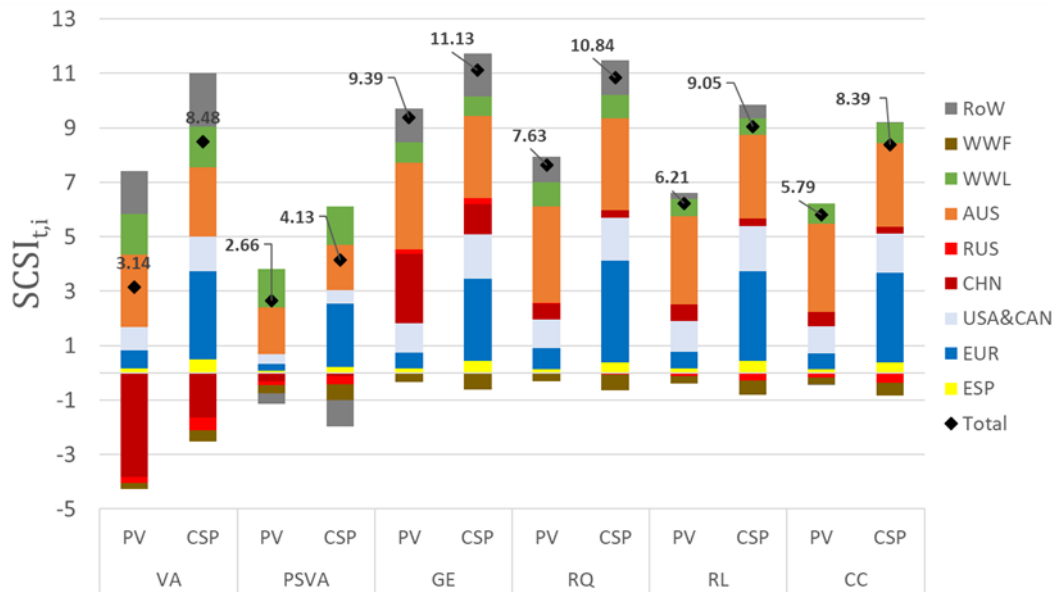


Figure 7. Results of the combined indicator Supply Chain Strength Indicator ($SCSI_{t,i}$) for each technology. RoW: Rest of the World; WWF: African Region; WWL: Latin America Region; AUS: Australia; RUS: Russia; CHN: China; USA&CAN: United States of America and Canada; REU: Rest of Europe Region; ESP: Spain.

The highest differences can be seen in the total value of SCSI for RQ, RL and CC, being higher the value achieved by the CSP supply chain due to the higher diversity and higher contribution from European countries. In addition, the higher share of Iron used by PV from low governance countries contributes to this result. Although, there is a great share of the supply from China, the Chinese supply has not a very visible role. However, this does not mean that was not relevant. What happens is that a great amount of metal coming from China is upgraded in terms of governance by the inclusion of the circularity component. In consequence, the negative scores are partially compensated.

As for metals, 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 great diversity of countries with high governance levels. Platinum, Silver and Tin would be the weakest supply chains. Despite Aluminium and Iron are quite abundant in the crust as well as they have a high circularity in Europe, they score low in the SCSi indicator. Reasons are less diverse supply chain as the mining is highly concentrated in countries with poor governance, as it can be seen in PSVA indicator.

4 Discussion

Comparing the two proposed analyses, the CARC offers a simpler framework and allows the individual analysis per criteria of risk. This analysis shows that CSP power plant deployment shows lower risks of metals availability. Focusing on the intra-European circularity component, CSP would performance better in most metals, however, PV performs much better in one of them (Iron), resulting a cumulated overall total result slightly in favour of the PV value chain (1.07 times better PV than CSP), but what that reflect is the higher intense use of iron in PV plants (with a high rate of input recycling). On the measurement of the dependence, the diversity indicator shows lower risks 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 case of Pt and Sn. Finally, the scores of Governance for PV supply chain are quite better for Cu, moderately better for Al, Au and Ag, and slightly better of Ni and Pt, while CSP reaches much better governance along the supply chain of Iron, and slightly better in Pb and Sn.

The SCSi provide a measure including availability, dependence and resilience, and allows to trace the countries and regions and the governance criteria scores that are behind the results. As observed in the figure 7, 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 et al., 2017), 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, since supply chain can be threat by illegal pathways which are frequently connected with corruption. This approach of analysis is useful for regulators and decision makers. For instance, in the deployment of a PV power plant, regulators should take care on diversity of the supply, should design mechanisms of protection and additional efforts on the matters of corruption in origin, and impulse commitments with third countries acting as suppliers on the RL developments and promulgation of more exigent standards.

However, this 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. The valuable developments of (Talens Peiró et al., 2022), also focused on the assessment of renewables supply chain from the European perspective using results from LCA. The authors use the Herfindahl-Hirschman Index (HHI) indicator that 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 allows to address a strength perspective instead of a risk perspective which facilitates the interpretation of the results. Also, the use of EMRIO framework instead of LCA allows tracing back the origin of all the metals extraction processes in the global value chain that are directly and indirectly demanded, and avoids the truncation errors of the LCA method (Font Vivanco, 2020; Ward et al., 2018). Own limitations of the EMRIO have to be taken in account. As widely recognized (Luo and Ierapetritou, 2020; Pomponi and Lenzen, 2018)), the sectorial aggregation can distort the results and cause deviations on the actual demand of the metals. Besides, the number of metals included in the environmental satellite accounts of *Domestic Extraction Used* is shorter than the ones included in the LCA databases that usually include many of the Critical Raw Materials (CRM). Comparisons have shown relevant discrepancies on the quantification of materials by these two methodologies (Ana Rosa Gamarra et al., 2023).

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. Regarding the indicators used in the assessment, the end-of-life recycling input rate (EOLRIR) could be also subject to criticism as circularity indicator. Several metals among the assessed (as bulk metals) are largely and efficiently recycled. However, their EOLRIR value is still relatively low, mainly because they are embedded in long-life capital goods, and they could be available for recycling only in the future. Other materials have instead very high values of the EOLRIR because the use and demand has been drastically reduced by legislative bans. 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 CRM, the EOLRIR is null or very low because they have been introduced only recently in innovative and complex products (e.g. e-vehicles, renewable energy plants, electronics) and technologies for their recycling are still not available or those have not been reported yet. Still data on secondary materials produced can refer to more general estimations, including average

sectorial and international data. This is why values for the European aggregated is used in the present study. Indeed, for several raw materials (including many CRMs), the EU countries are relying on imports and export of scraps, which are finally recycled by a limited number of specialized industries not evenly distributed in the European territory.

With respect to the availability, the economical reserves have been used in the SCSi as offer the possibility of allocate the resource to the country or region, however, reserves in the Earth crust and the new reserves discoveries could happen affecting the results of the SCSi. The use of the ADP could be less sensible to these events.

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 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 countries to secure its supply should be a priority. Additionally, fostering the implementation of CE strategies in the renewables manufacturing industry in Europe, maximizing the recovery of metals is also required.

The results of this methodological framework are not subject to volatilities such as those of prices or the import/export ratio, but are based on the quantification of direct and indirect extraction of material to satisfy flows, which are more perdurable along the time. Since the substitution of materials is much more difficult than that of any other input or productive factor, being relatively low variable, which gives robustness to the analysis compared to others based on prices.

Future lines of work are the application of the frame to other metals and energy technologies, as well as the combination with other methodologies. While solar technologies are based on common metals as (Fe, Al, Cu, etc.) and precious metals (Ag E.g.) assessed here, batteries and other renewables such as wind power have a stronger demand of Rare Earths and other CRMs. The integration of the methodological frameworks proposed here with Integrated Assessment models would improve the reliability of the scenarios proposed.

Other criteria can 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 (IEA, 2022). Fluctuation and volatility on prices of metals and its affordability could be a criterion (considering the CARC) or a component (considering the SCSi) to be included in future works.

5 Conclusions

This paper proposes a methodology based on EMRIO assessment to enable the analysis of risk and strengths of supply chain of metals associated to 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 with the objective of providing a holistic assessment. The quantification of 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). In order to provide a final general result encompassing all the key parameters, two perspectives of analysis are conducted: a comparative analysis of individual risk components (CARC) and a combined index (SCSI).

To test the method, the risk along ten-metal supply chain associated to two alternative solar technologies supply chains has been quantified, covering the three main orthogonal dimensions of the energy security (availability, dependence, resilience).

The results showed that in general the CSP power plant supply chain entails lower risk than PV power plant supply chain. The PV supply chain has a lower level of supplier diversification than that of CSP, and a generally lower level of governance in 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, specially the value chain of PV.

The case studies of solar technologies evaluated confirm the effectiveness of employing a relatively simple methodology for obtaining useful information regarding key supply risk and strength factors that allow 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 the dependence on foreign extraction of key metals and minerals for that, circularity and recycling policies are essential, and therefore, indicators should include those aspects.

As response to the limitations, future lines of work have been identified. Among these, the expansion of the analysis to be able to assess the supply of CRM for the deployment of

renewables is crucial. Notwithstanding the limitations discussed, the proposed method can be used to support the decision-making process of both public sector policy makers and private sector investors in deciding between alternatives identifying the geopolitical weaknesses along the value chain. Furthermore, this method may also be used by regulators to put in place the necessary measures to mitigate the identified risks and to foster the potential strengths.

Appendix A. Values of ADP, RP and EOLRIR.

Table 3. ADP characterization factor, RPR and EOLRIR_m.

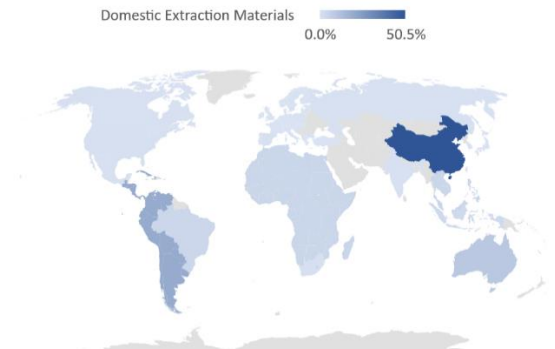
Name	Sym.	ADP	RP	EOLRIR
		kg Sb eq/kg	(kg m R ₂₀₁₅ /kg m P ₂₀₁₅)	%
Aluminium	Al	2.54E-08	7.68E+07	12.3 ¹
Copper	Cu	2.13E-02	2.66E+05	16.9 ¹
Gold	Au	1.37E+03	7.73E+04	19 ¹
Iron	Fe	6.92E-07	5.87E+06	31.5 ¹
Lead	Pb	1.87E-02	5.01E+05	75 ¹
Nickel	Ni	8.15E-04	4.16E+06	17 ¹
Platinum	Pt	9.71E+02	3.28E+05	25.3 ¹
Silver	Ag	8.64E+00	3.47E+05	20 ²
Tin	Sr	1.66E-06	2.98E+08	19 ²
Zinc	Zn	2.76E-03	8.61E+05	31 ¹

¹ Source: (EC-DG GROW, 2021)

² Source: (EC-DG Internal Market Industry Entrepreneurship and SMEs, 2021)

Appendix B. Supporting figures for the analysis of results of diversity, governance and SCSi.

a) PV power plant



b) CSP power plant

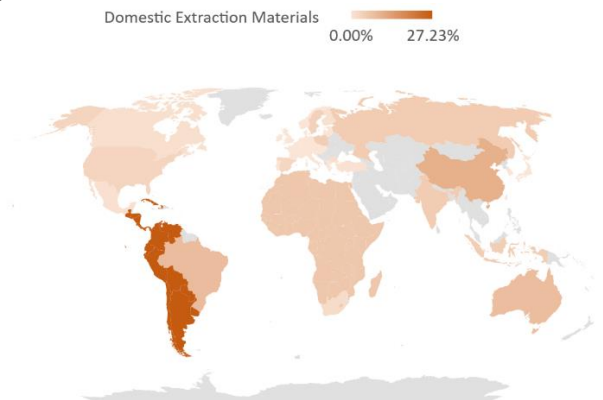


Figure B. 1. Contribution by origin to the material extraction required by the PV (a) and CSP (b) power plant deployment (%). Source: Own elaboration using Microsoft Excel with Bing Technology Extension, map data from the Australian Bureau of Statistics, GeoNames, Geospatial Data Edit, Navinfo, OpenStreetMap, Tomtom, Wikipedia.

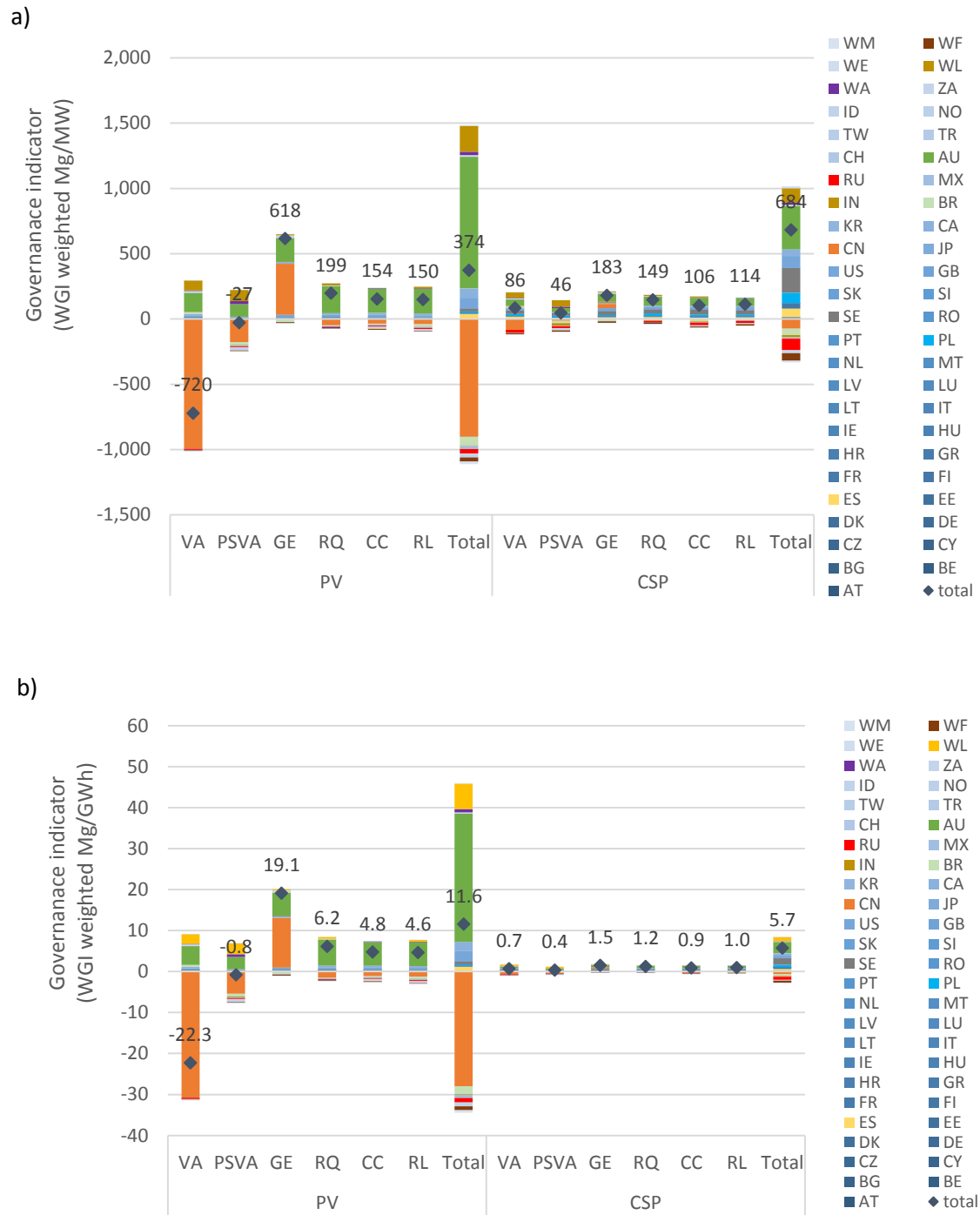
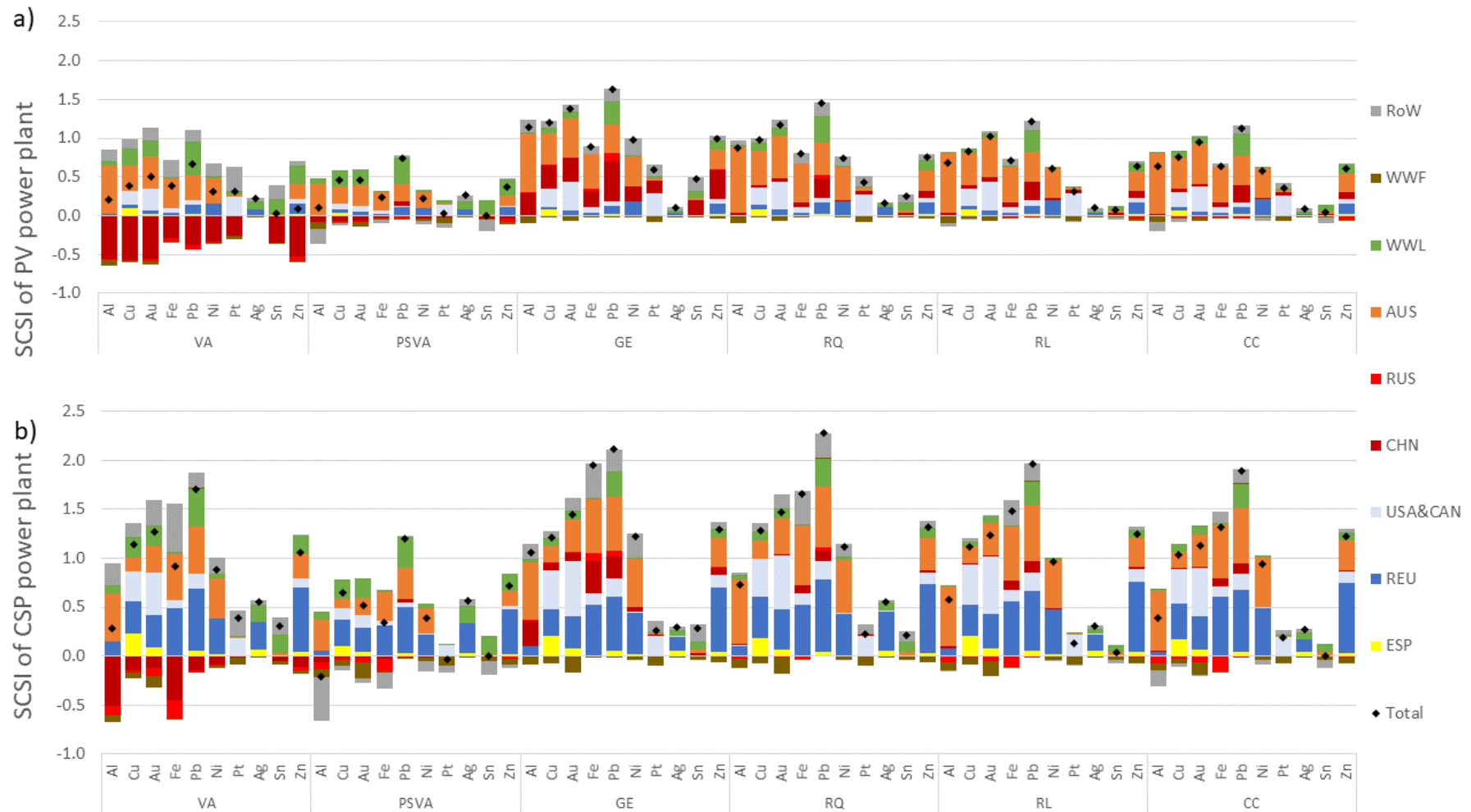


Figure B. 2. G_{WGI} of the supply chain by governance indicator, showing the contribution of the country or region (supplier) of each indicator for each metal in each case (PV, CSP) per installed capacity (MW) (a) and electricity produced (GWh) (b). List of countries or regions abbreviations: AT: Austria; BE: Belgium; BG: Bulgaria; CY: Cyprus; CZ: Czech Republic; DE: Germany; DK: Denmark; EE: Estonia; ES: Spain; FI: Finland; FR: France; GR: Greece; 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.



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4. RESULT 4: A COMPARISON AND METHODOLOGICAL PROPOSAL FOR HYBRID APPROACHES TO QUANTIFY ENVIRONMENTAL IMPACTS: A CASE STUDY FOR RENEWABLE ENERGIES

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A comparison and methodological proposal for hybrid approaches to quantify environmental impacts: A case study for renewable energies

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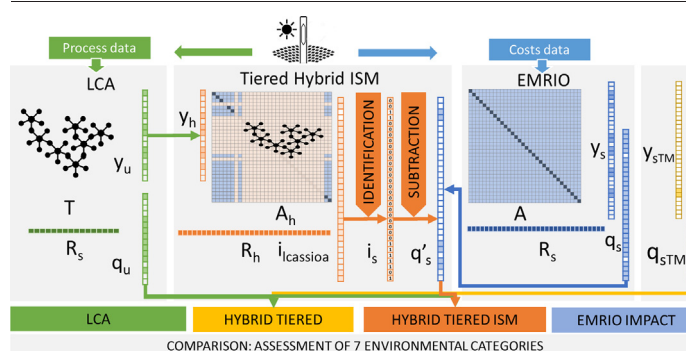
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HIGHLIGHTS

- A new proposed hybrid MRIO-LCA approach for environmental assessment is validated.
- Advantages and limitations of different methodologies are discussed.
- ISM expands the boundaries of the analysis avoiding double counting of impacts.
- ISM retains the technological representativeness of LCA.

GRAPHICAL ABSTRACT



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ABSTRACT

The transition towards a more sustainable and decarbonised energy system is mandatory for achieving global climate objectives, and counting on proper tools to evaluate sustainability is essential. Among sustainability assessment methodologies, hybrid approaches integrating Input-Output analysis (IOA) and Life Cycle Assessment (LCA) are often proposed to overcome limitations and take advantage of strengths of both methodologies. In this paper we propose a new hybrid tiered approach, named Identification and Subtraction Method (ISM). Through a case study of Concentrated Solar Power (CSP) technology, we test the proposed method assessing seven environmental indicators and compare the results obtained by different methodological approaches: Environmental Extended Multiregional Input-Output (EMRIO), LCA and two hybrid approaches.

Results showed that, in general, LCA and EMRIO provide the lowest and uppest impact values, respectively. The ISM method expands the LCA boundaries by including indirect impacts, avoiding double-counting and retaining the technological detail and representativeness of the LCA. The main advantage is the ability to establish with high accuracy the impact coming from the LCA system boundaries. Furthermore, ISM is easy to undertake for LCA practitioners, is a low time-consuming hybrid approach once the LCA and EMRIO models are run, and it does not require the alteration of the IO matrix as other hybrid methods. However, the need to perform the EMRIO and LCA analysis could imply high detailed data needs. An additional limitation of the model is that it is not able to include partial contributions from EMRIO sectors. The highest differences between results obtained by the different methods are found in the assessment of local impacts and the resources depletion, while the methods tend to agree more on global and regional impacts quantification. However, there are limitations to the implementation of the impact characterization methods that should be borne in mind when comparing the results of the different methods.

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1. Introduction

The need to boost a sustainable and fast energy transition globally (IPCC, 2022) makes it essential to rely on appropriate tools to assess the effects of different strategies. Nowadays, the methodologies to evaluate the environmental, economic and social impacts associated with renewable energy technologies face a big challenges. In order to tackle the significant hopes posed in the energy transition, applied research requires a multidisciplinary approach (Cazcarro et al., 2022), and go together on the research of the methods to support decision making and system design on the way towards a decarbonized and sustainable energy system considering the new challenges.

From the point of view of environmental impact assessment methods, two of the main methodologies are Life Cycle Assessment (LCA), and to a lesser extent, Environmentally Extended Input-Output Analysis (EEIO) (Balkau et al., 2021). LCA is a comprehensive framework for analyzing environmental impacts associated with the provision of goods and services within the economy (Guinée et al., 2002). LCA lists the physical inputs (such as materials, energy) and outputs (such as products, emissions, and wastes) for different steps along their life cycle (Shah et al., 2016). One of the limitations of LCA is the need for detailed technical data and the high amount of time required to perform a complete analysis. LCA provides relatively accurate estimates of the environmental impacts of specific processes and stages involved in the life cycle of a product or service. This allows the identification of hotspots which can guide improvement actions in different life cycle stages to reduce the environmental impact (Jiang et al., 2014). However, determining every process's inputs and outputs for the components and subcomponents of the product or service could result in a huge database and complex relationships between each process (Shah et al., 2016). As LCA always depends on defining a system boundary, its application involves truncation errors (Ward et al., 2018). In some cases, the data obtained by LCA is incomplete due to the complexity of the upstream requirements of suppliers and the services required in the supply chain. In LCA, the processes lying outside the elected boundary are considered negligible (Jiang et al., 2014). The truncation errors in LCA come from cutting off missing flows during the boundary selection (Luo et al., 2021). Some authors have found a very relevant potential deviation in impacts estimation caused by truncation in LCA (Mattila et al., 2010; Wiedmann et al., 2011). Therefore, LCA would, in principle, underestimate the environmental impact of the products or services studied. Irrespective of the foregoing, LCA has been widely applied to evaluate energy technologies and compare environmental implications of renewables and non-renewable energy sources. There are various works dedicated to the assessment of renewable energy technologies (UNECE, 2021), and specifically to the assessment of Concentrated Solar Power (CSP) (Burkhardt et al., 2012; Corona et al., 2016; Corona and San Miguel, 2018; Lechón et al., 2008; Whitaker et al., 2013).

Recent methodological developments have aimed at analyzing sustainability impacts of energy technologies by taking a macro scale perspective and accounting for the role of global value chains using environmental extended input-output EEIO (Balkau et al., 2021). EEIO analysis provides a more systemic overview of the origin and destination of intermediate and final products, with particular value in regional resource policy development (ibid). These models are based on the Input-output analysis (IOA). IOA models have the advantage of incorporating processes that would otherwise not be captured by process-based LCA (O'Connor and Hou, 2020). These processes include a wide range of services that are barely represented in LCA studies (e.g. renting of machinery or Engineering, Procurement and Construction (EPC) activities, or project management, among others). Additionally, the IOA avoids double counting since the input-output tables (IOT) are based on the principle of symmetry. IOT show a balanced picture of the economic inputs and outputs, representing the interconnections between economic sectors to satisfy the demand of commodities and the provision of services (Wiedmann et al., 2007). When the IO table includes several countries and/or regions, it is known as a Multiregional input-output table (MIOT) (Miller and Blair, 2009). The MIOTs are structured

by interlinking the flows between sectors and regions involved in the global economy, giving the assessment a planetary scope to the assessment. Thanks to environmental satellite accounts, the MIOTs are linked to the environmental flows at the sector level allowing the environmental extended multiregional input-output (EMRIO) analysis. EMRIO analysis allows the quantification of environmental impacts along the value chain.

Another advantage of the use of MIOT is that the possibility to add satellite accounts for socioeconomic and social impacts that allow the analysis of the economic and social dimensions of sustainability. This approach is usually known as the Triple-bottom line approach (Brown et al., 2006) as it assesses the three social, economic and environmental dimensions of sustainability simultaneously (Purvis et al., 2019). It can even be extended with additional analyses, such as geopolitics and security of supply issues (Gamarra et al., 2022). The main disadvantage of MIOT and its corresponding extensions is the high aggregation of processes and activities within the economy, since they are clustered in economic sectors assumed to be uniform in terms of technology and performance. Therefore, the main weakness of the approach is the sectoral aggregation, meaning the values reported in the MIOT and the associated environmental accounts do not correctly reflect a particular process or product belonging to heterogeneous sectors (EU-JRC, 2012). Other weaknesses of EMRIO approaches includes the lack of updated data, the use of monetary units (uncertainties subject to price fluctuations and inhomogeneity), insufficient handling of waste treatment, and a limited number of environmental indicators (Kjaer et al., 2015). Nevertheless, the use of EMRIO for sustainability analysis has been prolific in the last decade, measuring environmental impacts such as greenhouse gases (GHG) emissions of renewable energy policies and transition scenarios, e.g. in (van Fan et al., 2021; Wang et al., 2021; Wiebe et al., 2018). Several examples of environmental impact assessment of renewables in Spain using EMRIO can be found (de la Rúa and Lechón, 2016; Rodríguez-Serrano et al., 2017; Zafrilla et al., 2019).

In order to potentiate the advantages and limit the disadvantages of the methods (LCA and MIOT), hybrid approaches have been proposed reviewed (Crawford et al., 2017, 2018; Nakamura and Nansai, 2016) and discussed (Agez et al., 2020a, 2020b; Nakamura and Nansai, 2016; Pomponi and Lenzen, 2018; Yang et al., 2017). They had been typically grouped in three categories (Heijungs and Suh, 2002), but recent reviews have proposed four approaches (Crawford et al., 2018): i) tiered hybrid analysis, ii) path exchange hybrid analysis (PXC), iii) matrix augmentation (or IO-based LCA) and iv) integrated hybrid analysis.

Tiered hybrid analysis can be conducted by simply adding IO-based life cycle inventories (LCI) to process-based LCA results (Suh and Huppes, 2005). This hybridization system has several limitations. First, the IO-based LCI should be restricted to non-important processes for which there is no process-based information available. Otherwise, significant errors can be introduced if important processes are modelled using the aggregated IO information. Second, there could be double-counting problems in tiered hybrid analysis that should be avoided and some algorithms and methods to deal with them have been proposed in the literature with limitations (Lenzen, 2009; Strømman et al., 2009). Additionally, this hybrid method only remedies the truncation of foreground processes specific to each case study (for example, adding services not included in LCA inventories), but background processes are still truncated (Agez et al., 2020a, 2020b).

PXC was conceptualized by (Lenzen and Crawford, 2009), and relies on a conventional EEIO approach, including a Structural Path Analysis (SPA). The method consists of disaggregating the IOT into a series of mutually exclusive nodes that represent a good or service provided by a particular sector. A series of nodes is referred to as the pathway. In this method, a specific node can be modified using process data related to the value or the environmental flow associated with the transaction (Crawford et al., 2017). This method has been applied to the estimation of the carbon footprint of nuclear energy by (Zafrilla et al., 2014). As disadvantage, the complexity of this method and the amount of data to be handled have made it difficult to become a widely used (Crawford et al., 2018).

The economic IO-based LCA model (later renamed in literature renamed as Matrix Augmentation method) was developed by (Joshi,

1999) and later by (Suh and Huppes, 2005) as a means to analyze product systems. IO-based hybrid LCA consists of disaggregating industry sectors to improve process specificity. The environmental extension vectors should be disaggregated as well using detailed emission data of the disaggregated processes using life cycle inventories (ibid). The main weakness is the uncertainty in altering the MIOT, as the new sectors are completely proportional to the original sector, which limits the potential benefits of hybridization per se.

Finally, integrated hybrid LCA departs from constructing a hybrid matrix in which input-output and physical flows are fully incorporated at the unit process level. The main concern with this method is the potential for double counting. In the field of renewable energies, we can find some examples. E.g., (Gibon et al., 2015; Li et al., 2019; Whitaker et al., 2013) applied the integrated hybrid approach to the specific case of CSP technology. (Vélez-Henao and Vivanco, 2021) and (Wiedmann et al., 2011) assessed wind power case studies, in Colombia and in UK, respectively.

In this work, we propose a new approach for making a tiered hybrid analysis that seeks to expand the boundaries of an LCA using MRIO, increasing the completeness of the assessment while reducing the double-counting potential problems of the classical tiered method. The method avoids the complexity of the MRIOT alteration proposed in IO-based LCA, the integrated hybrid LCA or the PXC method. As a case study we use a CSP power plant with storage for renewable electricity generation.

The goals of the work are twofold, first we propose a new approach of tiered hybrid analysis to expand the boundaries of LCA using EMRIO, and second, we compare the results of the different approaches (LCA, EMRIO and two hybrid approaches) on the environmental assessment of CSP technology, based on seven indicators. The results will show to what extent the different methodologies are able to capture all the impacts produced in the value chain of CSP in different environmental aspects, and the potential advantages of using the proposed methodology.

The description and application of the methods, as well as the data sources and case study, are stated in Section 2. We first conduct a LCA and a EMRIO analysis of the case study. Then, we undertake a classical tiered approach (TM). For the second hybrid approach, we use a LCA software supported analysis using a hybrid EMRIO database (this approach is noted as LCASSIOA) to conduct a hybrid LCI. Then, a new proposed hybrid tiered approach is applied by combining knowledge from the undertaken LCA, EMRIO and LCASSIOA. Results on the seven environmental impacts assessed are presented in Section 3, grouped by three categories (local and regional impacts, global impacts and resources use and depletion). Moreover, in this section, we include the comparison of the results obtained by the methods and discuss the analysis's advantages, limitations and shortcomings, as well as a discussion of the related literature of case studies and hybrid methods. Finally, Section 4 presents the conclusions regarding the methodological approaches and key results of the CSP case study.

2. Methodology

This section presents all the details of the application of the four environmental assessment methods to the CSP plant case study, for subsequent comparison and analysis of the results. First, we explained the election of the case study and the main data sources details. Second, the applied methods (LCA, EMRIO, and two hybrid approaches) are described (epigraphs 2.2 to 2.4, in which a specific Section 2.4.2 is dedicated to the new methodological approach), i.e., how the study was designed and carried out. Also, specific epigraphs are dedicated to the description of data and assumptions to build the inventories and cost vectors. Finally, the environmental impact categories and how these are quantified in the assessment to allow the comparative analysis of results under the different methods are exposed (epigraph 2.5).

2.1. Case study on renewable energy technology: concentrated solar power plant

The CSP technology was chosen as a case study because of its potential crucial role in the global energy strategy, particularly for Spain. Nowadays,

photovoltaic (PV) and wind power have become the main drivers of renewable energy implementation around the world. Focusing on the PV, the recent developments on the PV technology conduct this technology towards a diversification on the application in *meso* and *micro* generation, such as heat generation using the energy surplus increasing efficiency (Harsito et al., 2022) and support of devices for sensing and communication networks (Singh, 2020). Nevertheless, their capacity to confront the challenge of substituting fossil sources is limited by the mismatch between resource availability and energy demand. CSP offers the advantage of storing the heat collected in the solar field, which is much simpler than storing electricity, and this thermal energy is converted to electricity when requested by the demand. This Thermal Energy Storage (TES) technology is a cost-effective solution for moving away from fossil fuels and transforming intermittent energy into dispatchable clean energy. This maximizes the amount of renewable energy in the mix, reducing curtailment and the need for fossil backup. Particularly in the current European context CSP deployment in Spain can play a significant role in facilitating the energy transition (Gamarra et al., 2023).

In our case, we depart from the detailed inventories and data costs developed by (Corona Bellostas, 2016). The mentioned work includes data on LCI and costs associated with a 100-MW tower CSP plus TES storage plant deployed in Spain along the whole life cycle. The author assessed the sustainability of a range of alternative scenarios of technological designs of plants comparing their environmental performance. We modelled the “only solar” design of the plant. A lifetime of 25 years and a capacity factor of 30 % was assumed. The total power produced along the life of the plant is 10,468,250 MWh.

2.2. LCA method and inventory

The LCA method is described in the standards ISO 14040 and ISO 14044. The method consists of four phases, which are undertaken iteratively: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation.

As we assess the environmental impact associated with the electricity produced by a 100 MW CSP power plant with TES along its whole life cycle, the functional unit selected is the unit of electricity produced (MWh). The LCA conducted has a “cradle to grave” LCA scope. That includes as main stages: the extraction of raw materials and equipment fabrication (MEQF), construction (CONS), operation and maintenance (OM), and the decommissioning and end-of-life stage (DEOL). Transport activities are considered in each of these stages.

As a bottom-up analysis method, the process-based LCA relies on material and energy flows originating from a product supply chain. In the LCI phase, exchanges between the product system and the background system -the broader economy- are traced back to their elementary exchanges between the economy and the environment (e.g. mineral ore from ground, CO₂ emissions to the atmosphere). The method allows the quantification of the potential of impacts of each material and energy exchanges in relation with one or more environmental impact category. Including the impacts caused throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects associated to a product or process.

2.2.1. Life cycle inventory and data sources

Among the four phases of the LCA, the LCI analysis is the most data-intensive and time-consuming phase. LCI involves collecting data and performing calculations to quantify the product system's material and energy inputs and outputs over its entire life cycle. Most of the components of the CSP plant under study are considered to be manufactured in Spain. Some exceptions are the extraction processes and the production of the molten salts for the TES, which are assumed to come from Chile, and the pumps and turbine for the power block, whose origin was assumed to be Germany. Several construction services and processes have been included in a high detailed (such as a 127 HP self-propelled telescopic crane, for example).

The specialized LCA database of materials and process scenarios Ecoinvent V.3.1 (Wernet et al., 2016a, 2016b), implemented in Simapro™, has been used to model the components and emissions by stages. Adaptations to the original LCI presented in (Corona Bellostas, 2016) were made: the electricity mix scenario was adapted considering the power mix of the year 2020 according to Red Eléctrica de España (REE) (REE, 2021). Since the solar field was identified as one of the main contributors to the impact, components such as the heliostats were updated and modelled in more detail. The mirrors and silver coating contents have been modelled following (García-Segura et al., 2021). The DEOL stage considers a decommissioning of the power plant components assuming the disassembly of the components with material losses below 10 %. Then, the treatment of the recovered materials depends on their nature and the different end of life alternatives are specified in the supplementary material 1 (SM1). The loads allocated to the recycled materials are modelled using the allocation to the point of substitution (APOS) in Ecoinvent database.

2.3. EMRIO method, costs vector and data sources

The input-output analysis (IOA) is based on input-output tables (IOTs), which consist of symmetrical tables collecting the economic inputs required to produce a unit of output in each economic sector. As the economy is composed of several interlinked sectors, the IOT contains the inter-industry flows and the final demand (y). Besides, MRIOTs are used to integrate the connections among different countries' economies. The total production of goods and services (x) to satisfy a specific demand (y) can be obtained by the IOA model by using Eq. (1),

$$x = (I - A)^{-1}y \quad (1)$$

where $(I - A)^{-1}$ is the Leontief inverse matrix (Leontief, 1936) expressing the total production (direct and indirect) of each sector required to satisfy the final demand. In the case under study, the demand vector (y) corresponds to the CSP investment vector (y_{CSP}), and the resulting value from Eq. (1) corresponds to the economic impacts derived from a change in the final demand caused by this specific investment. By combining MRIOT's information with regional and/or sectoral data (employment, greenhouse gas emissions, etc.), called satellite accounts, the analysis enables the estimation of the impacts of an investment in any sector or industry that are directly and indirectly stimulated. This extension of the analysis is achieved by including an extension vector (socioeconomic, environmental, etc.) which expresses the socioeconomic or environmental impact per monetary unit produced, for example, the kg of CO₂ emitted by a specific sector and year per unit of output produced by such specific sector. Eq. (2) expresses the calculation of the method of extension:

$$q_s = R_s(I - A)^{-1}y_{CSP} \quad (2)$$

where q_s represents the total sustainability impact (kg of CO₂, employees, etc.), R_s is the impact vector (e.g. kg of pollutants/M.EUR), and y_{CSP} is the investment vector. The investment vector, representing the costs of the CSP project, can be disaggregated into each stage of the life cycle (y_{CSP_MEQF} , y_{CSP_CONS} , y_{CSP_OPMT} , y_{CSP_DEOL}). The EMRIO provides the advantage of including services and immaterial inputs to the inventories. These expenditures have been aggregated in an additional stage that includes costs such as engineering, procurement, and construction (EPC) services, insurances, financial expenditures, taxes, etc. This stage has been called Associated Services and Immaterial Inventory, noted as ASII (and the vector of demand of the stage would be y_{CSP_ASII}).

2.3.1. Cost vector and MRIOT

The data on cost required to build the costs vector (y_{CSP}) has been based on the cost analysis presented in (Corona Bellostas, 2016). The costs are detailed per stage of the LCA. Monetary values have been updated to 2020 values using the Producer prices in industry in EU-27 (Eurostat) (Eurostat, 2020) for the costs of the components, equipment and materials

for the stage of MEQF, and for the rest of the stages, the Harmonised Price of Consumption Index has been used (INE) (INE, 2020).

Direct emissions in the OM stage due to combustion processes and direct water consumption were added directly to the impact quantification in the appropriate units. Greenhouse gas emissions from the natural gas combustion required to supply heat to the CSP power plant were estimated at 8.07E + 06 kg CO₂e (calculated in the LCA for the OM stage). Also, other direct emissions to the environment in this stage from combustion affecting the rest of the impacts were added (such as NO_x, SO₂, PM, CO, and direct water consumed). Material recycling at the EoL of CSP projects is especially relevant because it can considerably reduce the life cycle impact (Lamnatou and Chemisana, 2017). In this case study, the cost vector in DEOL includes the emissions from dismantling, decommissioning, recycling and landfilling, but also the benefits associated with the avoided material recovered in this stage, as is typically done in LCAs. For that, the avoided costs associated to recovery have been estimated. The amounts of materials recovered were calculated from the LCI performed in the LCA (see Section 2.2.1). From the fraction of material assumed to be recycled, we subtract an additional 30 % of lost or low quality materials (not available for sale). The prices for recycled construction aggregates, metal scrap, glass or plastic, were obtained from the COMTRADE database prices (UN COMTRADE, 2022), and prices for specific minerals and metals recovered from machinery and electronic wastes were based on the potential market value found in the literature (Ghimire and Ariya, 2020).

In this research, EXIOBASE3 (Stadler et al., 2018) was used as the database for the MRIOT. EXIOBASE3 is one of the most extensive EE-MRIO systems available worldwide. The data comes in two versions: a monetary version consistent with macro-economic accounts, and a hybrid mixed-unit version (physical and monetary). EXIOBASE 3 includes a classification of 163 industries by 200 products for 44 countries and five regions, for year 2011. Therefore, we assumed that the productive structure pattern remained unchanged from 2011. This is one of the main limitations of the IOA methodology.

2.3.2. LCA software-supported IOA (LCASSIOA)

Some IOT and MRIOT databases are included in LCA software to support the environmental analysis of production processes and value chains. (Kerkhof and Goedkoop, 2010) described and exemplified the application of these databases to the environmental assessment of products in the LCA Software Simapro™.

IO data by sectors and/or countries, and their associated environmental satellite accounts, are incorporated in the mentioned software in the same way as the LCA processes or materials from LCI databases - such as Ecoinvent. The software thus allows the environmental impact assessment of a process or product by assembling scenarios. The LCA of a product is modelled by assembling all the inputs and outputs from and to the environment and/or the technosphere. In the case of MRIOT databases, the sectors included represent the goods and services required by the specific process or product according to the LCI. A step forward to support the application of IO data to environmental analysis in LCA software was the use of MRIOTs in hybrids units (physical - energy and mass - and monetary), such as EXIOBASE3 (Stadler et al., 2018), which was also incorporated to LCA software by the software developers. The hybrid inventory is easily assembled in terms of units, avoiding mixing data from different databases, which provided a grade of consistency to the analysis. The software can calculate the contribution of each sector to the system of a product by solving the IO matrix with Leontief's inversion techniques. However, because of the huge amount of computational resources required to solve the IOA model with all the environmental flows incorporated in the commercial software are too high, a truncation still exists (Simapro&2.0 LCA Consultants, 2019).

For the CSP case study, we departed from the same LCI developed in the LCA in physical units (kg, MJ, tkm, hr, m³, etc.) and established a correspondence with the unit processes of the LCI and the EXIOBASE economic sectors (kg, MJ, M.EUR). For those unit processes representing a service, such as transport or the hours of a self-propelled telescopic crane, monetary conversion was done using the unit prices of production for domestic and

imported manufactured goods. Construction-related services prices were extracted from governmental estimates (GobEx, 2020). Transport costs are calculated by using prices obtained from the UNCTAD database (UNCTAD, 2016). These expenditure equivalents were then used to replace the corresponding unit processes of the original LCI representing the components and stages along the life cycle.

Additionally, the inventory associated with financial services, insurances, taxes and EPC (rarely modelled in LCA databases) were included in ASII stage.

As a result of the inventory analysis and software-supported modelling, in our framework we obtained the CSP power plant direct and indirect demands from the sectors and regions involved in each life cycle stage, providing the bridge between the LCA scope and the EMRIO results. We do not consider this approach as a hybridization method as it still relies on aggregated MRIOT information and does not use the more precise technological information from the process-based LCA. However, the LCASSIOA plays a role as its results are used in the proposed new tiered method explained below (ISM).

2.4. Hybrid approaches: tiered and identification-subtraction

Some of the hybrid methods undertaken in the literature involve MRIOT alteration. In our research, we aim to avoid MRIOT alteration since it can bring a potential lack of balance on economic sectors and their links with the satellite accounts. For that, we employ two methodological approaches combining insights from LCA and EMRIO.

2.4.1. Tiered hybrid approach

The classical tiered approach was conducted by adding to the LCA analysis the impact associated with financial services, insurances, taxes and EPC, as modelled with MRIOT. This impact is not usually included in LCA databases. We have grouped these processes in a stage (ASII). However, as noted earlier, many other services and immaterial insures (and their impacts) demanded indirectly by the background processes are ignored when using this approach. Therefore, this method only partially solves the truncation error attributed to LCA.

2.4.2. A new hybrid approach of identification and subtraction (ISM)

As the tiered hybrid approach presents some disadvantages, we propose a new tiered hybrid approach by combining the insights and results from the undertaken EMRIO and LCA methods, and the LCASSIOA approach. Fig. 1 depicts the methodological scheme of the proposed approach (noted as ISM) and the links with the LCA, EMRIO and LCASSIOA. The detailed formulation of the method is provided in the supplementary material 2 (SM2). Also, simple examples of demonstration of the method following the argumentation of the literature (Pomponi and Lenzen, 2018; Yang et al., 2017) are detailed in the Supplementary Material 3 (SM3).

As basis for the development of the ISM approach, we assume that EMRIO is the most complete in terms of background flows along the value chain, and LCA is more precise in quantifying the foreground processes. In the context of the case under study, the LCI from the LCA provides the most detailed figures on flows of energy and materials along the life cycle of the CSP plant. The LCASSIOA conducted following this LCI allows the identification of the sectors (in the specific country or region) demanded along the LCA according to the LCI inputs and outputs. Then, we adopt the assumption that those sectors contributing to the inventory in the LCASSIOA are those already included in the process-based model, and the rest of them correspond to those activities (and their impact) which are out of the LCA boundaries. Thus, the contribution of the sectors already included in each stage of the LCA are identified and subtracted from the MRIOT results (in each stage).

Besides, we consider that there are some sectors usually well-represented in LCA, such as transport processes, manufacture of vehicles, trailers and semi-trailers, the transmission of electricity, the collection, purification and distribution of water and construction. Therefore, we also subtract the contribution of those sectors from the specific origins of the

EMRIO. The sectors considered to be excluded from the LCA boundaries are listed in the (SM1).

The final results obtained through this hybrid approach combine process-based LCA and EMRIO outcomes avoiding the overlap of sectors (i.e., double counting). With this approach, we guarantee the technical representativeness of the foreground processes included (LCA results) while also maximising the assessment's completeness by adding through EMRIO the missing sector contributions.

On the one hand, the ISM increases the completeness of the assessment, as we added to the LCA results the contribution to the impacts of far sectors, and on the other, reduces the double-counting as the sectors that are in the LCASSIOA (and theoretically are included in the boundaries of the LCA) are identified and subtracted. This identification is possible thanks to the use of Exiobase (V3.3) for the LCASSIOA (hybrid) and EMRIO (monetary). I.e. the impact contributions added come from sectors whose exchanges are not captured by the sectors directly involved in the LCA inventory of processes (according to the LCASSIOA results). Then, at least a portion of the background impact excluded of the LCA boundaries is added (coming from the MRIOT). As those sectors are not involved in the value chain identified by the LCASSIOA, the double counting is necessarily reduced.

2.5. Environmental assessment

We assess seven categories of environmental impacts. The assessment methods selected are those included in the Environment Footprint (EF) method proposed by the European Commission (Fazio et al., 2018). In the Appendix, a description of characterization methods is provided. The selected environmental categories can be grouped in three categories:

- Global and regional impacts: Climate Change (CC) and Acidification terrestrial and freshwater (ACD);
- Local impacts on human health: Photochemical ozone formation - human health (POF) and Respiratory inorganics (RI);
- Resource use and depletion impacts: Water use (Wuse) and water scarcity (Wdep), Resource use: energy carriers ((ADP-E); Resource use: mineral and metals (ADP-MM).

The LCA characterization step was performed by using the EF method, as implemented in Simapro, that allows the characterization of more than 13,900 substances and 4000 raw materials. For the LCASSIOA approach, the characterization of substances was done through Simapro™, but adding the list of substances included in the EXIOBASE satellite accounts from the EMRIO model (a list of the 63 emission flows, water use and 29 mineral and energy resources). In the case of the EMRIO approach, the calculations were done using MATLAB, and the substances were characterized considering their impact on the different EF environmental impact categories selected. The characterization factors obtained from the EF method used in EMRIO modelling are listed in the SM1.

3. Results and discussion

This section contains the results of applying the five different assessment methods to the CSP case study, organised per impact category. Finally, a discussion on the variability of the results obtained by the different approaches is provided.

3.1. Global and regional impacts: climate change and acidification

3.1.1. Climate change

Results on climate change range between 22.1 and 34.7 kg CO₂e/MWh, as represented in Fig. 2. The lowest value is obtained by the LCA method, and the highest by the EMRIO. These results of total impact are in line with the values found in the LCA literature for this technology. Corona (2016) estimated an impact of 18.5 kg CO₂e/MWh. Whitaker et al. (2013) evaluated a 106-MW power tower concentrating solar power plant

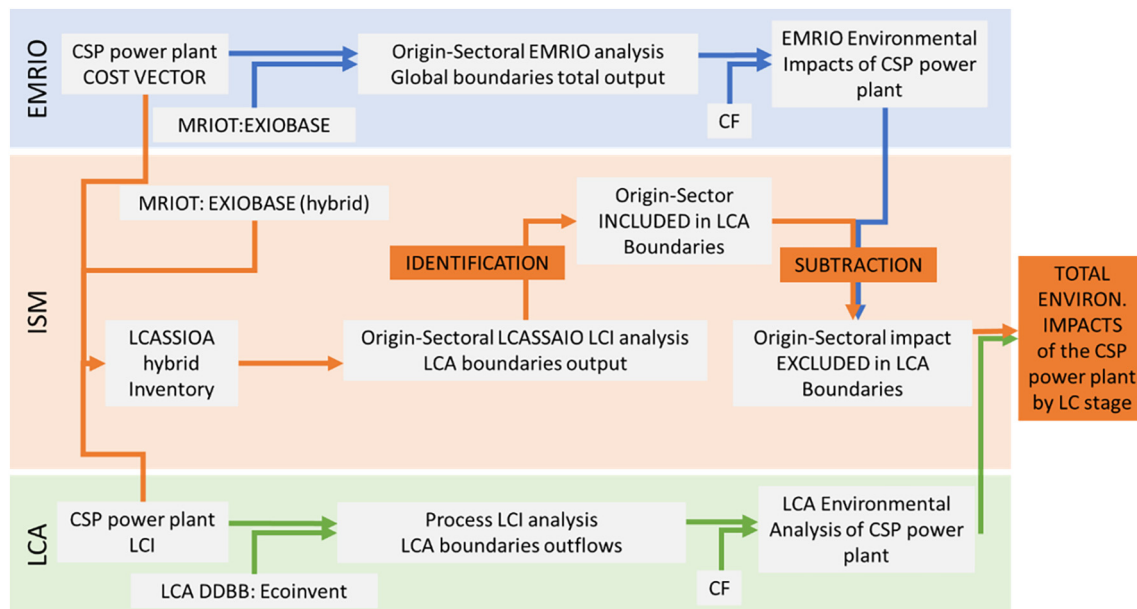


Fig. 1. Methodological scheme of the LCA, EMRIO and ISM. CF: Environmental impact characterization factors.

over its life cycle obtaining 37 kg CO₂e/MWh emissions, and the review provided in UNECE (2021) found an average value of 21.7 kg CO₂e/MWh. The hybrid approaches show intermediate values among LCA and EMRIO results. The TM approach provides a very similar result to the LCA, with the only difference caused by the indirect costs (1.65 kg CO₂e/MWh). The ISM approach provided a slightly higher result (23.7 kg CO₂e/MWh). LCASSIOA shows a lower result than the EMRIO, possibly due to the truncation that still exists in this method (27.6 kg CO₂e/MWh).

In every case, the stage of extraction of raw materials and manufacture of components (MEQF) is the stage with the highest contribution to CC. In the case of LCA, this stage has an impact of 18.2 kg CO₂e/MWh which means that 82 % of the CO₂e emitted along the life cycle is emitted in this stage. The process contribution is dominated by processes of production of metals, manufacture of flat glass, and production of energy in Europe and China. EMRIO results provide a quantification of 22.6 kg CO₂e/MWh in the MEQF stage, lowering the impact contribution of this state to a 65 %. The 50 % of the carbon emissions would happen in Spain, followed by Germany, Latin America and China. The sector of *Manufacture of basic iron and steel and of ferro-alloys and first products thereof*, the sector of *Manufacture of glass and glass products* as well as sectors associated with fuels and energy production are the main contributors in Spain.

The stage of construction (CONS) presents a wide variety of results. While using LCA and TM methods the impact is quantified at 3.45 kg CO₂e/MWh, with EMRIO method the impact is 9.81, with LCASSIOA is

5.92 and with ISM is 3.89 kg CO₂e/MWh. When applying the ISM, the results revealed that the impact added from EMRIO results is distributed among many different countries and sectors with small contributions. Only primary sectors such as agricultural sectors and *mining of precious metals*, and the sectors of recycling and landfill and other services in Spain have contributions over 1 %. Below 1 % contribution, we can find the sector of *Production of Electricity by coal* in Taiwan, the sector of *Extraction, liquefaction, and regasification of other petroleum and gaseous materials* from Africa, as well as primary sectors of agricultural production in Asia.

The CO₂e emissions in the OM stage are mainly caused by the direct emission from the in situ combustion of natural gas to provide heat to the thermal storage system (auxiliary boiler). The impact associated with the DEOL is negative in every case, which means that the recovery of materials in that stage would avoid the emission of CO₂e associated with extraction and production of a portion of materials, compensating the emissions produced in the recycling processes. The CO₂e results obtained for the DEOL stage are similar in every method, with differences lower than 1 kg CO₂e/MWh. The ISM negative estimation is slightly higher (− 4.30 kg CO₂e/MWh) than the EMRIO and LCA estimates. This result indicates that the overlapping between EMRIO and the sectors identified as included in the LCI (LCA boundaries) in this stage is lower than in other stages. Although results from EMRIO and LCA are quite similar, the sectors included in both methods are different. The specific avoided emissions associated with precious metal production and some primary sectors in Asia are

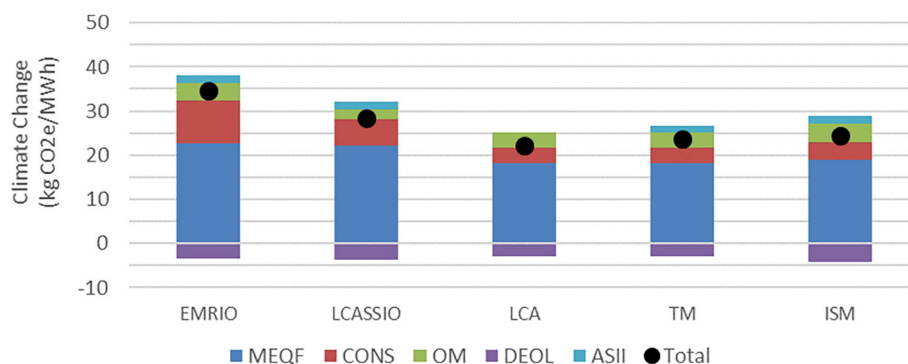


Fig. 2. Climate Change impact by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying five methods of quantification.

responsible for the higher value obtained in the ISM method as they are excluded from the LCA boundaries. That would mean that the truncation error from the LCA approach is quite large in this stage.

The ASII stage contribution to the total impact is small (around 1.7 kg CO₂e/MWh) and reveals that the direct expenditures in services are not the main cause of the underestimation in LCA results. Indirect services and immaterial expenditures associated with physical inputs and outputs seem to have a greater impact.

3.1.2. Acidification

The acidification impact along the whole life cycle ranges between 0.181 (LCASSIOA result) and 0.238 (EMRIO result) mol H⁺e/MWh. The result for the LCA and EMRIO approaches is similar, amounting to 0.223 mol H⁺e/MWh. The LCA and TM methods provide higher values than the LCASSIOA (Fig. 3). These values align with the upper range of the values reported in the LCA literature for this technology (Caldés and Lechón, 2021).

The MEQF stage shows similar values of acidification using the five methods. The EMRIO and LCASSIOA indicate high contribution from the same sectors, in particular the manufacture of basic iron and steel, fabricated metals, glass and electrical machinery and apparatus and sea and coastal water transport. Correspondingly, the LCA method identifies iron sinter, copper production (used in machinery), transoceanic transport and flat glass production as the main contributors to acidification. The remaining difference between EMRIO and LCASSIOA comes from primary sectors whose impact on acidification is high such as Raw milk or Cattle farming around the world (Africa and Asia). The difference on total results would apparently come from the release of substances in sectors excluded from the LCI of the CONS and DEOL stages.

According to the ISM approach only the 9 % emissions from the sectors involved would have been excluded from the boundaries of the LCA (and LCASSIOA). However, while LCASSIOA and LCA account for 0.031 and 0.035 mol H⁺e/MWh for CONS respectively, EMRIO estimates reach 0.07 mol H⁺e/MWh. While in LCA and LCASSIOA the contribution of processes and sectors is more concentrated distributed, the EMRIO impacts are more dispersed among sectors. The LCA method identifies six processes as main contributors (clinker production, iron sinter, concrete production, blasting, transoceanic transport and combustion in machinery) accounting for 50 % of CONS impact. Correspondingly, 50 % of the impact in the LCASSIOA model is generated in Spain from the related six sectors (*Manufacture of cement, Manufacture of basic iron, Manufacture of bricks, tiles and construction products, Manufacture of other non-metallic mineral products, as well as the emissions from combustion in machinery and Sea and coastal transport*).

EMRIO results for CONS show contributions from the same and other sectors as not negligible in acidifying emissions. These sectors are located in Spain (*Manufacture of other non-metallic mineral products n.e.c., Construction, Manufacture of cement, lime and plaster, Re-processing of ash into clinker, Manufacture of basic iron and steel and of ferro-alloys and first products thereof, Manufacture of ceramics, and Production of electricity by coal*) and abroad

(*Mining of copper ores and concentrates in Latin America, and Forestry, logging and related service activities in Asia*). These sectors are also included in the LCASSIOA but with a lower representation. As we consider that process-based LCA and consequently LCASSIOA provide a more precise quantification of impacts within their scope (better technological representativeness), the impacts from these sectors are not incorporated in the ISM. Note that the ISM it is not able to quantify the partial contribution of a specific sector from a determined region.

A wide portion of the difference is due to the indirect emissions, which ISM is able to identify and quantify, coming from primary sectors (agriculture and mining) and indirect services (as some sectors of recycling and landfill) in Spain, China and Rest of Asia, Latin America and Africa. These emissions would occur in Spain (21 %), Africa (24 %), Asia (19 %), and China (6 %).

At the DEOL stage, the avoided impact quantified by LCA method (−0.008 mol H⁺e/MWh) is much lower than that of EMRIO (−0.026 mol H⁺e/MWh). LCASSIOA and ISM found an avoided acidification impact of 0.0202 and 0.0205 mol H⁺e/MWh, respectively. These differences are due to the fact that recycling processes for WEEE (Waste of Electric and Electronic Equipment) from databases (Ecoinvent, in this case) do not consider the specific recovery of precious metals and therefore, the emissions avoided from these materials were not included. However, in the EMRIO analysis the recovery of silver and gold has been allocated to the mining and precious metals production in Spain as an avoided production.

There are also indirect emissions avoided that come from mining of copper ores and concentrates in Latin America, Africa and Asia as well as agricultural activities in Asia, Latin America and Africa.

3.2. Local impacts: photochemical ozone formation and respiratory inorganics

3.2.1. Photochemical ozone formation

Results on POFP impact along the whole life cycle using the different methods indicates relevant differences. The results range between 0.110 (LCASSIOA result) and 0.248 (EMRIO result) kg NMVOCe/MWh. A similar trend to acidification results is found but with larger differences between values (Fig. 4).

In the MEQF stage, the impact provided by the EMRIO method (0.175 kg NMVOC e/MWh) is higher than the rest of the methods. LCA and the other methods provide similar results (from 0.073 to 0.095 kg NMVOC e/MWh).

The main sectors causing POFP in the MEQF stage, according to EMRIO, are the *Manufacture of basic iron and steel and of ferro-alloys and first products thereof* (18 %) followed by *Mining of coal and lignite; extraction of peat* (5 %), *Manufacture of glass and glass products* (3 %), the *Re-processing of secondary steel into new steel* (2 %) and the *Production of electricity by coal* (2 %) in Spain. Abroad the domestic border, the *Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c. in Latin America* (5 %), the *Mining of coal and lignite; extraction of peat in China* (3 %), the *Extraction of crude petroleum and services related to crude oil extraction, excluding*

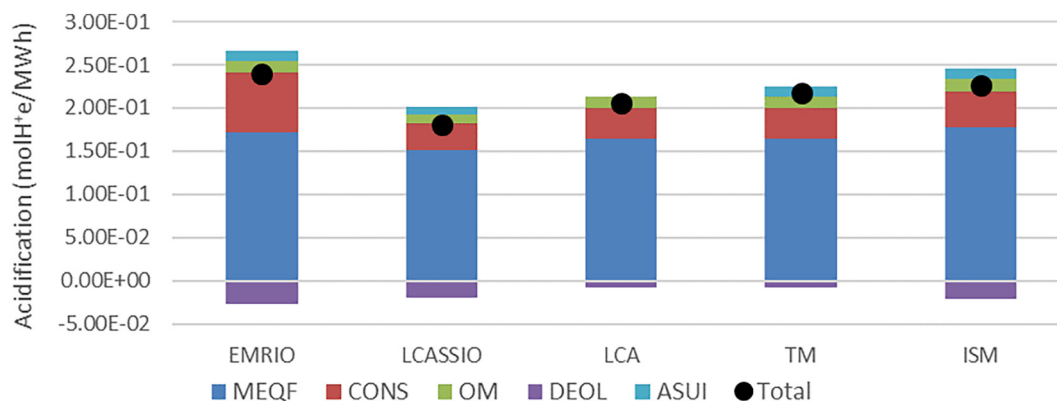


Fig. 3. Acidification impact by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying five methods of quantification.

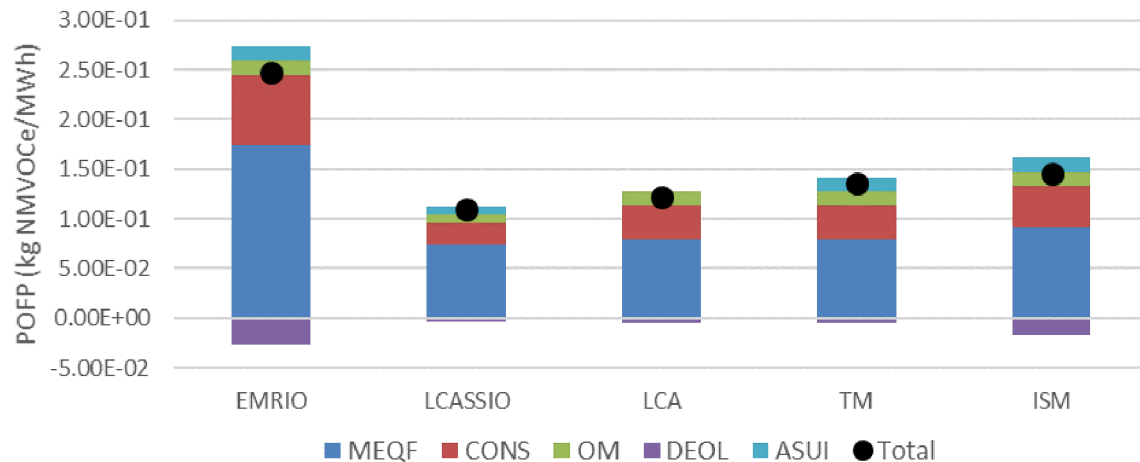


Fig. 4. Photochemical ozone formation potential impact by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying five methods of quantification.

surveying in Russia (2 %) and Africa (2 %). Then, the contributions are due to other Process of sea and coastal transport, Manufacture of metals and energy-related in Europe and other regions. The LCASSIOA reveals a similar list of sectors but with different contributions: the manufacture of metal products, except machinery and equipment in Spain (25 %) and China (2 %), the Manufacture of basic iron and steel and of ferro-alloys (18 %), the Sea and coastal transport (6 %).

Among the LCA results for the MEQF stage, it is worth highlighting the contribution of the coking process used in the industry of metal manufacturing (11 %), the transoceanic transport operation and manufacturing of ships (14 %), the iron sinter (7 %), blasting (5.5 %) and flat glass production (4.5 %). ISM results are slightly higher than LCA results. The impact from sectors incorporated from EMRIO - which would be excluded from the LCA and LCASSIOA scope - would be emitted in the Mining of precious metals in Brazil and Russia, Manufacture of basic iron and steel and of ferro-alloys and first products thereof in some European countries, and a numerous but small contributions from agricultural sectors in Latin America, Asia and China.

The reason for the much higher impact estimation of EMRIO in this impact would most likely come from the high sectoral aggregation of the MRIOT that do not represent well the specific processes involved in the life cycle. The other source of discrepancy would be the better representation of the global value chains in EMRIO that allows identifying imports of intermediate products in the value chain and their associated impacts. This identification is not easy in LCA, especially in background processes. However, this reason is less likely because the ISM method included these imports and, still, did not result in a POFP impact as high as the EMRIO method. Therefore, the difference must come from the sectorial aggregation issue.

The OM stage results are quite similar for every approach, being a bit lower in the LCASSIOA method. The rest of methods quantify the impact in this stage as minor but with similar results among them (0.013–0.015). The DEOL stage also shows remarkable differences between the EMRIO results and the rest of the methods. The recovery of materials in decommissioning by recycling and re-processing avoids emissions mainly from the Manufacture of basic iron and steel and of ferro-alloys and first products thereof, as well as from extractive industries in Spain and Latin America and North America, as well as in China. Also relevant are the emissions from agricultural sectors in Asia. This stage encompasses also positive emissions associated to the own activity of decommissioning. Even after the addition of positive and avoided contribution by sectors, the impact from some sectors is positive (Re-processing of ash into clinker, Construction and landfill of inert/metal/hazardous wastes).

When it comes to the ISM results for the DEOL stage, the added EMRIO sectors are mainly tertiary sectors such as Wholesale trade and commission trade, except of motor vehicles and motorcycles in Spain and Retail trade, except

of motor vehicles and motorcycles and repair of personal and household goods in Asia and some primary sectors of agricultural product cultivation in Asia.

3.2.2. Respiratory diseases

The quantification of the Respiratory Inorganics shows a very high variability on results depending on the method used (Fig. 5). The impact along the whole life cycle ranges between 1.5E-6 (LCA result) and 1.01E-5 (EMRIO result) disease inc./MWh. ISM's total estimate of respiratory diseases impact is close to LCA results being also 1.5E-6 disease inc./MWh. LCASSIOA provide higher values than LCA and TM methods. In every case, the MEQF is the main contributor to the total impact.

The emissions involved in this impact are particular matter, ammonia, nitrogen oxides and sulphur oxides released to the air. Mechanical (grinding, refining, sieve, mixing, abrasion, crushing, etc.) as well chemical processes (such as combustion) are susceptible to emit these substances to the atmosphere. Also, physic-chemical reactions in the atmosphere happen before the pollutants reach receptors and cause changes in diseases in population.

The EMRIO results show that the main sectors implied in the impact of MEQF stage are the Manufacture of basic iron and steel and of ferro-alloys and first products thereof (27 %). Then, the Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c. in Latin America would be responsible for the 8 %. Other sectors from Spain involved are the Manufacture of cement, lime and plaster (4 %), the Re-processing of ash into clinker (3 %), Re-processing of secondary steel into new steel (3 %), and the Production of electricity by coal.

In the LCA and TM results of MEQF stage the main contributors are the processes of iron production (13 %) and processes related to coal mining and electricity production with coal in China, the combustion of diesel in machinery and the steel production. Besides, the share of impact of flat glass production (5.6 %) is among the top ten processes.

In the construction stage (CONS) the diesel burned in building machinery is the most important contributor (33 %), followed by iron sinter (19 %), coal mining and coal-fired electricity production (25 %) and concrete production (7 %). Clinker production, transport by road and excavation works are the following contributors but under the 5 % of share. For DEOL stage the avoided impact of iron production (iron sinter, pig iron, iron pellet) and coal-fired production are the key players. However, there are relevant emissions caused by diesel burned in building machinery used in the dismantling and decommissioning of the plant and the emission of particular matter for the concrete recycling processes.

In the ISM method, the indirect emissions incorporated to the impact of MEQF by LCA are low and represent a small portion of the EMRIO emissions. As a result, the impact is only a 16 % higher for MEQF stage than in the LCA, coming from sectors located out of Spain. Therefore, the activities provided by these sectors are well represented by purely process-based

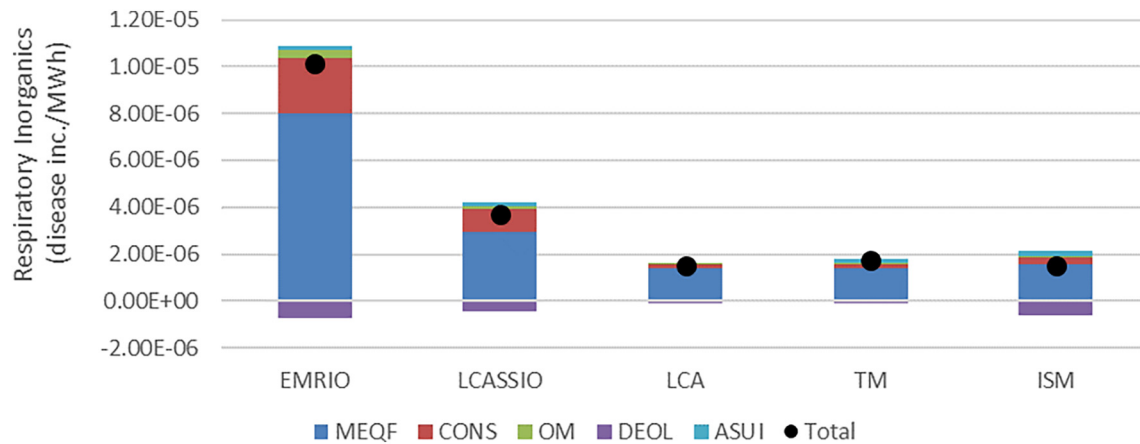


Fig. 5. Respiratory inorganics impact by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying five methods of quantification.

inventories. Differences in total impact estimation are not due to the cut off but, but most likely to the lack of representativeness of the MRIOT sectors for this specific technology and impact.

On the contrary, the attributable impact to the LCA boundaries is 34 % in CONS, and 63 % in OM. The impact attributed to the DEOL stage in the LCA is almost negligible. The EMRIO contribution to ISM impacts is high, in this case, the emission avoided would happen in the sectors of *Mining of metals* in Spain, and then, *Quarrying of stone, Manufacture of cement, lime and plaster, Manufacture of basic iron and steel and of ferro-alloys and first products thereof*, and *Production of electricity by coal* in China.

3.3. Global resources use: energy, water, minerals and metals

3.3.1. Water scarcity

Table 1 shows the obtained results for water consumption and water depletion per kWh produced as calculated with the five methods. The water consumption results shows low variability among methods (2.07 m³/MWh provided by LCA, to 2.7 provided by ISM and EMRIO), and alignment with literature values (Klein and Rubin, 2013; Meldrum et al., 2013). The total impact value calculated by ISM method slightly overpasses the EMRIO result. However, the contribution of the different stages to the total results is very different in each method.

The water consumption in the OM stage (used in the operation of the turbine and water consumed in cleaning) provided by all the methods contributes the highest share to the total water consumption, except in the case of ISM, in which the MEQF stage has the highest contribution.

The stage of MEQF shows the highest differences among ISM and the rest of methods. At this stage, the LCA shows that the water used in electricity production by hydropower for the manufacture and processing of raw materials and components would be responsible for most of the impacts.

Table 1

Water consumption and water depletion impact by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying the five methods of quantification.

		MEQF	CONS	OM	DEOL	ASII	TOTAL
Water use (m ³ /MWh)	EMRIO	0.78	0.34	1.66	-0.27	0.15	2.66
	LCASSIOA	0.64	0.14	1.61	-0.09	0.08	2.38
	LCA	0.78	0.10	1.23	-0.04	0.00	2.07
	TM	0.78	0.10	1.23	-0.04	0.15	2.22
	ISM	1.30	0.33	1.25	-0.33	0.15	2.71
	LCASSIOA	27.65	6.19	56.18	-3.81	3.30	89.51
Water depletion (m ³ depriv. /MWh)	EMRIO	40.04	18.37	128.45	-12.00	8.12	182.97
	LCASSIOA	27.65	6.19	56.18	-3.81	3.30	89.51
	LCA	50.69	15.44	20.52	-0.07	0.00	86.58
	TM	50.69	15.44	20.52	-0.07	8.12	94.70
	ISM	75.94	27.03	148.18	-11.75	8.12	247.53

In the LCASSIOA case, the sectors of manufacture of metals, basic iron and steel would be the main contributors, while the EMRIO sectoral analysis shows that the main contributions would be indirect water footprint from agricultural production sectors around the world (Asia, Africa and Latin America), which are very intensive in the water demand, followed by the *Wholesale trade and commission trade, except of motor vehicles and motorcycles*. The discrepancy in impact contributions between EMRIO and LCA is due to the arbitrary selection of system boundaries in LCA that fails to consider a significant part of the impact produced. While the hybrid TM is unable to incorporate these impacts, the proposed ISM does. The analysis with ISM shows a reduced overlap among LCA and EMRIO since the indirect contributions from agricultural sectors are out of the LCA boundaries, and therefore a relevant share of the contribution from EMRIO results has to be added to LCA results. On the one hand, the results show that the high impact on water of these primary sector makes that low and indirect demands along the value chain of the CSP power plant cause a great impact. On the other, it can be argued that indirect water footprint cannot be the most important contributor to the overall water footprint of the CSP plant and EMRIO results must be overestimating the impacts due to sectoral aggregation. However, ISM analysis shows that it is not the sectoral aggregation the cause of the higher estimation of water footprint in EMRIO, but the relevant contributions from very far sectors in the value chain. However, sectoral aggregation seems to cause a slight underestimation of the impact in the sectors included in the LCA scope in the EMRIO analysis compared with the ISM method.

For the water scarcity impact analysis, the complexity is even higher, and differences are maximized by the regionalization of the origin of the water that is a step forward in the assessment of resources depletion, and is essential as a criterion for sustainability assessment given the great inequality on the distribution of water resources around the world. The AWARE method for water scarcity provided a factor to weight the consumption of water depending on the availability of water in a specific origin (country/region). While EMRIO databases provide a detailed regionalization per se, not all the scenarios of LCA databases have regionalized water consumptions and need to be adapted to the specific cases in order to perform a regionalization of the water resources. This is especially difficult in background scenarios far from the foreground processes modelled. The use of available scenarios for fuels or raw materials “at regional storage” in “GLO” or “RER” regions can cause large differences and inconsistent results. Consequently, much water is supposed to be consumed in regions with low scarcity values.

A limitation observed in the LCASSIOA results for water depletion is that the water consumption by Spanish sectors, e.g. the *Collection and purification of water* sector in Spain, is not regionalized, leading to an unrepresentative value for water characterization, i.e. a general value of 0.04295 m³ depriv./kg is used instead of the Spanish value of 0.077 m³ depriv. /

kg. Only direct consumption of water was characterized (by the analyst) with the corresponding Spanish scarcity value. Therefore, the value of water scarcity by LCASSIOA is much lower in MEQF (the stage in which more regions are involved) than in EMRIO. The contribution of DEOL in the LCA and LCASSIOA results is also lower than that by EMRIO.

3.3.2. Energy use

The analysis of the energy use impact category for renewable energy technologies is quite relevant, since it reflects the use of fossil energy to produce renewable energy. The impact category represents the abiotic depletion of fossil energy carriers (ADP-E) caused by the power production in the case study CSP power plant. The trend of results is similar to that obtained for other impact categories (Fig. 6a, on the top). The lowest value is found when applying LCA (236 MJ/MWh), following LCASSIOA (266 MJ/MWh), TM (280 MJ/MWh), ISM (315 MJ/MWh), and finally, EMRIO (606 MJ/MWh). The LCA literature provides values of similar impact categories (CED) in the range 274 MJ/MWh (Corona, 2016), 350 MJ/MWh (UNECE, 2021) and 490 MJ/MWh (Whitaker et al., 2013).

Again, the main stage is MEQF in every case. In the EMRIO, the contribution in this stage is highly distributed between sectors. In Spain, it highlights the sector of *Manufacture of basic iron and steel and of ferro-alloys and first products thereof* (12 %), *Manufacture of glass and glass products* (8 %), the *Petroleum refinery* sector, and the *Production of electricity by gas and by coal*. Then, below 2 % are the *Production of electricity by coal* in Germany, Russia and China. In CONS, the EMRIO also shows a much bigger impact than the rest of methods, especially the sectors of *Manufacture of other non-metallic mineral products n.e.c.* (13 %), *Construction* (12 %) and *Petroleum Refinery* (11 %) in Spain. In the DEOL stage the avoided energy use estimate by EMRIO duplicates the result of LCA.

LCASSIOA coincides with EMRIO in the identification of the main sectors. According to LCA, the impact in MEQF would be mostly caused by hard coal mining in China, petroleum and gas production to supply energy to the processes of steel production and copper production, as well as metal working for heliostat manufacture.

The ISM method identifies several sectors already included in the LCI's MEQF, so a large contribution from EMRIO is removed (only the 2.4 % of the flows involving the fossil energy use would have been excluded of the LCA boundaries). The major contribution would fall over the energy

carriers manufacture sectors such as the *Manufacture of gas; distribution of gaseous fuels through mains* in Spain, Germany, and China. Similarly, in the CONS stage only the 2 % of EMRIO impact is added to LCA, mostly coming from the sector of the *Manufacture of gas; distribution of gaseous fuels through mains* (15 %) but also from *Recycling of waste and scrap* (10 %) and other sectors post and telecommunications, financial intermediation and other business activities.

The TM shows a relevant contribution of ASII stage, slightly larger than the impact of CONS, OM and DEOL. In the DEOL stage, 24 % of the EMRIO estimate of energy use would be added to the LCA, mostly coming from the sectors from the *Mining of precious metal ores and concentrates* and *precious metals production* in Spain, remotely following tertiary sectors.

The LCASSIOA result for the DEOL stage is slightly positive, since the avoided impacts in sectors such as *Manufacture of basic iron and steel*, *Manufacture of glass, manufacture of reprocessing of secondary metals or quarrying of sand and clay*, reducing the need of fossil energy carriers, is lower than the own DEOL processes.

3.3.3. Minerals and metals depletion

We focused on the abiotic depletion impact of minerals and metals (ADP-MM). The analysis shows a huge diversity of results depending on the method (Fig. 6b, on the bottom). Beylot et al. (2020) found results on the impact by EMRIO higher than LCA in factor of 48 when comparing the impacts associated to European trade in some sectors. Similarly, we found that the total impact according to EMRIO is 30 times higher than the total impact quantified by process-based LCA.

The impact along the whole life cycle is in the range of 0.022 kg Sbe/MWh (LCA result) up to 0.6 kg Sbe/MWh (EMRIO result) kg Sbe/MWh. Quantifications using the ISM and LCASSIOA reach intermediate values of impact (0.22 and 0.33 kg Sbe/MWh, respectively). The literature on LCA of CSP also shows a high variability for this impact with published values ranging from 0.0645 kg Sbe/MWh (UNECE, 2021), up to 0.09–0.68 kg Sbe/MWh (Telsnig et al., 2017). Studies of new CSP configurations show values extremely low (1.28E-03 kg Sbe/MWh) (Agostini et al., 2021).

The LCA points out tellurium, silver and copper as the main contributors to the impact (28 %, 23 % and 22 % of the impact, respectively in MEQF stage) for the heliostat fabrication. In the case of EMRIO gold would be

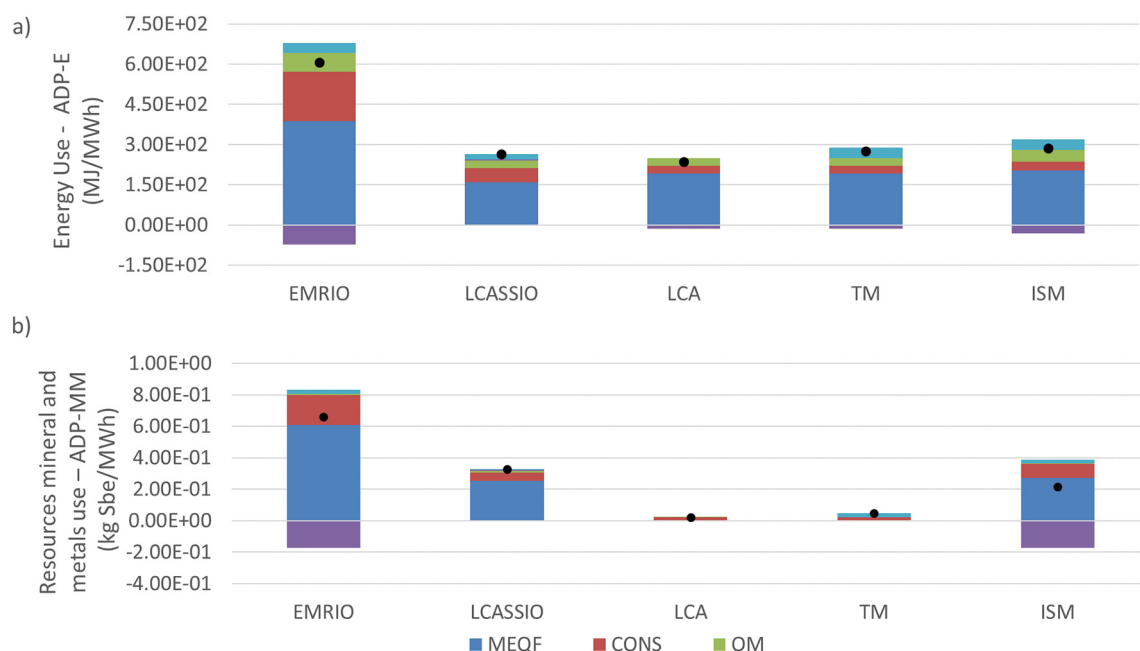


Fig. 6. Energy use (ADP-E) on the top (a) and mineral and metals use (ADP-MM) on the bottom (b) by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying five methods of quantification.

the main substance involved (96 % in MEQF), distantly followed by the Platinum Group of Metals (PGMs) and silver (3.2 % and 0.4 % in MEQF stage, respectively). The same contributors and figures are provided by the LCASSIOA (99 % gold, 0.04 % silver and 0.003 % platinum).

While the EMRIO, LCASSIO and ISM methods indicate the stage of MEQF as main contributor to the impact, the LCA and TM do not. In fact, LCA fails to account for almost all of the impacts associated to the MEQF stage and most of the impacts of the construction stage.

The ISM incorporates a 40 % of the impact from EMRIO to the LCA quantification. The impact would come from *Mining of precious metal ores and concentrates* from out of European frontiers, and in a marginal contribution from inside Europe. Therefore, it seems that LCA cannot account for mining processes outside the European frontiers that seem to be very relevant.

3.4. Variability on total results: synthesis of the approaches comparison

Fig. 7 shows the difference, in percentage values, between the results obtained by each methodological approach and the average result obtained per category. Generally, the EMRIO and LCA provide the highest and lowest impact values, respectively, with hybrid approaches falling somewhere in between, with the exception water impact assessments, in which ISM approach provides the maximum values. Methodologically it is reasonable to expect hybrid results to be between the LCA and the EMRIO results, but it will depend on the hybrid method used, the data sources and data availability and assumptions of the case study and how well the MRIO sectors used represent the materials and processes involved (aggregation error). As Pomponi and Lenzen showed, the truncation error of process-based LCA usually outweighs the aggregation error of hybrid LCA and MRIO. Additionally, Perkins and Suh (2019) demonstrated that truncation error of LCA introduces an underestimation bias in the results while the aggregation error of MRIO does not have a unique direction and is more random depending on the concrete case. Then, it is expected that LCA produce the lowest results while MRIO the highest and hybrid approaches fall in between. We have included results obtained in the literature on the comparison of hybrid methods in different case studies.

Water consumption impact results estimations are very close among different approaches. Conversely, water depletion results (including scarcity) diverge quite a lot. We argue that, both EMRIO and LCA could underestimate the impact on water depletion. On the one hand, LCA ignores the water consumption from very far sectors in the global value chain from countries with high water scarcity involved (i.e. primary sector consumptions embodied in intermediate products). On the other hand, EMRIO has a low technological detail related to the production of some materials or power plant components (i.e. water deprived due to hydropower activity

to support some metals manufacture in Europe is one of the activities identified as relevant contributors by LCA, but that is not seen in EMRIO results). Thus, an advantage of ISM is its ability to add to the accurate but incomplete results of the LCA the embodied water in components and intermediate products coming from EMRIO.

In general, methods tend to differ mainly in the assessment of local impacts and depletion of resources, such as energy and minerals and metals, while the results obtained with different methodological approaches tend to be more similar in the assessment of global and regional impacts (Climate Change and Acidification). The highest deviations are found in the estimation of impacts from Respiratory Inorganics and Mineral and Metals abiotic Depletion, where MRIO results are considerably higher. In this case, the ISM method proposed reveals that EMRIO is likely overestimating the impacts due to the high sectoral aggregation issue that does not precisely represent the technology used in components and intermediate products manufacture, since the missing sectors in LCA do not add much impact to the total results (LCA and ISM results are very similar). The same can be said about energy consumption and, to a lesser extent, about minerals and metals depletion. Nonetheless, there are limitations in the application of impact characterization methods and in the quantification of potential impacts related to the coverage of substances involved in each impact category that must be considered. In particular, EMRIO extension vectors include a shorter list of substances in general than LCA.

Nevertheless, this comparison allows identifying those impact categories in which methods tend to converge and puts the focus on the need for further research on data and methods for the most divergent impact results. These trends could be not representative for other sort of technologies, products or services, since we have used just one specific case study to validate the method.

Similar divergences in some of the impact categories, such as Minerals and metals depletion or Respiratory inorganics, have been found by others (Beylot et al., 2020). (Steubing et al., 2022) found divergences in climate change impacts of sectors using LCA and EMRIO. Therefore, the validation of the proposed methods in other technologies should be the subject to further research.

Although developers of LCA-MRIO hybrid methods claim that they produce more accurate results than process-based LCA, the hybrid methods merits have been criticised in literature (Yang et al., 2017) and it is still a matter of debate (Pomponi and Lenzen, 2018). Some works in the literature have carried out comparative studies of hybrid methods applied to the environmental assessment of different case studies. For instance, Wiedmann et al. (2011) explored two options for hybrid life cycle assessment (hybrid LCA), Input-Output-based Hybrid LCA and Integrated Hybrid LCA, to account for the indirect greenhouse gas (GHG) emissions of energy technologies using wind power generation in the UK as a case study. They found that

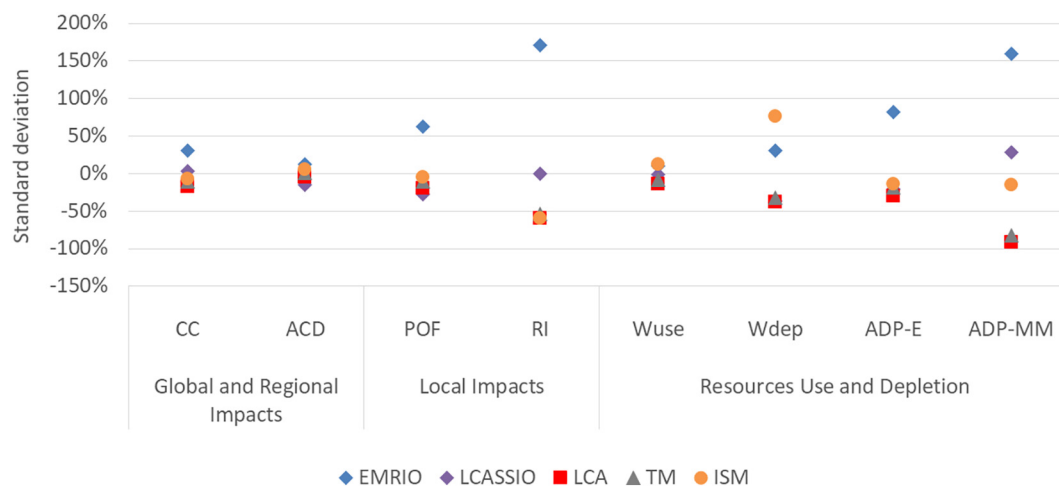


Fig. 7. Dispersion of the results obtained by each of the approaches in the assessment of the different environmental impact categories.

hybrid methods resulted in a higher value of GHG emissions than process-based LCA, and amount of kg CO₂e/kWh. Perkins and Suh (2019) investigated the use of hybridization by applying the tiered hybrid method to quantify the environmental impact of one use of an average jacket. They found that hybridization effectively moved the mean of the life cycle (GHG emissions to a value 38 % higher. These results were the ones expected since after analyzing the data sources for LCA and IO they concluded that in LCA the truncation error is unidirectional and it often results in an underestimation bias, while the errors in the input-output data, or other proxy data for cut-offs are generally random. Luo and Ierapetritou (2020) reviewed different LCA and hybrid methodologies and applied them to the comparative study of two biomass-based systems. They ran the process LCA, the tiered hybrid LCA, and the integrated hybrid LCA after binary correction for double counting. They highlight the choice of LCA method, especially hybrid methods, under different data availability. Among the some of the techniques of correction (binary and SSM) applied after the Integrated hybrid are closely related to the ISM, as approach a manner to not to correct the results, but to distinguish the sectors to excluded from the process LCA, in order to include or not their contribution to the impact in the final result. However, the ISM acts directly over results of the EMRIO, and the binary and SSM corrections are included in the hybrid matrix creation.

Differences among the methods do not change the main conclusion of the case study, which shows the highest impact contributions from the manufacturing stage (MEQF) of the CSP plant, followed by construction activities (CONS) and operation and maintenance (OM). CSP has been revealed to be a low-carbon and clean technology. We found values ranging from 23 to 34 g CO₂e/kWh for CSP in the present study, and carbon footprint of renewables in the LCA literature is 8 to 83 g CO₂e/kWh for photovoltaics (PV), hydropower from 6 to 147 g CO₂e/kWh, and wind 7 and 23 g CO₂e/kWh (UNECE, 2022). Obviously, all those are much lower than the values for fossil technologies. The same can be said about the energy carriers use category (Hertwich et al., 2015). In terms of ACD, POFC and RI, our results are in the same range as PV, hydro and wind (UNECE, 2022) and lower than the values found for biomass (Mahmud and Farjana, 2022) and fossil technologies. Related to the water use of CSP, our results show a moderate profile in comparison with other RES (quite higher water demand than wind, and lower than some configurations of PV, and much lower than the average of biomass and fossil thermal plants (UNECE, 2022)). As for the metal and mineral resource use, it is difficult to conclude the position of our CSP results with respect to other renewables due to the high disperse results on this category. The maximum value (0.6 kg Sbe/MWh, EMRIO) is lower than the value found for PV and wind, and in the range of fossils and nuclear (ibid).

Several future lines of research arise from the present work. First, the proposed ISM method could be applied to other case studies for further validation and better insights into the method's advantages when assessing other types of product systems. Also, the method serves researchers for sensitivity purposes on environmental impact assessment. Second, these methods could be applied and compared considering other relevant impacts (e.g. land use) not only environmental (also socioeconomic or social impacts), as well as other different databases.

4. Conclusions

In the present paper, we proposed a novel hybrid methodological approach for quantification of environmental impacts and compared it with other methods of analysis in the context of decision making on renewable technologies, by using as case study the environmental assessment of a CSP power plant located in Spain. The aim is to provide a time-efficient alternative of hybridization that avoids double-counting, contributing to enlarge the body of knowledge on sustainability assessment methods applied to renewable energy technologies. The development of hybrid methods to combine the usually applied methods of environmental quantification (EMRIO and LCA) still present limitations (such as the associated with double counting of impacts that are complex to sort out, or the uncertainties

and complexity associated with altering MRIO tables). Given these limitations, we have proposed here a new tiered hybrid method approach, and compare the results obtained with the original methods and the conventional tiered approach.

Except for Climate change and Water consumption (without scarcity ponderation), the different methods tested in this study presented significant discrepancies in absolute impact results. In many cases, EMRIO and LCA provide the extreme values, and the hybrid approaches are in between. In general, the tiered hybrid method (TM) fails to incorporate all the missing impacts in LCA, since many services and immaterial processes of background processes are not included. However, the proposed ISM analysis revealed that this is not the only cause for underestimated impacts in the TM method. Many processes far in the supply chain, such as those involving primary sectors, have been revealed to play an essential role in some impacts categories such as water consumption and mineral and metals depletion. The ISM approach manages to expand the LCA boundaries by adding the EMRIO impacts typically not covered by LCA, avoiding double counting while retaining the technological detail and representativeness of the process-based LCA. In many cases, the added impacts come from primary and tertiary sectors, but also from sectors located in countries not directly involved in the flows of the inventory but in the global value chains of the intermediate products. The highest differences between methods are found in the assessment of local impacts and resources depletion (either energy or minerals and metals), while the methods tend to agree more on the quantification of global and regional impacts. However, there are limitations on the implementation of the impact characterization methods and the quantification of the potential impacts that should be considered when comparing the results of the different methods. In particular, EMRIO satellite accounts do not consider all the substances that LCA databases do.

As for the results on the environmental performance of the CSP as a case study, the quantification using the different methods shows the highest impact contributions from the manufacturing stage (MEQF) of the CSP plant, followed by construction activities (CONS) and operation and maintenance (OM). CSP has been found to be a low-carbon (23 to 34 g CO₂e/kWh) and cleaner technology in comparison with other renewables in many categories. Water impact categories reveal a moderate profile. The results of the mineral and metals use are found in a wide range depending on the method.

Several future lines of research arise from the present work, mainly oriented to test the method in a variety of study cases, as well as to probe the performance and application to assess other sustainability impact categories.

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CRediT authorship contribution statement

Ana R. Gamarra: Conceptualization, Methodology, Data curation, Writing- Original draft preparation, Visualization, Investigation. Yolanda Lechón: Writing- Reviewing and Editing, Supervision; Santacruz Banacloche: Methodology, Writing- Reviewing and Editing. Blanca Corona: Writing- Reviewing and Editing; Juan Manuel de Andrés: Writing- Reviewing and Editing.

Data availability

The specific data used and methodological details are provided in the supplementary materials (SM1, SM2 and SM3). For further information, please contact the corresponding author.

Declaration of competing interest

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

Appendix A

	Indicator	Method and definition	Unit
Global and regional impacts	Climate Change (CC)	Global Warming Potential 100 years, IPCC method (Myhre et al., 2013)	kg CO ₂ e
	Acidification terrestrial and freshwater (ACS)	Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit (Posch et al., 2008; Seppälä et al., 2006)	mol H ⁺ e
Local impact on human health	Photochemical ozone formation - human health (POF)	Expression of the potential contribution to photochemical ozone formation. Only for Europe. Considering a marginal increase in ozone formation, the LOTOS-EUROS spatially differentiated model averages over 14,000 grid cells to define European factors (van Zelm et al., 2008).	kg NMVOCse
	Respiratory inorganics (RI)	Disease incidence due to kg of particular matter (PM _{2.5}) emitted, NO _x , NH ₃ , SO ₂ , SO ₃ . The indicator is calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum-risk level. Exposure model based on archetypes (urban, rural, and indoor within urban and rural areas (UNEP-SETAC Life Cycle Initiative, 2016).	Disease incidence
Resource use and depletion impacts	Water use (Wuse) and water scarcity (Wdep)	Relative Available Water REremaining (AWARE) per area in a watershed, after the demand of humans and aquatic ecosystems has been met (Boulay et al., 2018).	m ³ water e. deprived.
	Resource use: energy carriers (ADP-E)	Abiotic resource depletion fossil fuels; based on lower heating value (Van Oers et al., 2002).	MJ
	Resource use: mineral and metals (ADP-MM)	Abiotic resource depletion (ADP ultimate reserve). ADP for mineral and metal resources, based on (Van Oers et al., 2002).	kg Sbe

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5. Similarities with the recent research

An analysis of similarity of the papers published containing the results of the present research is presented. Connected Papers (<https://www.connectedpapers.com/>) is a tool to help researchers and applied scientists find and explore articles relevant to their field. The tool provides a graphical output, for which ~50,000 scientific papers and literature are analysed and then a few dozen with the strongest connections to a given article are selected. In the graph, the articles are sorted according to their similarity. This means that even articles that do not directly cite each other may be strongly connected and very close to each other. The complete analysis and results are detailed in the [Annex 4](#).

The similarity metric used in this tool is based on the concepts of Co-citation and Bibliographic Coupling. According to this metric, it is assumed that two papers that have strongly overlapping citations and references have a higher probability of dealing with a related topic. Next, another algorithm constructs a forced directed graph to distribute the articles so that similar articles are clustered together and less similar articles are moved away. When selecting nodes, the shortest path from each node to the source item in the similarity space is highlighted. Then, looking at graphs (see figures in the [Annex 4](#)) the more intensity of the colour indicated the more recent date of publication (even after the original assessed). The distance with the original publication assessed, indicated the scored similarity. The complete list of references and similarities analysis is included in the tables of the Annex 4. The database it relies on is connected to the Semantic Scholar Paper Corpus.

The analysis of papers showed that:

- [Result 1](#) connects with research from very specific the fields of supply chain analysis, energy assessment and energy policy strategies, and EMRIO methodology → this research is a novel approach
- [Result 2](#) connects with research from many fields, very heterogeneous, bringing many assessments of sustainability and energy field → this research broadens the assessment of sustainability
- [Result 4](#) is revealed as be part of a field of research dedicated to hybrid modelling EMRIO-LCA, keeping the link with the renewable energy investment assessment on CSP → very close to the most recent developments

[Result 3](#) cannot be assessed by connected papers since it is have been not published yet (currently *Under Review*).

IV. DISCUSSION

In this section the general discussion highlighting the results and findings reached along the research, as well as the disadvantages and limitations of the developed methodological proposals is presented.

The research has been developed as a sequential chain of methodological developments, in which each of the reached steps forwards to expand and improve the methodological scope developed came from the previous step, departing from the current sustainability analysis frameworks. In the following, the research questions are addressed and framed according to the gap found. The link among the different investigations and how they contribute to satisfy the research questions is discussed. Also, the limitations found and the potential challenges are included.

1. RQ1. What are the main components of the supply risk along the value chain of energy investments?

In this thesis, the main components to properly characterize and quantify the risk along the supply chain of energy investments have been identified. These components are the availability of resources, the dependence on the origins of each resource and the intermediate suppliers, and the resilience of the end-user (or importer) to adapt to the potential contingences increasing recycling strategies. Additionally, governance issues have been identified as highly relevant for the analysis of these three components providing a fine-tune characterization of them. This proposal is based on argument of that these four aspects would cover the three dimensions found as fundamental and orthogonal. The representation of the three dimensions' framework (Figure 15) helps to understand how reach the minimization of vulnerabilities along the supply chain.

Table 8 shows the three dimensions, and the key components of the risks along the supply chain.

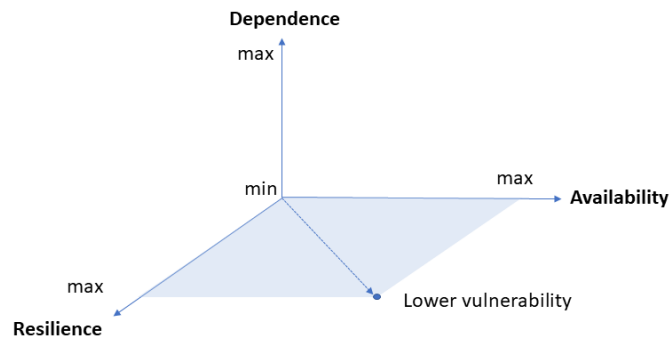


Figure 15. Three orthogonal dimensions of energy security to minimize vulnerability of the energy systems supply chain.

Table 8. Dimensions and fundamental components for the risk's assessment along the supply chain.

Dimensions	Key Components
Availability	Availability
Resilience	Resilience
Dependence	Dependence
	Governance Level

This research is mainly addressed in Research Line I. Figure 16 depicts the portion of the methodological scheme of the research and the link with the Research line II (results from EMRIO).

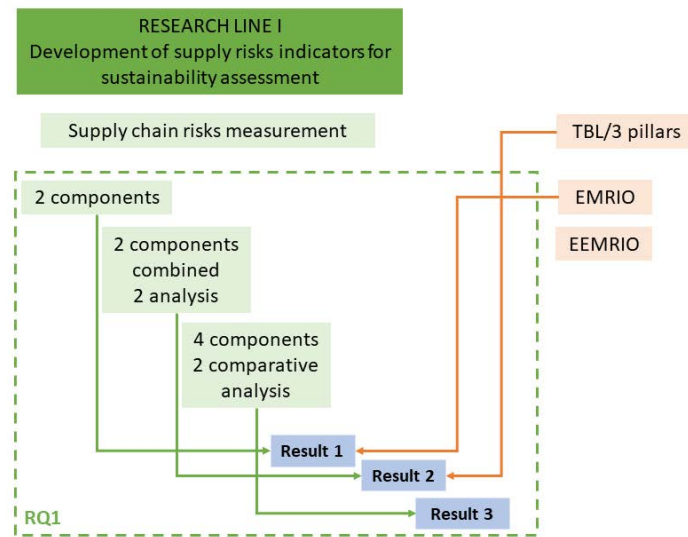


Figure 16. Portion of the methodological scheme addressing RQ1.

This three dimensions' framework formulation to assess the risk of supply is an outcome of a review of the literature on energy security conceptualisation from the social sciences and the geopolitics fields of research and has been contextualized and adapted to the special case of energy investments for energy transition towards decarbonization. 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 minimised. (Cherp, Jewell 2014b) defined energy security as *"low vulnerability of the vital energy systems"*. In this thesis, the decomposition of these key or vital aspects related to the supply chain in the context of energy investments has been worked out. The approach followed allowed a comprehensive examination of vulnerabilities as a combination of risk exposure and resilience, and the identification of the links between these essential components and the critical functions they play for society support. From the point of view of the decomposition in dimensions, this approach implies identifying the roots of the risks, and then, determining the components in an adhoc process depending on the subject of application.

Among the multitude of energy security dimensions proposed in literature, they have been selected those that: 1) include the vital dimensions of the energy system, and 2) are applicable to the characterization of the risks along the supply chain. Findings showed that many of them were applicable to the supply risks assessment, but not many were out of the three orthogonal dimensions as all of them were very dependent on any of these three dimensions. For instance, the Four A's framework of energy security introduced by the Asia Pacific Energy Research Centre (APERC 2007) to define energy security dimensions includes the following four: Availability (to ensure that energy supplies are available in sufficient amount); Affordability (to have these resources available at sufficiently-low prices); Accessibility (focuses on ensuring all citizens have access to energy, ensuring that reliable infrastructure or a robust supply, but this is generally

interpreted in practice as ensuring that energy prices are kept low); and Acceptability (related to the negative impacts of energy, such as pollution and environmental damage). From the supply chain risks perspective, the approach assumed in this thesis concurs on the use of the availability dimension and it is argued here that affordability and accessibility would be determined by the own availability of the resources as well as on the quantitative and qualitative dependence on the suppliers providing the resource. Acceptability could entail risks of refusal for determined decisions of energy investments, which are more related to internal geopolitical risks rather than supply chain risks and could be addressed in a framework of sustainability assessment focused on the social pillar.

Other framework found in literature was the one proposed by Sovacool and Mukherjee (Sovacool, Mukherjee 2011) with five dimensions: availability, affordability, technology development, sustainability and regulation. This framework is more oriented to analysing national energy security policies while our framework is more focused on supply risks and aspects such as affordability and technology development are not so relevant for us. However, some elements from this framework could be incorporated to the supply chain risks assessment. For example, regulation can be used as characterization criteria of the origin of supply along the value chain. Somehow this dimension is incorporated to the proposed framework in [Result 3](#) since the governance assessment as part of the qualification of the dependences proposed in this thesis includes the regulation and government practices in the country of origin. Sustainability in this framework is the global umbrella in which the risks supply analysis is included, instead of being a component as in the Sovacool and Mukherjee's framework. Another research conducted by Cox (Cox 2017) in a study focused on low carbon electricity systems used a dashboard of indicators for the assessment of the electricity system clustered in four dimensions: availability, affordability, reliability (defined as the ability to cope with short-term shocks) and sustainability (focused on environmental sustainability). This new dimension proposed by Cox (Cox 2017), reliability, is covered by the three dimensions framework proposed in this thesis by the resilience dimension. While in the energy system the supply to end-users is more exposed to threats with very immediate effects (i.e. disruption of networks of electricity transmission to end-users), in the supply chain perspective the risks are more related to long-term resilience (long-term storage of equipment, capacity building, resources for manufacturing and repairs, alternative suppliers, own-industry promotion, multilateral agreements, etc.).

Therefore, the three dimensions' framework (Dependence, Availability and Resilience) proposed in this thesis is assumed to contain the fundamental dimensions to be addressed to measure the supply risks.

The research showed in [Result 1](#) (Gamarra, Y. Lechón, et al. 2022) addressed the dependence axis from a dual analysis: diversity and governance. Results obtained provided a quantitative measurement not only of the risks associated with the direct suppliers; but also allowed the identification of indirect contributions from the countries included in the global value. This is exemplified in the case of the indirect contribution of China to the supply chain of several components in the solar thermal power plant examined in [Result 1](#), which plays a relevant role in the governance analysis and serves to reveal potential supply risks in the value chain.

Other example to quantify the risk along the value chain based on the dual analysis diversity-governance was included as part to the sustainability EMRIO sustainability assessment presented in the [Result 2](#). In this paper, the supply risk analysis of two types of CSP technologies - Parabolic trough (PT) and Central Receiver (CR) - is performed under three alternative scenarios of supply with different origin of some key components: Pure Spanish, Alliance with Germany, and China as supplier of some components. In this case, the analysis to assess the risk of supply used a combined indicator by using the entropy and the governance criteria based on a) the total demand of good and services (as in the [Result 1](#)) as well as b) the demand of domestic extraction of silver. This second analysis of the risks of silver supply was carried out as it could be a key raw material for the deployment of the CSP technologies in the next years ((Pihl et al. 2012)).

The worst results of the risk indicator were obtained in the scenarios in which China was a direct supplier of some key components, but closely followed by the scenario of Pure Spanish supply. These, in principle, unexpected results were explained in the Pure Spanish scenario by the shares of Poland as silver supplier and the contribution from Latin America, Africa and Asia that are regions with countries with low governance scores. Therefore, the diversity and governance combined analysis, using MRIO outcomes as main data source was proved to be able to provide a measurement of the risk along the value chain identifying the direct and indirect contribution of the different origins.

The dependence dimension was demonstrated to be fully addressed by the geopolitical dual analysis: quantitative dependence measured as diversity, and the qualitative dependence weighted by governance.

The analysis of materials' supply risk conducted in the [Result 2](#) addressed the two other dimensions (availability and resilience) and served to complement the dual analysis of dependence and governance along the value chain. The comparison of scenarios provided different level of risk under the different scenarios (technologies and country-origin of the

components), but the findings revealed the strong link between availability and resilience (as resilience has been argued as the ability of each system to increase the own availability of resources by using recycling and circularity). The quantification of the silver extraction along the value chain in each of the scenarios showed that the Alliance with Germany scenario was more efficient in the use of resources, which can be explained by the better efficiency and better recycling rates of the German economic sectors, which is, in turn, a sign of long-term resilience. The research presented in the Result 3 addressed the addition of these last two dimensions and fully develops the four key components framework proposed in this thesis.

2. RQ2. How can the existing EMRIO methodology be used to assess the risks of supply along the value chain?

One of the main contributions to the state of the art of this thesis is the connection between the MRIO outcomes and the dependence analysis which allows revealing potentially important risks that otherwise would remain unnoticed. The regionalization of the outcomes provided by MRIO is the main advantage since it allows assessing the risks of supply along the value chain associated to the participation of the countries and regions involved both directly and indirectly. Besides, the extension of the MRIO model using the environmental satellite accounts (EMRIO) enable the assessment of the risks focused on the trade of specific goods (e.g. a set of main metals).

The methodological proposal and demonstration of the application of EMRIO to the assessment of the supply risk dimensions discussed above along the value chain are included in [Result 1](#), [Result 2](#) and [Result 3](#), linking Research Line I and Research Line II. Figure 17 depicts the portion of the methodological scheme of the research and the link with the Research line II (results from EMRIO, EEMRIO and TBL assessment).

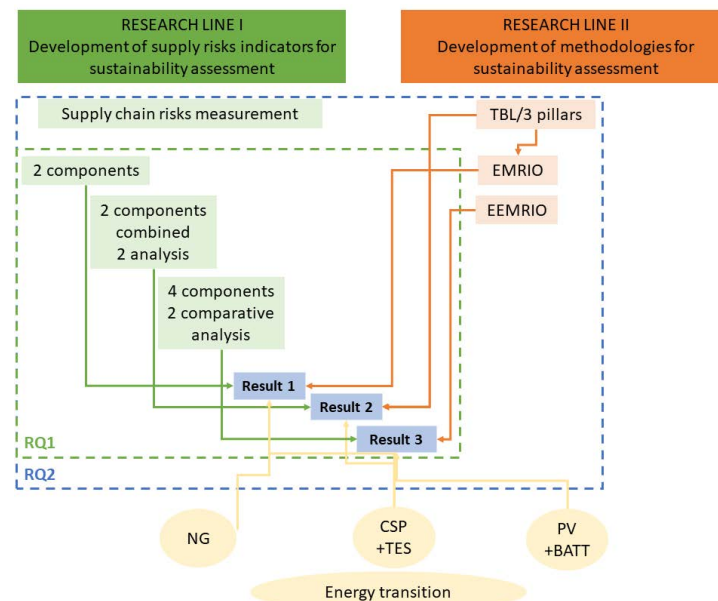


Figure 17. Portion of the methodological scheme addressing RQ2.

In [Result 1](#) the dependence on the different suppliers was measured quantitatively using the concentration and diversity metrics over the results of the MRIO, as it has been discussed in RQ1 above. Additionally, using the output of production of goods and services, a range of sustainability indicators addressing the three sustainability pillars were applied.

For the dependence analysis, some concepts traditionally used in the dependence analysis in the energy field associated to fossil fuels value chains were used, such as the concept of concentration of market (measured by the Herfindahl-Hirschman Index, HHI) but also, new and less-used approaches to measure diversity (such as the Entropy, E) were proposed.

It was discussed that none of these metrics (HHI and E) measures disparity between the different suppliers, understood as “the manner and degree in which the options differ from each other” (Lilliestam 2013) and, then, cannot capture the complete concept of diversity (Stirling, Waxman 1999; Stirling, Stirling, Andy 2010). **To address this limitation, the use of governance indicators characterising the different countries or regions is proposed in this thesis.** In this application of the HHI and E indexes, the different categories of suppliers are the different countries or regions included in the MRIOT structure. The application of governance indicators allowed weighting the demand of goods and services from the different suppliers along the value chain, both directly and indirectly. An example is the analysis of diversity using the entropy (E) metric in [Result 2](#), in which the highest diversity of the supply of goods and services along the value chain was found for the Chinese scenarios. On the contrary, the Pure Spanish scenarios reached the lowest diversity due to the higher domestic demand from Spain and Europe. However, when applied the combined indicator (DG_{WGIx}) that incorporates governance, the European alliance reveals as the lowest risk scenario.

There are, however, some limitations on the proposed approach. First, could be criticised that the dependence dimension could be not completely addressed by the dual analysis governance-diversity. On the one hand, in the analysis it is assumed that a high diversity of suppliers always means low vulnerability, but that it is not always the case. For instance, it could happen that a supplier provides an exclusive good or service (very concentrated value chain) to a set of importers, and the product or service is of high value for exporter national economy as has a main role in the Gross Domestic Product (GDP). The size of the imports to each importer can generate a situation of coercion, since despite there is a high dependence, this dependence is mutual. I.e. the importer needs imports, but the exporter also needs to export the product. These complex relationships are not captured by the method proposed in this thesis.

Secondly, issues related to some geopolitics aspects –such as exogenous geopolitical risks associated with unstable regions or supranational influences on governance- are not captured by the assessment proposed. For instance, the method cannot assess the fact that a country can have good governance at home but has lower level governance neighbours or is a rogue state (Russia) prone to conflict, or a global power (USA, China) with a power politics agenda. For example, in the case of the USA as a supplier of CSP plants in Mexico assessed in the [Result 1](#),

the highest risks could most probably emerge from USA exerting power politics, and less probably from causes associated with the USA's governance standards.

As for availability of resources and resilience dimension, by using the available satellite accounts for constructing extension vectors, EMRIO framework allows the quantification of some categories of impact on use of resources as a consequence of the investment, such as the amount of materials extracted in a place and traded in a country or region. These impacts are part of sustainability impact assessment (Banacloche, Cadarso, et al. 2020; Gamarra, Banacloche, et al. 2023), for example, for the accounting of the abiotic depletion potential (ADP) involved in the value chain (Beylot, Corrado, Sala 2020; Castellani et al. 2019). However, these results can provide the input for the quantification of the risk associated to these resources' supply chain and the dependence on imports (Gamarra, Y. Lechón, et al. 2022; Yamamoto et al. 2022).

In the literature, mainly in LCA, the use of resources has been traditionally based on the assessment of scarcity using the resource depletion, for example Abiotic depletion Potential (ADP) (Van Oers et al. 2002; van Oers, Guinée, Heijungs 2020) as the indicator. However, **in this thesis, we propose to analyse the availability component based on the intensity on the use of abundant resources expressed as the inverse of ADP ($1/ADP_m$) and the economic reserve-production ratio ($eRPR_{mc}$)** which adds robustness to the analysis of risks.

However, when using this approach for the availability assessment, it is pivotal the use of updated data, since new deposits of the different metals and minerals can be found or policies on extractions in each country sovereign can be changed. Therefore, the limitations of the assessment results using the MRIOT "Domestic Extraction" satellite accounts and depletion indicators (as ADP) have to be considered, as new reserves may have been discovered in the meantime.

Relevant differences on the quantification of materials and impact on resources use categories have been found among methodologies (e.g. EMRIO and LCA). To address this limitation hybrid approaches LCA-MRIO are proposed. The hybrid approaches can help to obtain fine-tuned assessments of the resources use indicators. These hybrid approaches have been used in [Result 4](#) (Gamarra, Lechón, et al. 2023).

As for resilience component, the proposed way to measure it using EMRIO results is linked with the extent to which circular economy (CE) practices are implemented in the importer countries. Recovery and storage of limited resources would increase the ability to allocate those resources, prioritising the use and taking more control on the resource consumption. When the

production of resources is located in few locations around the world, their recovery and storage is the main strategy to increase the resilience of the system demanding these scarce resources. CE strategies such as recycling and recovery of materials represent the opportunity of importer countries following a logic of “resources and storage”, which impulse the displacement rates of primary raw material (Zink, Geyer, Startz 2017) from abroad by the secondary raw materials domestically recovered. The effect of this displacement has been also named “redistribution effects” (Santillán-Saldivar et al. 2021). Also, related to the other dimensions of supply chain risk assessment, the CE practices reduce the dependence on located resources and contribute to the diversification of the supply of raw materials (e.g. stocks in non-producer countries). CE is a way of organizing industrial systems that supports resilience through decoupling economic growth from new material consumption (Kennedy, Linnenluecke 2022). (Cherrafi et al. 2022) uses the example of the global pandemic disruption of the flow and pricing of raw materials and finished products in order to illustrate how the CE is able to increase the resilience of the supply chain, since it increases stocks and availability, and can help to buffer volatility of prices and reduce foreign dependence. Certainly, there are other strategies that can also contribute to the resilience of the supply chain beyond storage, such as reducing demand (efficiency increase and preventing highly consumptive behaviours), research and development on new materials and innovations that can achieve substitution of scarce materials by abundant resources and urban mining, among others. However, in the mid-term, circularity on critical and specific materials is seen as the more tangible opportunity. Therefore, the proposed indicator to measure resilience in this thesis is based on the net recovery of materials, EOL-RIR.

Other approaches to evaluate resilience in the literature have been based on specific cases of disruptions in a specific system. For instance, the ‘global resilience analysis’ (GRA) approach (Sweetapple et al. 2019; Butler et al. 2017) focuses on system failure modes instead of the threats that may cause them, thereby overcoming the challenge of identifying and characterizing all possible threats (of which many are unforeseeable) and enabling the potential effects of these threats to be captured without needing to identify their root cause. On the contrary, the approach proposed in this thesis focused on circularity and is basically based on measuring how the investment contributes to create a more resilient supply chain to satisfy the own demands in the future, being more applicable for a range of cases. As a limitation, the use of EOL-RIR is only representative for Europe. While the analysed case studies in [Result 3](#) are investments for power plants deployed in Spain, and therefore the European rates for the set of metals was valid for the assessment, the resilience analysis for the supply risks analysis of the investments in other regions would need appropriate rates.

Comparing the two proposed analyses included in [Result 3](#), one of them offers a simpler framework and allows the individual analysis per risk criteria (Figure 18). The two alternatives can be easily compared by each of the components of risk as the ratio provided highlights which one of the compared investments performs better. For instance, the analysis of the case study showed that CSP power plant deployment shows lower risks of metals availability than the PV alternative. Focusing on the resilience, CSP would performance better in most metals, however, PV performed much better in one of them (Iron), resulting on a cumulated overall total result slightly in favour of the PV value chain (1.07 times better PV than CSP). What that result reflects is the higher intense use of iron in PV plants but with a high rate of input recycling.

On the dependence measurement, the diversity indicator shows lower risks 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 case of Pt and Sn. Finally, the scores of Governance for PV supply chain are quite better for Cu, moderately better for Al, Au and Ag, and slightly better of Ni and Pt, while CSP reaches much better governance along the supply chain of Iron, and slightly better in Pb and Sn. However, results are not conclusive. From these results it cannot be concluded that one value chain is better than the other in terms of supply chain risks, since CSP score better for availability and diversity, but worse for resilience and governance.

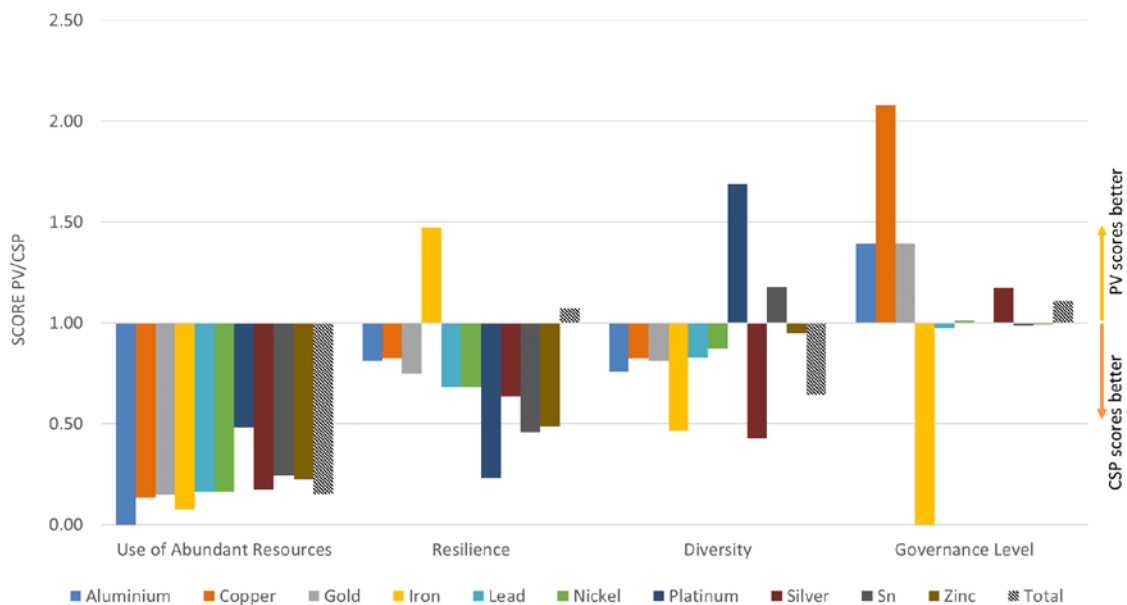


Figure 18. Risks' component comparative analysis (CARC) results.
Values over 1 means a better score (lower risk) of PV for the criterion. Values below 1 means a better score (lower risk) of CSP value chain for the criterion. Result 3.

The second method proposes a way of including availability, dependence and resilience in a combined indicator that results in a total score (Figure 19), and simultaneously, allows tracing the countries and regions and the governance criteria scores that are behind the results. Figure 20 shows the results obtained in the assessment of the two alternative solar investments considered in [Result 3](#). As it can be observed, the highest differences are found in the total (cumulated) SCSI for Rule of Law (RL), Regulatory Quality (RQ) and Control of Corruption (CC). According to (Blengini et al. 2017), 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). The role of CC is also relevant, since supply chain can be threatened by illegal pathways which are frequently connected with corruption. This approach of analysis is useful for regulators and decision makers. For instance, in the deployment of a PV power plant, regulators should take care on diversity of the supply, should design mechanisms of protection and additional efforts on the matters of corruption in origin, and impulse commitments with third countries acting as suppliers on the RL developments and promulgation of more exigent standards. However, this approach presents the disadvantage of the aggregation of the component which hides the contribution by component, and therefore, they cannot be easily disentangled.

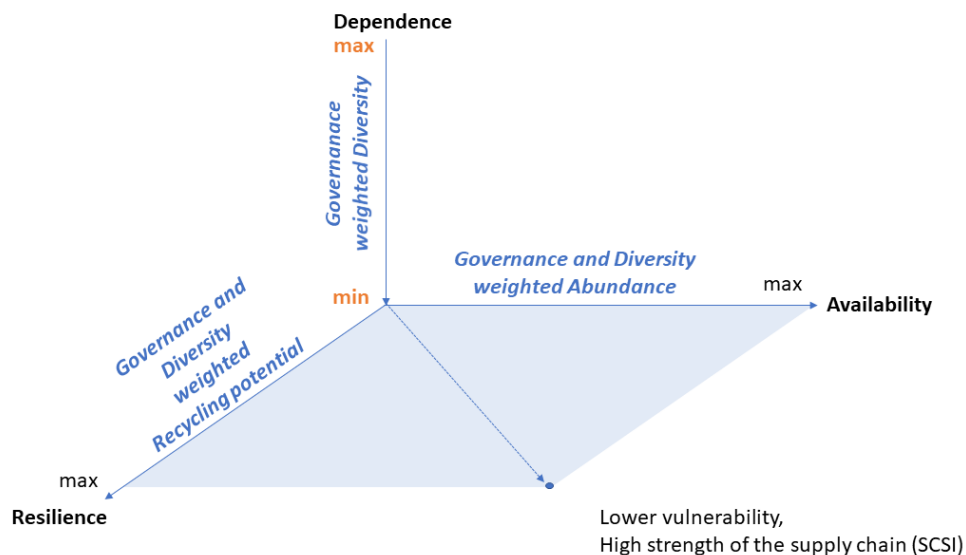


Figure 19. Representation of the SCSI approach considering the three dimensions (axis) and components (blue text) of risks of supply.

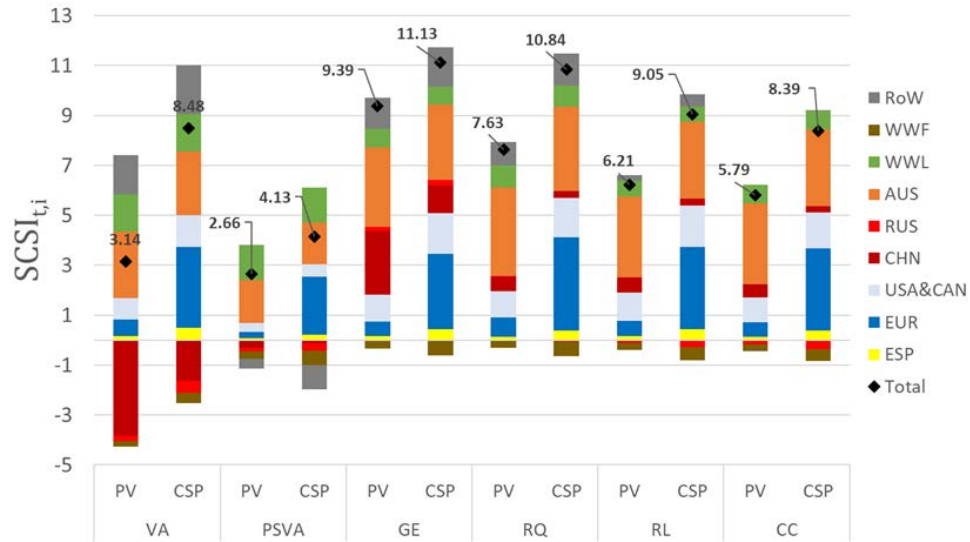


Figure 20. Results of the combined indicator Supply Chain Strength Indicator (SCSI_{tj}) for each technology.

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. Result 3.

3. RQ3. How can a complete and simpler hybrid method incorporating the pros and cons of the existing sustainability methodologies (EMRIO and LCSA) be developed?

The methodological proposal of the hybrid method ISM combining consists of a tiered method in which contributions from the two original methods are added up. The demonstration is focused on the environmental pillar combining LCA and Environmental EMRIO (EEMRIO). The main novelty of the approach is the method to more precisely determine the scope covered by LCA and EMRIO, avoiding double counting to a large extent. The method is developed in two steps: (1) the identification of the LCA scope in terms of sectoral-country contributions to the impacts assessed; and 2) the subsequent subtraction of this scope from the total EMRIO results, in order to finally add up both contributions to get the final result following the tiered hybrid method logics.

This development is mainly undertaken in Research Line II (Figure 21), which has been focused on improving the quantification of impacts by proposing a new method of hybridization. The methodological proposal and the comparison with other approaches (LCA, EMRIO and original hybrid tiered) is included in the [Result 4](#) (Gamarra, Lechón, et al. 2023).

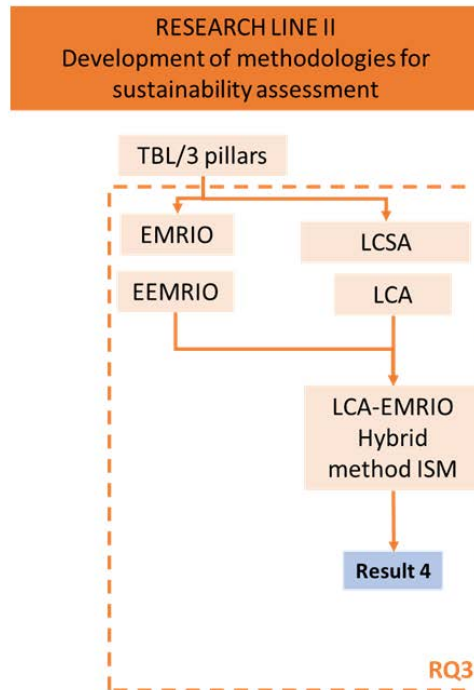


Figure 21. Portion of the methodological scheme addressing RQ3.

With the purpose of describing and demonstrating the proposed hybrid method, the research addressing this question has been focused on the assessment of some environmental impacts such as Climate change or Resource Use (Abiotic Depletion Potential), among others.

The proposed hybridization method is used to address the environmental dimension of the sustainability. As showed in Figure 21, the EEMRIO (Environmentally extended MRIO) and the environmental LCA (focused on environmental impacts analysis) are combined. There were three main reasons to focus the demonstration on the environmental assessment. First, the development on hybrid methods have been traditionally proposed in the environmental impact assessment (Crawford et al. 2018; Zhang, Gibbemeyer, Bakshi 2014; Lenzen 2009; Suh, Huppes 2005b; Wiedmann et al. 2011) (Pomponi, Lenzen 2018; Agez et al. 2018; Luo, Ierapetritou 2020)); second, the inclusion of additional sustainability dimensions (such as the inclusion of social impacts) will result in an additional layer of complexity (Hardadi, Pizzol 2017) that could hinder the understanding of the methodological development; and third, the proposed method addresses one of the main criticisms of EMRIO in the literature that claims that EMRIO could overestimate some environmental impacts (Beylot, Corrado, Sala 2020; Castellani, Beylot, Sala 2019), highlighting the categories dedicated to resources use and raw material estimations, with an impact on the supply chain risks analysis (Research Line II).

In spite of the fact that this research on the hybrid method only involved the assessment of the environment pillar, this methodological proposal must be understood as a general method, and therefore, the ISM would provide the framework to enable the assessment of other impacts (such as social or socioeconomic impacts) if data on costs and employment (LCC, S-LCA) are detailed enough. It should be considered that there are still unresolved challenges in the inclusion of social impacts in quantitative assessment frameworks such as LCA and MRIO, but significant progress has been made in recent years (Hardadi, Pizzol 2017). Examples of databases created to integrate social impact assessment and IOA already exist, including notably the Social Hotspot Database (SHDB) (Benoit Norris, Norris, Aulisio 2013) – used in the whole sustainability framework assessment included in the [Result 2](#) - and the Product Social Impact Life Cycle Assessment (PSILCA) database (Maister et al. 2020). However, these are not hybridization methods as such, but extensions of the EMRIO framework using social risk data. Combining the detailed social impact assessment carried out in a S-LCA for a given project, with the more general social risks arising in the value chain of such project would be a way of hybridizing both methods (socially extended EMRIO and S-LCA). No such hybridising attempts have been found in literature and this could be a future research line that could benefit from the advances made in this thesis for the environmental dimension.

Focusing on the RQ3, the aim was developing a complete and simpler hybrid method maintaining the pros and avoiding the cons of the both original methods (EEMRIO and LCA). The proposed method is simpler than the approaches proposed in literature because: 1) the method avoids the alteration of the MRIOT matrix reducing complexity, assumptions and uncertainties; and 2) the ISM method implies that, thanks to the proposed intermediate step, the scope potentially duplicated in both methods can be more precisely established, and in consequence, need to make complex and arbitrary assumptions is reduced. This intermediate step has been noted as LCASSIOA (LCA software supported Input-Output Analysis).

The results presented in [Result 4](#) showed the success of the ISM method in complementing the LCA results by incorporating the EMRIO outputs using a time-efficient alternative of hybridization that avoids double-counting to a large-extent. The results showed that with the only exception of some impact categories (Climate change and Water consumption (without scarcity ponderation)), the different methods compared presented substantial discrepancies in absolute impact results. In most of the cases, EMRIO and LCA provided the extreme values (the highest and the lowest) and the hybrid approaches were found in between them. In general, the traditional tiered hybrid method (TM) failed to incorporate all the not covered impacts in LCA, since many services and immaterial processes of background processes were not included. However, the results obtained from the proposed ISM method indicated that this was not the only reason for the underestimation of impacts by the TM method. Many processes that were far in the supply chain, such as those involving primary sectors, have been identified to have an essential contribution in some impacts categories such as water consumption and mineral and metals depletion (all called Resource use or Abiotic Depletion Potential). These processes cannot be incorporated in the traditional TM method but can be identified and added up using the proposed ISM method.

In many cases, the added impacts come from primary and tertiary sectors, but also from sectors located in countries not directly involved in the flows of the inventory but in the global value chains of the intermediate products.

The highest differences between methods were found in the assessment of local impacts and resource depletion (either energy or minerals and metals), while the methods tend to agree more on the quantification of global and regional impacts (Figure 22). However, there are limitations on the implementation of the impact characterization methods and the quantification of the potential impacts that should be considered when comparing the results of the different methods. In particular, EMRIO satellite accounts do not consider all the substances that LCA databases do.

Figure 22 shows the deviation of the results reached by each methodological approach with respect to the average result obtained per category of impact. As previously mentioned, generally, EMRIO and LCA provide the extreme values, with hybrid approaches falling somewhere in between, with the exception of water impact assessments, in which ISM approach provides the maximum values. Methodologically it is reasonable to expect hybrid results to be between the LCA and the EMRIO results, but it will depend on the hybrid method used, the data sources and data availability and assumptions of the case study and how well the MRIO sectors used represent the materials and processes involved (aggregation error). As Pomponi and Lenzen (Pomponi, Lenzen 2018) showed, the truncation error of process-based LCA usually outweighs the aggregation error of hybrid LCA and EMRIO. Additionally, (Perkins, Suh 2019) demonstrated that truncation error of LCA introduces an underestimation bias in the results while the aggregation error of MRIO does not have a unique direction and is more random and depends more on the concrete case specificities.

Regarding water impact assessment, results showed that water consumption impact results estimations are very close among the different approaches. However, when looking at water depletion results (including scarcity), methods tend to diverge quite a lot. On the one hand, LCA tends to ignore water consumption from very far sectors in the global value chain from countries with high water scarcity (i.e. primary sector consumptions embodied in intermediate products) due to the general inability of LCA to precisely characterize regional contributions in background products and processes. On the other hand, EMRIO has the ability to precisely spot regional contributions but has a low technological detail related to the production of some materials or power components (i.e. water deprived due to hydropower activity to support some metals manufacture in Europe is one of the activities identified as relevant contributors by LCA, but that is not seen in EMRIO results). Thus, an advantage of ISM is its ability to add to the accurate but incomplete results of the LCA the correctly characterised embodied water in components and intermediate products coming from the different regions and sectors in EMRIO.

As mentioned before, in general, methods tend to differ mainly in the assessment of local impacts and depletion of resources, such as energy, minerals and metals, while the results obtained with different methodological approaches tend to be more similar in the assessment of global and regional impacts (Climate Change and Acidification). The highest deviations are found in the estimation of impacts from Respiratory Inorganics and Mineral and Metals abiotic Depletion, where EMRIO results are considerably higher. In this case, the ISM method proposed reveals that EMRIO is likely overestimating the impacts due to the high sectorial aggregation issue that does not precisely represent the technology used in components and intermediate

products manufacture, since the missing sectors in LCA do not add much impact to the total results (LCA and ISM results are very similar). The same can be said about energy consumption and, to a lesser extent, about minerals and metals depletion. Nevertheless, this comparison allows identifying those impact categories in which methods tend to converge and puts the focus on the need for further research on data and methods for the most divergent impact results. Similar divergences in some of the impact categories, such as Minerals and metals depletion or Respiratory inorganics, have been found by others (Beylot, Corrado, Sala 2020).

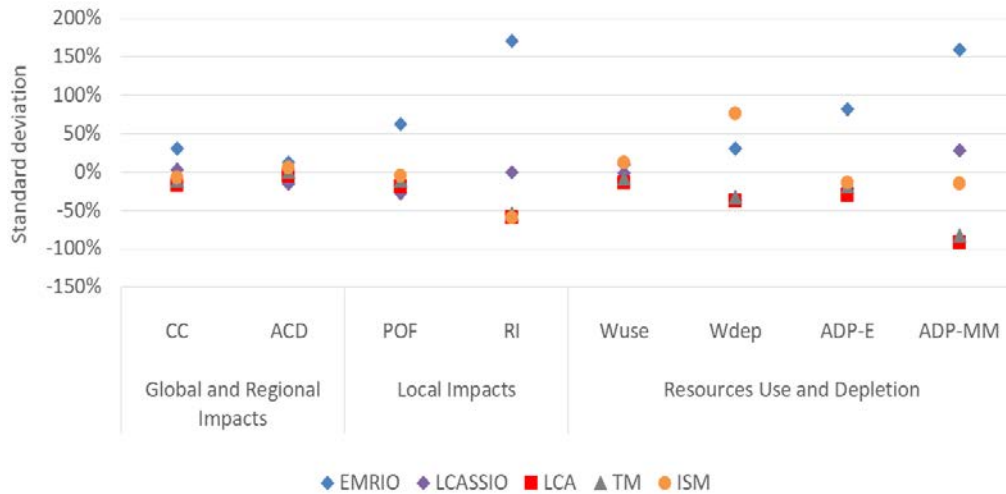


Figure 22. Dispersion of the results obtained by each of the approaches in the assessment of the different environmental impact categories.
Source: Result 4 (Gamarra, Lechón, et al. 2023).

Although developers of LCA-MRIO hybrid methods claim that they produce more accurate results than process-based LCA, the hybrid methods merits have been criticised in literature (Yang, Heijungs, Brandão 2017) and it is still an issue of debate (Pomponi, Lenzen 2018). Some works in the literature have carried out comparative studies of hybrid methods applied to the environmental assessment of different case studies. For instance, (Wiedmann et al. 2011) explored two options for hybrid life cycle assessment (hybrid LCA), Input-Output-based Hybrid LCA and Integrated Hybrid LCA, to account for the indirect GHG emissions of energy technologies using wind power generation in the UK as a case study. They found that hybrid methods resulted in a higher value of GHG emissions than process-based LCA. Perkins and Suh (Perkins, Suh 2019) investigated the use of hybridization by applying the tiered hybrid method to quantify the environmental impact of one use of an average jacket. They found that hybridization effectively moved the mean of the life cycle (GHG emissions to a value 38% higher). These results were the ones expected since after analysing the data sources for LCA and EMRIO they concluded that in LCA the truncation error is unidirectional and it often results in an underestimation bias, while

the errors in the input-output data, or other proxy data for cut-offs are generally random. (Luo, Ierapetritou 2020) reviewed different LCA and hybrid methodologies and applied them to the comparative study of two biomass-based systems. They ran the process LCA, the tiered hybrid LCA, and the integrated hybrid LCA after binary correction for double counting. They highlight the choice of LCA method, especially hybrid methods, under different data availability. Some of the techniques of correction (binary and Strømman and Solli's method (SSM)(Strømman, Solli 2008)) applied after the Integrated hybrid are closely related to the ISM, as approach a manner to not to correct the results, but to distinguish the sectors to excluded from the process LCA, in order to include or not their contribution to the impact in the final result. However, the ISM acts directly over results of the EMRIO, and the binary and SSM corrections are included in the hybrid matrix creation.

Some of the own limitations of EMRIO and LCA still remain in the proposed ISM method. As LCA is very detailed, conclusions obtained in the analysis of specific cases are not generalizable as data is shaped to the scenario assessed, and the assumptions should need consider. The static nature of the analysis and the long time-lag in updating the IO data tables is a recognized limitation of MRIO-based methods that cannot be solved by the ISM method. The MRIO analysis is static since MRIO tables and databases depicts the economy at a certain point in time. In the case of the [Result 1](#), the assessment is based on the 2011 WIOD Input-Output table (Corsatea et al. 2019). In the [Result 2](#) and 3, Exiobase 3.4 (year 2011)(Stadler et al. 2018) was used. Finally, Exiobase 3.8. for the year 2018 was used (Stadler et al. 2019) for the EMRIO analysis conducted in the [Result 4](#).

The advances on computing capacities have made possible for MRIOTs developers go forward on solving this limitation. Additional more satellite accounts, more regions and products are step by step being added to the most important MRIO data bases. Implicit limitations of the MRIO methodology do not allow for the analysis of dynamic scenarios with individual changes in the indirect demand. For instance, the assessments undertaken in [Result 2](#) or [Result 4](#) could not include the change in the intensity of silver use or the set of metals by the sectors demanding the metals. Others researchers resort to methodologies such as computable general equilibrium models (CGE) (Bekkers et al. 2019; Caceres, Cerdeiro, Mano 2019; Itakura 2019) or combine MRIO and CGE (Böhringer, Schneider, Asane-Otoo 2016), but these approaches also add other limitations related to the uncertainties of assumptions involved in CGE methods.

4. RQ4. Which results are obtained from the assessment of sustainability and supply risks of key energy technologies for the energy transition?

The methodological proposal of this thesis for the assessment of sustainability and supply risks along the value chain has been tested in several cases studies of key technologies for the energy transition. In the following, the main findings are discussed.

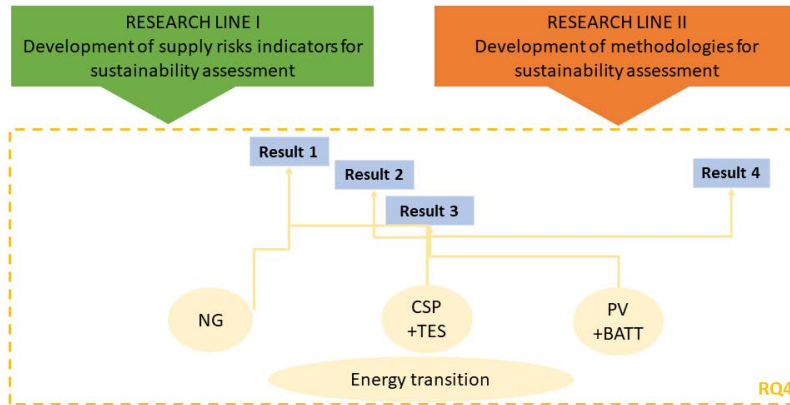


Figure 23. Portion of the methodological scheme addressing RQ4.

Renewable technologies can achieve better scores on diversity and governance than its fossil counterparts, but not all the risks come from imports and not all renewable energy investments entail lower risks along the value chain than investments in fossil technologies.

The assessment carried in the STEP 1 of the Research Line I allows the comparison between the deployment of two alternative energy investments in Mexico: a NGCC power plant and a CSP power plant. The results indicated that the NGCC supply chain had a lower level of supplier diversification along the value chain than that of CSP and a generally higher level of geopolitical risk. This was caused because NGCC suppliers of components and intermediate products along the value chain score worse in most of the indicators. By applying this first approach considering only diversity and governance, results suggested that CSP deployment in Mexico would not only increase the renewable power production reducing the carbon emissions of the energy sector (Rodríguez-Serrano 2017), but could also have a lower associated geopolitical supply risks.

The assessment also showed the important unfavourable contribution that Mexico's low governance score plays in the total CSP related results. Nevertheless, that does not mean that importing from abroad is better than domestic supply, but it calls for CSP support' policies that include mitigation measures to address the identified risks (Political Stability and Absence of Violence (PSVA)) and take care on the design of policies and regulations of the domestic industry.

When results per unit of energy produced were compared (Figure 24), the CSP baseline scenario reached better levels of governance than NGCC in the indicators related to Voice and accountability (VA), Government Effectiveness (GE), Regulatory Quality (RQ) and Rule of Law (RL), and slightly better for Control of Corruption (CC); but it scored worse in the indicator related to Political Stability and Absence of Violence (PSVA), mainly, as pointed out above, due to the role of Mexico. Two sensitivity analysis with two alternative set of providers for key components for CSP were conducted to show the impact of the election of key industrial partners and technology providers to deploy the power plant. In one of them, these key components would come from Europe (EUR) and, in the other one, would come from China (CHN). The sensitivity analysis revealed considerable differences on results. While CSP plant with European supply reaches quite high levels of governance, Chinese value chain supply presented the lowest values among the CSP scenarios in some governance indicators among the assessed (PSVA, CC, VA, RL, even worse than NGCC scenario).

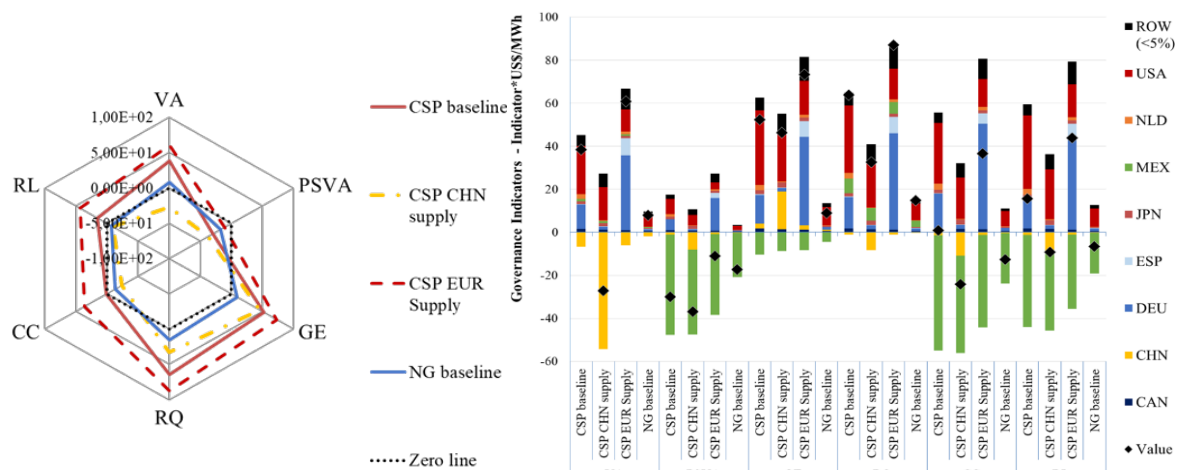


Figure 24. Governance analysis of the scenarios assessed in the Result 2.

Source: (Gamarra, Y. Lechón, et al. 2022). The scenarios assessed were Natural Gas (NG, blue line), Concentrated Solar Power (CSP) baseline (red line), and sensitivity scenarios (European supply in discontinuous red line and Chinese supply in yellow). On the left, the total cost effect related to the power production by governance criteria (US\$*Indicator/MWh). On the right, the total cost effect related to the power production by governance criteria and countries contributions (US\$*Indicator/MWh).

CSP deployment in a country like Spain could achieve better sustainability performance with lower supply risks if cooperation agreements with European countries are in place. However, the penetration of Chinese industries in CSP plant deployment in Europe will worsen the global sustainability of these plants.

The cooperative approach scenario assessed in [Result 2](#) for CSP deployment seems to perform better than a pure Spanish investment regarding the sustainability indicators analysed (especially in the case of central receiver technology). The scenario in which Germany

manufactures some key components of the CSP plants becomes the most attractive option as it retains wealth inside the European Union, minimizes the Carbon and Water footprints and the indicator of silver Extraction, reduces the risks of incurring unfair wages and child labour that may occur all along the supply chains (mostly outside the European Union) and decreases the risk of supply.

In the comparison of the two other scenarios (Pure Spanish investment and Chinese manufacturing) per each technology (Parabolic trough, PT, and Central receiver, CR), results showed that the penetration of the Chinese CSP industry in the European market will worsen the global sustainability of the CSP plants. The creation of value added at both the European and global levels would be reduced. In term of job creation, although this scenario rises total job creation, this increase only happens in China at the expense of the decrease in the potential European employment. Carbon and water footprints would also be higher, as well as the risk of unfair wages and child labour. The same is showed by the need for silver extraction in origin, and, therefore, the associated risk of supply of this metal. These negative impacts could be minimized if China moved to a fair, inclusive and low-carbon energy transition. Recent times it has been showed that China is increasing the use and diversity of low carbon sources in electricity generation (WEC 2019), as the Chinese Government is working on this pathway when they announce the New Plan for Renewable Energy Development in 2022 with higher targets for renewables (IEA-WEO 2022).

As for the analysis of risks along the value chain, the results obtained in [Result 2](#) when applying the combined indicator of diversity and governance (DG_{WGIix}) to the assessment of total production of goods and services (over the total output), showed that the best scores were achieved under the European Alliance scenarios for all the governance criteria, mainly due to the German contribution. Surprisingly, the Pure Spanish and the Chinese supply scenarios were revealed as pretty similar in the indicator for some governance criteria: Control of Corruption (CC), Rule of Law (RL) and Regulatory quality (RQ), with the Chinese supply being slightly better than the Pure Spanish in the Central Receiver scenarios. As discussed in the [Result 2](#), the reason was found in the high diversity of the Chinese scenarios, and the very distributed contribution from the OECD and some countries included in the Rest of the World (ROW) region, which added positive scores for Chinese scenarios in terms of governance. On the contrary, the higher contribution associated to the Pure Spanish scenario from countries from Latin America affects negatively the final scores. Conversely, as for other governance criteria, the VA indicator represents a penalty for the Chinese scenarios with the notable lowest score.

Concerning the supply risk analysis associated to silver extraction requirements along the value chain, the best scores are also reached in the scenarios under the European Alliance scenario in all governance criteria and specifically in the scenario Central Receiver. Although the main silver extraction would occur in Latin America (WL), some countries with a low quota of participation are behind this result (such as Poland, the fifth producer around the world (Philip Newman et al. 2022)), as their weight in the combined indicator increases with the number of different origins and a more spread out share. On the contrary, the contribution of Bulgaria caused a negative impact for some criteria (such as CC, GE or RL). Again, The Chinese and Pure Spanish Scenarios reached similar scores, slightly better for the second one. While the shares of Poland and other European countries are slightly lower than those in the European Alliance scenarios, the contribution from Latin America (mainly Mexico, (Philip Newman et al. 2022)), Africa and Asia was higher, being regions with worse scores of governance criteria in general.

Central receivers are found as the best option adding benefits in sustainability, suggesting that their deployment should be prioritized, for example, by including a merit order premium in CSP auctions for this technology. However, the higher needs of silver extraction of central receivers lead to higher risks of supply of this key material for this technology except in the case of the European cooperation approach, since the lower diversity is compensated by a better quality of governance and higher intra-European contribution. In spite of that, the lower needs of extraction of silver under this scenario should be further analysed but potential reasons could be related to the higher efficiency and higher recycling rates of German economic sectors. That could be plausible as showed by the data from the Metal Focus World Silver Survey 2022 (Philip Newman et al. 2022), in which while the demand by Chinese sectors⁵ were 8,167 tons and by German sectors⁴ were 1,697 tons, the ton of recycled silver were 705 and 306 tons, in China and Germany respectively. That means that in 2018, in the Chinese economy less than 8 tons of silver are recycled per each 100 tons that are demanded while in the German economy 18 tons of silver are recycled by each 100 tons that are demanded. Therefore, the benefits of CSP for sustainability would be maximized under European cooperation alliances in which German companies manufacture the key components.

It is essential to consider that technology-research on the next decade could substantially contribute to reduce the supply risks in Europe. Supply risk strongly depends on the prevailing trade relationships between the sectors consuming the materials (glass production sector for

⁵ The figures includes the amounts demanded by the main involved sector in the value chain of Silver identified in the report Metal Focus World Silver Survey 2022 (Philip Newman et al. 2022), except physical investment. Therefore, these includes Industrial Photograph, Jewelry, Silverware, Silver De-Hedging.

silver in the CSP case and the sectors and countries extracting them). Two factors affect the level of material extraction: 1) the rate of recycled material used, 2) the efficiency of the process using this material. Technology research can influence both processes that favour recycling (separation, etc...) at the end of life, developing production processes that minimize the use of materials (lower thickness, etc...) and favouring suppliers from countries with high levels of governance.

Policies to foster recycling industries and recycling practices within industry must be impulsed. Imposing some requirements to the suppliers of materials in terms of recyclability (e.g. regulate the mandatory level of recycling rates minimum thresholds) or promoting certification schemes for the sustainability of extraction activities (e.g. case of illegal rare earths in China (Standaert 2019) could help in the lowering of supply risk (as well as other impacts)).

The supply chain of metals for the of deployment PV with batteries storage shows lower strength than the deployment of CSP with TES. PV supply chain showed a lower level of supplier diversification than that of CSP, and a generally lower level of governance in origin. This implies that the extraction of the metals required to deploy each MWh of CSP with thermal storage would come from a more diverse set of countries and regions, and/or from countries with better governance levels than in the case of PV with batteries. Even considering the metal (mainly iron) recycling contribution to the European stock assessed for PV, and therefore, the positive effect on in the resilience term of the SCSi, the total result showed a higher weakness of metals supply chain than in the case of CSP, as shown in Figure 25 and Figure 26.

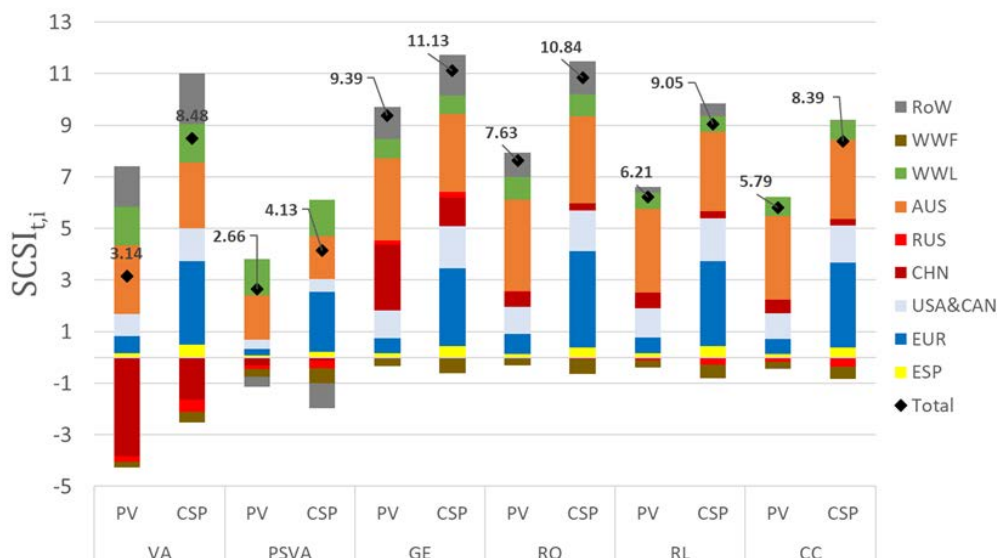


Figure 25. Results of the combined indicator Supply Chain Strength Indicator (SCSi) for each technology and regional contribution.

RoW: Rest of the World; WWF: African Region; WWL: Latin America Region; AUS: Australia; RUS: Russia; CHN: China; USA&CAN: United States of America

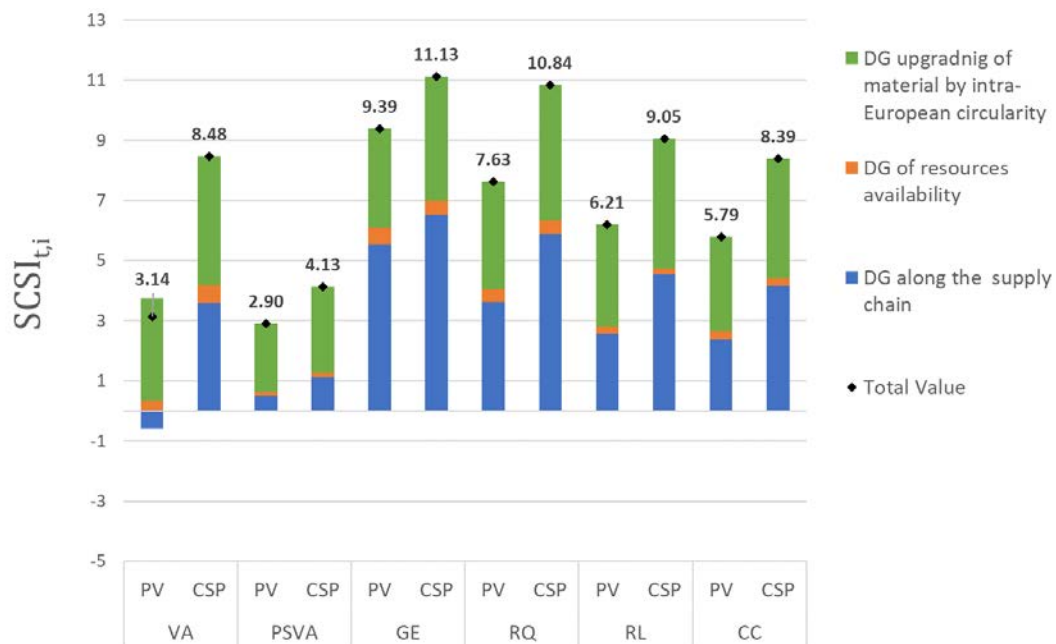


Figure 26. Results of the combined indicator Supply Chain Strength Indicator for each technology and contribution by dimension. DG-dependence and governance.

The limitations of the scenarios compared in [Result 3](#) can be discussed, as the most favourable CSP scenario in terms of supply found in [Result 2](#) (European Agreement scenario) was confronted with the PV supply scenario (with a high contribution of Chinese components). However, this scenario is entirely reasonable and reflects the current state of PV deployment, as shown by recent figures on the origin of PV manufacturing (China accounts for three-quarters of the manufacturing and assembly of solar PV modules and EV batteries according to the last World Energy Outlook Report of the International Energy Agency (IEA-WEO 2022)).

V. CONCLUSIONS

1. Main conclusions

The conducted research, split in two lines of development and endorsed with four main individual research contributions, provides insights for sustainability practitioners, policymakers, policy regulators and investors to assess the sustainability and to address specific analysis of the risks and strengths associated to the supply chain of energy investments.

The main conclusions arising from this research are the following:

- **Sustainability assessments of energy investments should include the analysis of the global value chain:** Given the current global market globalisation, manufacture chain fragmentation and unequal distribution of resources along the planet, hidden interdependencies along the value chain of global trade networks might result in supply risks. Sustainability assessment should include these considerations. The identification of better strategies considering the whole value chain is crucial to avoid potential threatens, design prevention and mitigation mechanisms such as collaboration agreements, and develop appropriate regulations.
- **Integrated sustainability assessment is a powerful tool that can incorporate the supply risk assessment:** the methodological developments of Research Line I enrich the EMRIO based sustainability assessment of energy investments by providing a method to assess supply risks along the value chain. The ability of EMRIO to capture and quantify direct and indirect effects and to trace back the countries and regions involved in the global value chain enables the identification and quantification of hidden contributions, and therefore, the supply risk associated to them.
- **The assessment of the three orthogonal main dimensions (Dependence, Availability and Resilience) of energy security in the energy transition can be covered by the proposed four-component framework.** While in the past, fossil fuel energy markets and trade relationships involved a small number of countries and the balance among exports, imports and storage were enough to assess the risks, a new framework of dependencies and energy security challenges have emerged with the large scale implementation of renewable energy technologies required for the energy transition. Due to the fragmentation of global supply chains, the geographical landscape of dependence relationships has changed and many other actors have entered the playing field. Due to the high demand of different raw materials (critical and non-critical) by renewable technologies, constrains and risks in the supply of these minerals and metals could be a limited factor for their large scale deployment. Strategies to increase resilience should go beyond storage and should incentivise resource use efficiency and the recovery of raw materials from waste streams

in line with circular economy practices. Then, new methods of supply risk assessment should also include this source of resilience. Potential risks of supply are not only affected by the diversity of potential suppliers but also by the disparity among them. The inclusion of the governance criteria provides the weighted quantification of the risks (or strengths) considering the levels of governance focused on specific aspects. The four-component assessment of risk of the value chain proposed in this thesis covers the three dimensions of energy security (Dependence, Availability and Resilience) adapted to the new landscape originated by the current energy transition.

- **The proposed hybrid Identification and Subtraction Method (ISM) for environmental sustainability assessment succeeds in improving the quantification of impacts as it increases the completeness of the assessment and simultaneously avoids the double counting of the classical tiered method and the complexity of other hybrid methods.** The main innovation of the approach is the method for determining more precisely the scope covered by LCA and EMRIO. In general, the method is able to add to the LCA impacts those occurring in economic sectors in countries or regions far apart in the value chain that can be quantified by EMRIO. Comparing the results obtained by EMRIO, LCA, the classical hybrid tiered method and the ISM method, the largest differences were found in the assessment of local impacts and resource depletion, while the methods tend to agree more on the quantification of global and regional impacts. More precise results on resource use provided by the ISM would help to more accurately determine risks along the value chain.
- **The use of case studies of interest for the energy transition allowed the validation of the proposed methodologies providing findings useful for decision-makers, regulators and investors.** European deployment of renewables should be accompanied by measures to secure supply, such as cooperation agreements, and should also encourage the recovery of secondary material by maximising European resilience. As for the CSP case study analysis, the findings suggest that energy policy strategies should focus on reinforcing the local and European CSP industry through cooperation mechanisms and the impulse of circularity practices that would ensure that CSP can contribute to energy security, while providing clean, renewable, dispatchable and flexible electricity to the European electricity mix, and promoting employment and economic growth, and, thus, a more sustainable energy system.

2. Broader implications for policy making

Risks on supply is high on the policy agenda as a result of the global energy crisis sparked by Russia's invasion of Ukraine. In the case of Europe, in response to this crisis, the energy transition has been accelerated. The current ongoing policy support for renewables deployment have allowed that around 50 GW were installed in the EU in 2022 especially wind and solar (IEA-WEO 2022). NG demand in the EU fell in 2022 by 13%, its sharpest drop in history. This new installed power avoided the need of around 11 billion of cubic meters of NG in the power sector (IEA 2023). However, as showed in the previous chapters, the supply chain associated to renewables is not exempt of risks. The globalised value chains involve several metals mining and extraction activities around the world, mainly outside of Europe that has become a clear importer of raw materials. In order to reduce this new strategic dependency, the Critical Raw Material Act is presented in parallel to the EU's Net Zero Industry Act, and aims to scale up the EU manufacture of key carbon neutral or "net-zero" technologies to ensure secure, sustainable and competitive supply chains for clean energy in view of reaching the EU's climate and energy ambitions (EC 2023).

The methodological proposals and results reached in this thesis allow to identify some points to decision-makers and policy regulators to focus on:

Efforts on reducing dependence:

- **Identify the strongest supply chains, the origin of weaknesses and act to prevent risks, and do it fast.** Identify direct and indirect suppliers and their impacts on total dependence, diversity and governance. The supply chain needs to be fast adapted to prevent the replication of conventional schemes of risks related to fossil fuels (stakeholders' supremacies, markets control, etc.). The risks of an inadequate supply are becoming evident. Price spikes in copper, lithium and other materials have broken a decades-long run of cost declines in clean energy technologies such as wind and solar PV (IEA 2023) .

The methodologies developed in this thesis can indeed help policy makers in identifying the strongest supply chains

- **Encourage multilateral agreements: collaboration instead of competition.** The International Energy Agency provides us some facts and figures on foreseen deployment of renewables. As the new global energy economy emerges, many nations are competing to install new technologies from solar panels and wind turbines to electric cars and heat

pumps (IEA 2023). The world is set to add as much renewable power in the next five years as it did in the previous 20 years – an amount equivalent to the entire electricity capacity of China today (ibid). Europe must shore up its critical mineral supply chains to counter the risk of being left behind as other regions of the world speed up their efforts to secure supplies (ibid). In this context, strengthening the cooperation with reliable trading partners globally to reduce the EU's current dependencies on just one or a few countries is a key European priority (EC 2023)..

Methods developed in this thesis can also be used to identify potential reliable trading partners along the supply chain

Efforts on overall Sustainability:

- **Manage ongoing energy and climate targets without harming economic activity, guarantying social inclusion and promoting broader environmental targets.**

Multidisciplinary assessment of energy strategies and investments should include the energy trilemma within the three pillars of sustainability making use and integrating the most widely used frameworks of sustainability assessment. The trilemma refers to the complicated objectives that governments face in securing competitive energy supplies while providing universal energy access and promoting environmental protection. It thus addresses three fundamental aspects of energy: security of supply, social equity and environmental impact mitigation.

Energy security, understood as effective management of energy supply from domestic and external sources (for both net energy importers and exporters), reliability of energy infrastructures and the ability of energy companies to meet current and future demand (for countries that are net energy exporters, this also refers to the ability to maintain revenues from external sales markets). Social equity, which refers to the accessibility and affordability of energy supply for the whole population. And environmental impact mitigation thanks to energy efficiency and savings (both on the supply and demand side) and development of renewable and other low-carbon energy supply.

Methods developed in this thesis can be used to assess the overall sustainability of energy investments identifying potential hot spots and designing mitigation strategies

Policies to foster industry of recycling and recycling in industry must be boosted. The security benefits of recycling have been demonstrated in this thesis. Imposing some requirements to the suppliers of materials in terms of recyclability (e.g. that regulate the mandatory level of recycling rates minimum thresholds) or promoting certification schemes

for the sustainability of extraction activities (e.g. case of illegal rare earths in China (Standaert 2019) could help in reducing supply risk (as well as other impacts). Putting in place better collection systems, harmonised waste regulations and a sound investment framework for recycling facilities are vital to position the EU as a leader in the space. The circular economy introduced by the European Commission and specifically for batteries recycling, will ensure that there is a new legal framework to guarantee standards and targets for recycling.

Methods developed in this thesis can be used to evaluate the benefits for the intra-European circularity of the different alternatives of energy investment and the associated supply risk mitigation

3. Future lines of research

The further developments and future lines of research arising from the research conducted in this thesis are diverse and can unfold in several directions.

First, the natural next step would be to combine the two lines of research. I.e., assess the risks (or strengths) along the supply chain of a case study of deployment of a renewable technology, using the risk assessment method developed in the Research Line I, and considering the results of metal and mineral extraction provided by the ISM method developed in the Research line II. This further research would contribute to provide accurate results due to two main reasons: 1) a more precise inventory of the amount and origin of material requirements coming from the LCA contribution; and simultaneously, 2) the inclusion of the indirect extraction of materials coming from the contribution of EMRIO to the hybrid ISM method.

Even keeping the two lines of research individually, a set of improvements can be still developed.

Further developments and future lines for the Research Line I

- Research for incorporating exogenous geopolitical aspects using spatial statistical tools such as nearest neighbour analysis of governance or clustered analysis (Seyedan, Mafakheri 2020) or the weighting of bilateral relationships and supremacy position of some countries on the supply chain.
- The application of the method to other materials relevant for other energy technologies such as for example CRMs, as well as the combination with other methodologies or tools for scenario development such as energy modelling (Talens Peiró et al. 2022) or CGE (Perdana, Vielle, Schenckery 2022)

Further developments and future lines for the Research Line II

- The proposed ISM method could be applied to other case studies for further validation and better insights into the method's advantages when assessing other types of product systems.
- The method can be standardized to help researchers its application for environmental impact assessments.
- The method could be applied considering other relevant impacts (e.g. land use) not only environmental (also socioeconomic or social impacts), as well as other different databases.

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VII. ANNEXES

Annex 1. Bibliometric search results.

The tool provided by Clarivate included in the platform Web of Science (WoS) allows to assess the existing literature related to specific topics included a wide global body of literature (the Web of Science Core Collection). Figure 1. 1 depicts the seven searches conducted. The numbers in the figure represent the results of seven searches that have been carried out as a result of entering in the search engine the word strings of each block (plus those of the previous one). Each of the levels is additive to the upper one, i.e., the intermediate level includes the words of the upper one, and those of the lower one includes the words of the upper and the intermediate one. Finally, the last rectangular block in the base is a search including all the key terms.

Results of the searches:

- Search 1 [“Sustainability” (All Fields⁶) AND “assessment” (All Fields) AND “method”]: as big numbers on the topic **16,646 publications** selected from Web of Science Core Collection with the higher contribution to the categories Environmental Sciences (42.7%), Green Sustainable Science Technology (32.9%), Environmental Studies (22.3%), Engineering Environmental (12.7%) and Energy Fuels (7.98%).
- Search 2 [“Sustainability” (Topic) AND “assessment” (Topic) AND “method” (Keyword Plus®) AND “2000-2022” (Year Published)]: narrowing the search by specifying where looking for (topic and Keyword Plus®) and the period (before year 2000)] the proliferation decreases and just only **402 publications** are found. Same top categories are showed, but with a slightly lower contribution (Environmental Sciences (36.2%), Green Sustainable Science Technology (30.562%), Environmental Studies (17.359%), Engineering Environmental (13.936%)), with exception of a higher contribution to Energy Fuels category (13.203%). The 402 publications have reached 9,704 total citations with a growing trend over the time on new publications and citations.

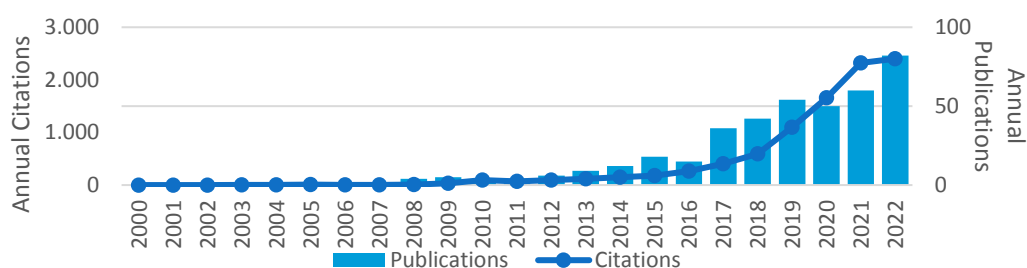


Figure 1. 1. Summary of results of the Search 2. Times Cited and Publications Over Time.

⁶ All fields includes coincidences in title, abstract, author keywords, and Keywords Plus ® (a parameter for capturing the content and scientific concepts presented in articles (Zhang et al. 2016))

- Search 3, adding **“Supply chain risks”**: [“sustainability” (Topic) AND “assessment” (All Fields) AND “method” (All Fields) AND “2000-2022” (Year Published) AND “supply chain risks” (All Fields) and 2000-2022 (Publication Years)] displays **136 publications**. The top categories contribution belonged to Environmental Sciences (47.1%), Green Sustainable Science Technology (19.8%), Engineering Environmental (28.7%), Environmental Studies (14.8%) and Energy Fuels (7.3%), and two new categories raised: Management (10.5%) and Operations Research Management Science (5.8%). These publications have reached the 3,622 total times cited.

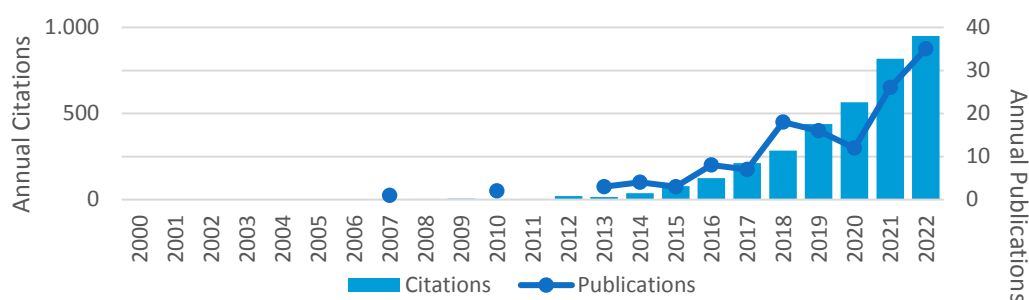


Figure 1. 2. . Summary of results of the Search 3. Times Cited and Publications Over Time.

- Search 4, adding **“life cycle hybrid method”**: [“sustainability” (Topic) AND “assessment” (All Fields) AND “method” (All Fields) AND “2000-2022” (Year Published) AND “life cycle input-output hybrid” (All Fields) generated **184 publications**. These publications reach more 5,259 total citations with a growing trend over the time on new publications and citations. The top categories were Environmental Sciences (46.2%), Green Sustainable Science Technology (35.3%), Engineering Environmental (29.9%), Energy Fuels (23.4%), Environmental Studies (12.5%), Engineering Chemical (7.6%).

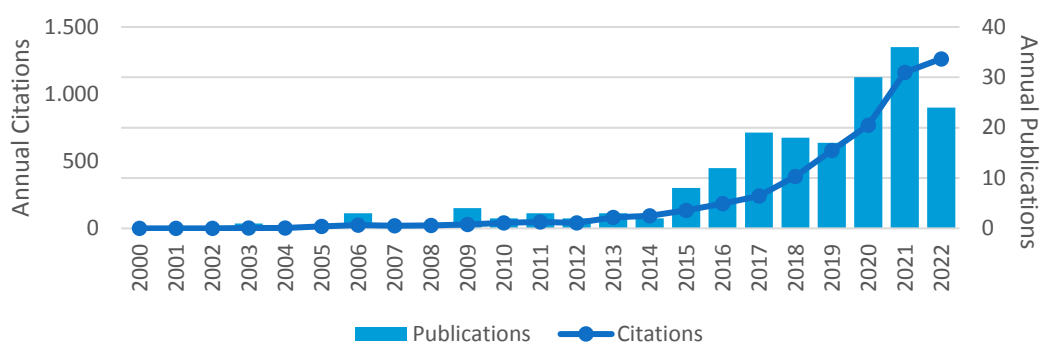


Figure 1. 3. Summary result of Search 4. Times Cited and Publications Over Time.

- Search 5, adding **“energy”** to search 4 21 results were reached from Web of Science Core Collection with 1,105 citations in total with an irregular progress over the time from the year 2000 to 2022. The 21 publications Environmental Sciences (47.62%), Engineering Environmental (38%), Green Sustainable Science Technology (38 %), Energy Fuels

(19.048%), Engineering Chemical (19.048%), Environmental Studies (14.286%), Transportation (9.524%), Transportation Science Technology (9.524%)

- **Search 6, adding “energy” to search 3** were reached 36 results from Web of Science Core Collection with 1,105 citations in total with an irregular progress over the time from the year 2000 to 2022. Green Sustainable Science Technology (52.778%), Environmental Sciences (50%), Engineering Environmental (39%), Energy Fuels (28%), Environmental Studies (16.7%)

Search 7, All together: Does not produce results.

Figure 1. 4 depicts the seven searches conducted. The numbers in the figure represent the results of seven searches that have been carried out as a result of entering in the search engine the word strings of each block (plus those of the previous one). Each of the levels is additive to the upper one, i.e., the intermediate level includes the words of the upper one, and those of the lower one includes the words of the upper and the intermediate one. Finally, the last rectangular block in the base is a search including all the key terms.

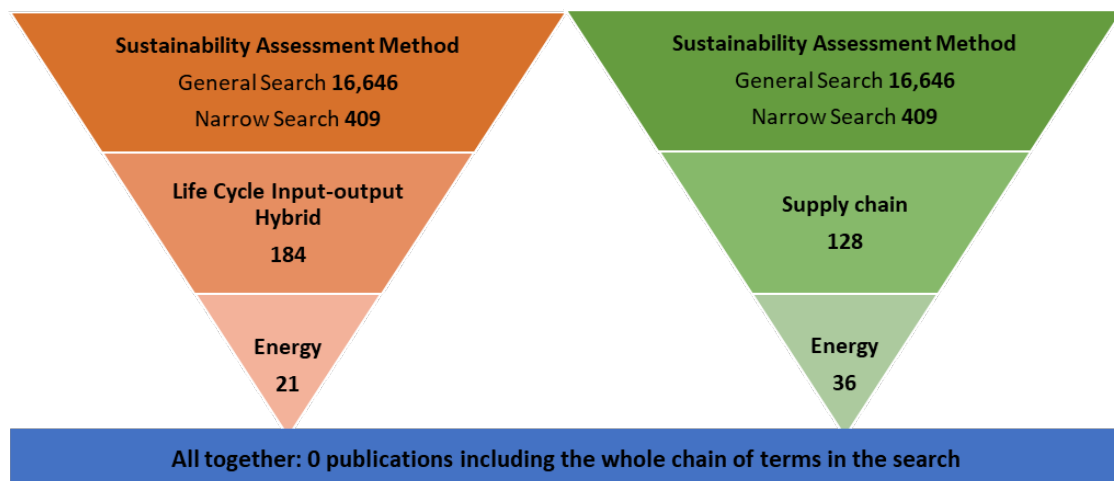


Figure 1. 4. Summary of results of the bibliometric analysis by searching in WoS.

Annex 2. Complete list publications.

- Gamarra, A.R., Lechón, Y., Banacloche, S., de Andrés, J.M. Metals' supply chain risk analysis of renewable energy investments. A methodological proposal and a case study of solar power plants in Spain. UNDER REVIEW in the Journal of Cleaner Production.
- Gamarra, A.R., Lechón, Y., Escribano, G., Lilliestam, J., Lázaro L., Caldés, N. Assessing dependence and governance as value chain risks: Natural Gas versus Concentrated Solar power plants in Mexico, Environmental Impact Assessment Review, Volume 93, 2022, 106708, ISSN 0195-9255, <https://doi.org/10.1016/j.eiar.2021.106708>.
- Gamarra, A.R., Banacloche, S., Lechón, Y., del Río, P. Assessing the sustainability impacts of concentrated solar power deployment in Europe in the context of global value chains, Renewable and Sustainable Energy Reviews, Volume 171, 2023, 113004, ISSN 1364-0321, <https://doi.org/10.1016/j.rser.2022.113004>
- Gamarra, A.R., Lechón, Y., Banacloche, S., Corona, B., de Andrés, J.M. A comparison and methodological proposal for hybrid approaches to quantify environmental impacts: A case study for renewable energies, Science of The Total Environment, Volume 867, 2023, 161502, ISSN 0048-9697, <https://doi.org/10.1016/j.scitotenv.2023.161502>

Participation in Book chapters and papers:

- Gamarra, A.R., Banacloche, Caldés N., Lechón, Y., 2023. The Socioeconomic Benefits of Renewable Energy Projects, in: Río, P. del, Ragwitz, M. (Eds.), Handbook on the Economics of Renewable Energy. Edward Elgar Publishing, Inc. ISBN 978-1800379015.
<https://www.e-elgar.com/shop/gbp/handbook-on-the-economics-of-renewable-energy-9781800379015.html>
- Gamarra, A.R., Lechón, Y., Banacloche, S., ¿Qué cantidad de riqueza y empleo genera la energía eólica?, in Tecnología y Sostenibilidad de la Energía Eólica (Editores G. San Miguel et al.) Editorial Mundiprensa - Paraninfo, ISBN: 9788484769606
- Banacloche, S., Gamarra, A.R., Lechón, Y., Bustreo, C. Socioeconomic and environmental impacts of bringing the sun to earth: A sustainability analysis of a fusion power plant deployment, Energy, Volume 209, 2020, 118460, ISSN 0360-5442, <https://doi.org/10.1016/j.energy.2020.118460>

Participation in Conferences, Workshops and Congresses:

- Extending MRIO analysis of energy technologies with dependence and governance aspects
Ana Rosa Gamarra; Yolanda Lechón, Lohan Lilliestam; Gonzalo Escribano; Lara Lázaro-Touza
L; Natalia Caldés. 27th Internacional Input Output Association Conference. Glasgow
(Scotland, UK). 30/06/2019.
- Hibridación Input-Output para la mejora del análisis de la Huella Hídrica de los cultivos de
biocombustibles en España: Resultados preliminares. Banacloche, S., Gamarra, A.R.,
Garraín, D., Lechón, Y. VIII Jornadas de Análisis Input-Output. Santiago de Compostela
(Spain). 12/09/2019
- Supply risk analysis of silver for solar thermal power plants. An analysis of global value
chains. Gamarra, A.R., Banacloche, S., Lechón, Y.. 1st AMPEA-E3S joint workshop on
“Sustainability Assessment of materials and technologies for a clean energy transition”.
26/03/2022. Online.
- Análisis del riesgo de suministro de plata para centrales termosolares considerando las
cadenas globales de valor. Gamarra, A.R., Banacloche, S., Lechón, Y. REDMENTES
workshop. Alcalá de Henares. 26/05/2022

Annex 3. Characterization of impacts

As EMRIO analysis as LCA or hybrid methods for environmental analysis provide results of the the environmental burden is obtained in term of amounts of substance or item (emissions of pollutants, effluents and wastes). In LCA those emissions, effluents and wastes are obtained from the Inventory Analysis phase. In EMRIO, those amounts are obtained from the environmental extension using the different satellite accounts.

Impact categories often assessed include climate change (or Global warming potential), ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related), respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion. However, the different substances have a different contribution in relation with determined impact categories.

Each substance is characterized by contribute to one or more environmental impact in a different level and there are several methods to measure. Each method of characterization provides the selection of substances involved and the factors of characterization for each of them. A factor or characterization (FC) quantitatively reflect the contribution of a determined substance to a determined impact category considering a method and a specific unit of equivalence. FC is a quantitative representation of the (relative) importance of a specific substance for an environmental impact.

E.g. considering the impact category Global Warming Potential (GWP100), the emissions of the substance Methane (CH_4) is 22 kg CO_2 -eq/ kg of CH_4 , while the emission of Carbon Dioxide (CO_2) is 22 kg CO_2 -eq/ kg of CO_2 . There are some emissions involved in different impacts categories (e.g. NO_x emissions to air contributes to acidification, eutrophication, human toxicity).

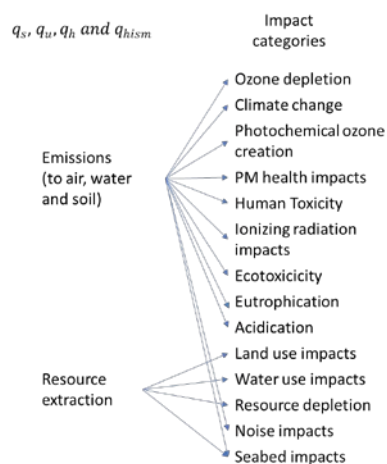


Figure 3. 1. Characterization emissions and raw materials and Impact categories.

Following the methodology and notation presented in the Research Line II of the methodology and the [Result 4](#), the substances or flows quantified in the inventory of emissions and resources in LCA or the environmental output from EMRIO (q_s , q_u , q_h and q_{hism}) are assigned to each of these impact categories. They are then converted into indicators of impact using factors calculated by impact assessment methods (e.g. IPCC, Recipe, etc.,). These factors reflect pressures per unit emission or resource consumed in the context of each impact category. Emissions and resources consumed, as well as different product options, can then be cross-compared in terms of the indicators.

Annex 4. Detailed results of the analysis of similarities.

Analysis of similarities of the Result 1

The analysis of the [Result 1](#) using the tool Connected papers showed that the work presented there put in connection two prolific fields of knowledge and another little one (Figure 4. 1). The most similar paper to [Result 1](#) is the [Result 2](#) (see Table 4. 1 of the Annex 2).

One big group (upper-left) more focused on risk of supply, disparities and dependence, material flows assessment and the connection with index of human development and natural resources governance. Those are stated in the graph around Liu et al (2022), who conducted analysis of material flow among multiple phases of cobalt industrial chain based on a complex network and being. Papers in this group are (Ebrahimi Salari et al. 2022)(The threshold effect of Human Development Index on the relationship between financial development and oil revenue), (Zheng, Wang 2022)(Impacts on human development index due to combinations of renewables and ICTs – new evidence from 26 countries), (Xun et al. 2020) (End-of-life recycling rates of platinum group metals in the automotive industry: Insight into regional disparities), (Yamamoto et al. 2022) (The role of recycling in alleviating supply chain risk–Insights from a stock-flow perspective),or (Xun et al. 2021) (Mapping global fuel cell vehicle industry chain and assessing potential supply risks). More details in Table 4. 1 of the Annex 4.

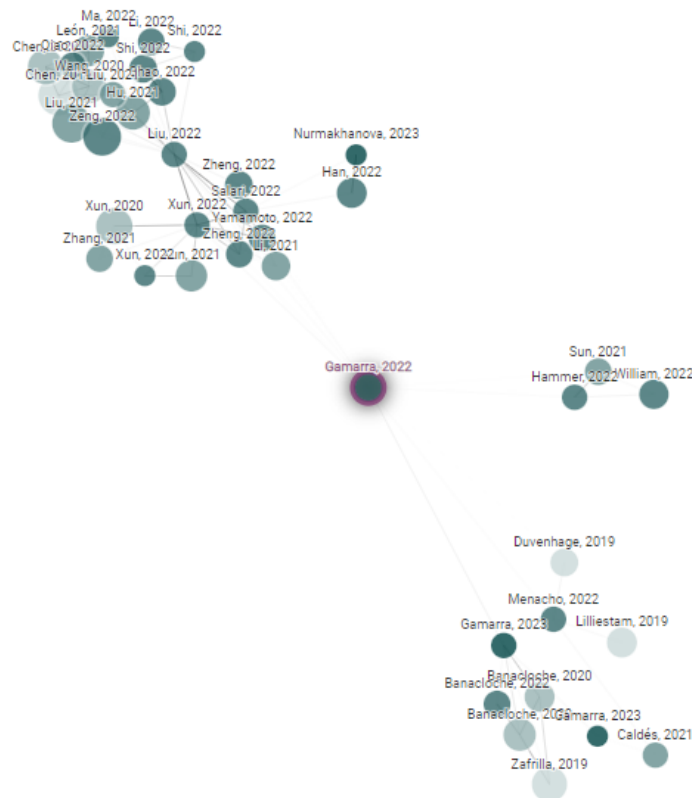


Figure 4. 1. Literature similarities analysis of the paper Result 1.

Assessing dependence and governance as value chain risks: Natural Gas versus Concentrated Solar power plants in Mexico (Gamarra, Y. Lechón, et al. 2022) . Graph exported from Connected Papers the 17th Jan 2023. The complete list of reference is in Annex 2.

The other smaller but also relevant group is the structured around (Gamarra, Banacloche, et al. 2023)([Result 2](#)) (down-right), where papers connected to CSP deployment assessment as well as other solar technologies is included, with the particularity that most of them are based on TBL analysis, EMRIO or at least contains data on costs analysis for deployment. Papers in this group are (Banacloche, Gamarra, et al. 2020)(Socioeconomic and environmental impacts of bringing the sun to earth: A sustainability analysis of a fusion power plant deployment), (Hahn Menacho, Rodrigues, Behrens 2022)(A triple bottom line assessment of concentrated solar power generation in China and Europe 2020–2050), Banacloche et al (2020) (Assessment of the sustainability of Mexico green investments in the road to Paris). More details in **Table 4. 1** at the end of the Annex 4.

Finally the smaller group is only composed by three papers ((Sun et al. 2022; William, Fengrong 2022; Hammer, Millar, Hennige 2022)) dedicated to the public policy and mitigation strategies analysis considering countries contributions and value chain analysis in different sectors.

Analysis of similarities of the Result 2

In the case of the analysis of the [Result 2](#) using the tool Connected Papers, they are much more spread (Figure 4. 2). In the middle, more or less in the core, papers assessing TBL of renewables or green policy and strategies assessed with MRIO surround the original [Result 2](#). The most similar paper to [Result 2](#) is the (Banacloche, Gamarra, et al. 2020) (Socioeconomic and environmental impacts of bringing the sun to earth: A sustainability analysis of a fusion power plant deployment and) follow by the [Result 1](#). Five small groups can be identified: group 1 (upper-left), the supply chain risks, dependencies and resources analysis (as in [Result 1](#)); group 2 (upper-right) a lower related as showed the higher distance, is a very technological related papers on technologies as hydrogen production (e.g.(Meng et al. 2019)) or lower related); group 3, focused on socioeconomic analysis based on EMRIO (e.g. Cameron, 2015, Mont,2018, Ramos, 2019),; group 4 (down, right) focused on the sustainability assessment modelling based on nexus such as “Environmental-Health-Economic” or three pillars approaches “GHG-Healthy-Equitable”; and group five, dedicated to deep in EMRIO and LCA developments and related research (e.g. (Jakobs, Schulte, Pauliuk 2021; Agez, Wood, et al. 2020)). The complete list can be found in Table 4. 2 at the end of the Annex 4.

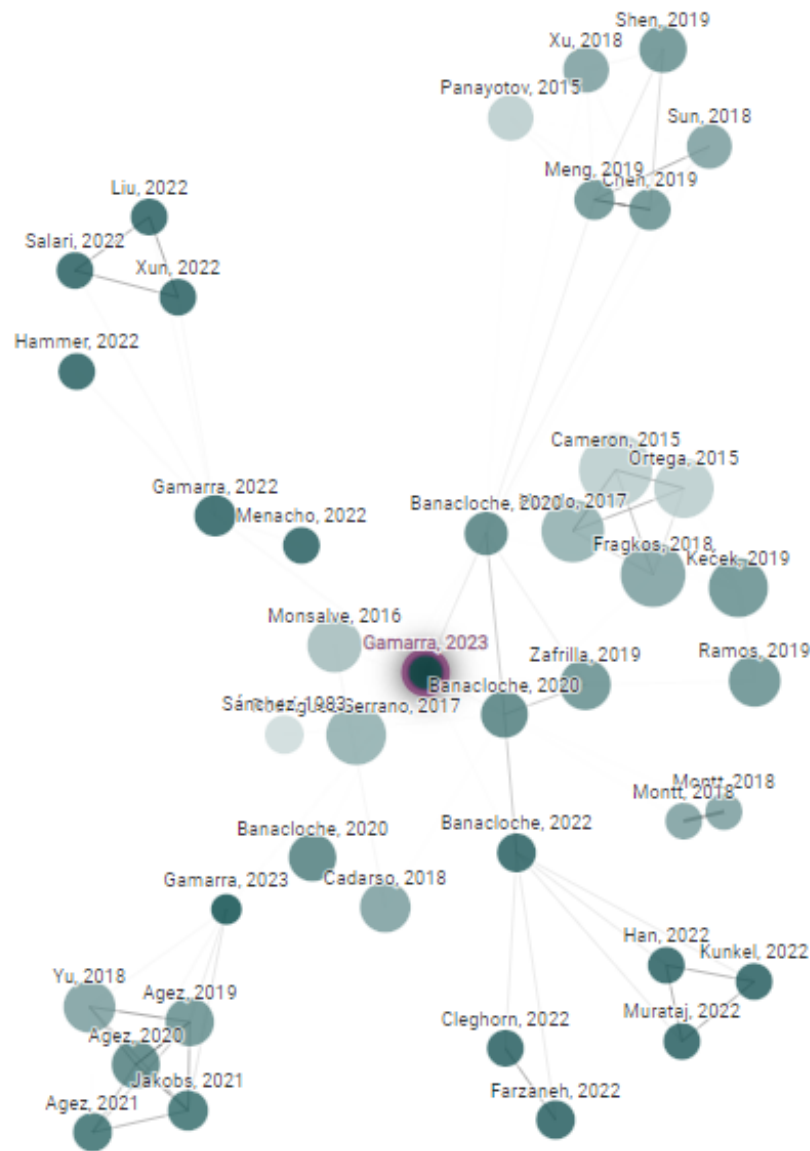


Figure 4. 2. Literature similarities analysis of the paper Result 2.
Assessing the sustainability impacts of concentrated solar power deployment in Europe in the context of global value chains (Gamarra, Banacloche, et al. 2023). Graph exported from Connected Papers the 17th Jan 2023.

Analysis of similarities of the Result 4

The similarities analysis of the **Result 4** (Figure 4. 3)using Connected Papers consists of a very homogeneous group pursuing similar objectives: improving the results obtained in (mainly) environmental assessments by proposed hybridization among EMRIO and LCA, studying databases of EMRIO and LCA, uncertainties, variances, and related development on the both methods converging to combine these. Also, with a substantial distance, (Caldés, Lechón 2020) and (Gamarra, Banacloche, et al. 2023) (**Result 2**) appears as they assess with EMRIO the case of CSP. More details are in Table 4. 3 at the end of the Annex 4.

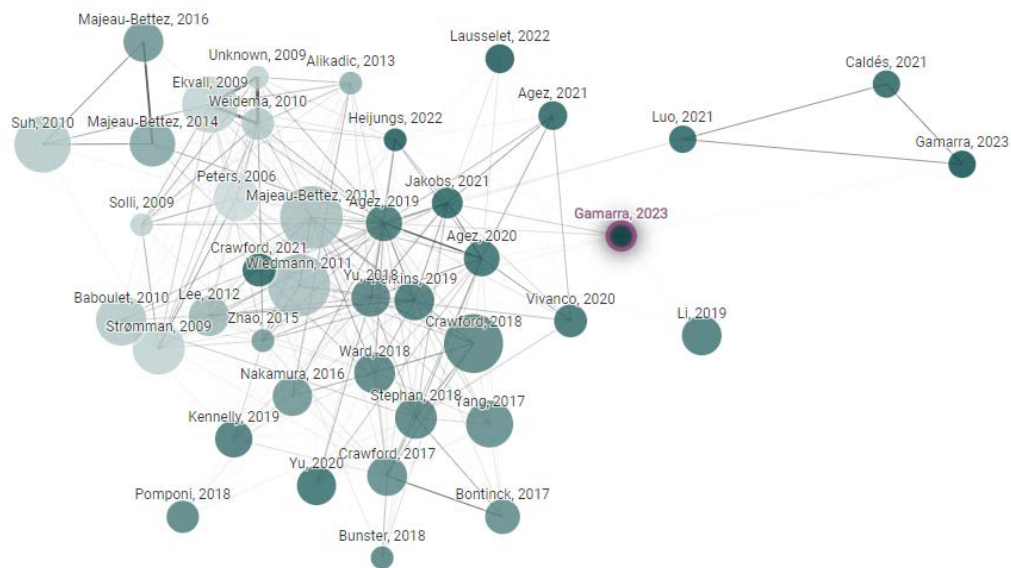


Figure 4. 3. Literature similarities analysis of the paper Result 4.
A comparison and methodological proposal for hybrid approaches to quantify environmental impacts: A case study for renewable energies (Gamarra, Lechón, et al. 2023). Graph exported from Connected Papers the 17th Jan 2023.

Table 4. 1 Analysis of Similarities of the Result 1.

Title	Authors	Year	Citations	References	Similarity
Assessing dependence and governance as value chain risks: Natural Gas versus Concentrated Solar power plants in Mexico	A. R. Gamarra, Y. Lechón, Gonzalo Escribano, J. Lilliestam, L. Lázaro, N. Caldés	2022	4	54	100
Assessing the sustainability impacts of concentrated solar power deployment in Europe in the context of global value chains	A. R. Gamarra, S. Banacloche, Y. Lechón, P. Del Río	2023	1	48	10.8
Comparing supply chains of platinum group metal catalysts in internal combustion engine and fuel cell vehicles: a supply risk perspective	Dengye Xun, Xin Sun, Zongwei Liu, F. Zhao, Han Hao	2022	1	49	9
Reducing carbon emissions in aquaculture: Using Carbon Disclosures to identify unbalanced mitigation strategies	Alienor Jue Hammer, Charles Millar, S. Hennige	2022	1	50	8
Analysis of material flow among multiple phases of cobalt industrial chain based on a complex network	Meng Liu, Huajiao Li, Jinsheng Zhou, Sida Feng, Yanli Wang, Xingxing Wang	2022	1	37	8
The threshold effect of HDI on the relationship between financial development and oil revenues	Taghi Ebrahimi Salari, Ali Akbar Naji Meidani, Zeinab Shabani Koshalshahi, Amir Abbas Ajori Ayask	2022	1	41	8
A triple bottom line assessment of concentrated solar power generation in China and Europe 2020–2050	A.J. Hahn Menacho, João F. D. Rodrigues, P. Behrens	2022	1	28	8
Impacts on human development index due to combinations of renewables and ICTs —new evidence from 26 countries	Jiajia Zheng, Xingwu Wang	2022	2	59	6.8
Socioeconomic and environmental impacts of bringing the sun to earth: A sustainability analysis of a fusion power plant deployment	S. Banacloche, A. R. Gamarra, Y. Lechón, C. Bustreo	2020	6	81	6.7
End-of-life recycling rates of platinum group metals in the automotive industry: Insight into regional disparities	Dengye Xun, Han Hao, Xin Sun, Zongwei Liu, F. Zhao	2020	23	59	6.6

Title	Authors	Year	Citations	References	Similarity
The role of recycling in alleviating supply chain risk—Insights from a stock-flow perspective using a hybrid input-output database	Tales Yamamoto, S. Merciai, J. Mogollón, A. Tukker	2022	2	44	6.5
The Belt & Road Initiative and the Public and Private Debts of participating Countries: The Role of China's Economic Policy Uncertainty	Yunpeng Sun, Zhou Lu, Qun Bao, Ying Li, Haoning Li	2021	2	35	6.5
Assessment of the sustainability of Mexico green investments in the road to Paris	S. Banacloche, M. Cadarso, F. Monsalve, Y. Lechón	2020	11	84	6.1
Mapping global fuel cell vehicle industry chain and assessing potential supply risks	Dengye Xun, Xin Sun, Jingxuan Geng, Zongwei Liu, F. Zhao, Han Hao	2021	9	72	6
Economic policy uncertainty and industry innovation: Cross country evidence	Mbanyele William, Wang Fengrong	2022	5	55	5.5
Water and CSP – A preliminary methodology for strategic water demand assessment	D. Duvenhage, A. Brent, W. Stafford, O. Craig	2019	3	30	5.5
Analysis on the Evolution Characteristics of Kaolin International Trade Pattern Based on Complex Networks	Shuxian Zheng, Xuan Zhou, Wanli Xing, Peirong Zhao	2022	3	50	5.5
Electrochemical desulfurization of galena-stibnite in molten salts to prepare liquid Sb–Pb alloy for liquid metal battery	Xianyang Li, Jiakang Qu, Zhuqing Zhao, Yan Zhao, Hongwei Xie, Huayi Yin	2021	4	31	5.5
Modeling the evolvement of regional fuel cell vehicle supply chain: Implications for enhancing supply chain sustainability	Dengye Xun, Han Hao, Xin Sun, Jingxuan Geng, Zongwei Liu, F. Zhao	2022	0	27	5.5
Trade structure and risk transmission in the international automotive Li-ion batteries trade	Xiaoqian Hu, Chao Wang, Xiangyu Zhu, Cuiyou Yao, P. Ghadimi	2021	15	69	5.4
Cobalt material flow in the United States from 1995 to 2015	Litao Liu, Huilan Zhao, Xiaojie Liu, T. Dai, Gang Liu	2021	1	37	5.3

Title	Authors	Year	Citations	References	Similarity
The impact of country risks on cobalt trade patterns from the perspective of the industrial chain	Yingli Li, Jian-bai Huang, Hongwei Zhang	2022	2	32	5.3
Carbon capture penetration in Mexico's 2050 horizon: A sustainability assessment of Mexican CCS policy	S. Banacloche, Y. Lechón, A. Rodríguez-Martínez	2022	2	34	5.2
A comparison and methodological proposal for hybrid approaches to quantify environmental impacts: A case study for renewable energies.	A. R. Gamarra, Y. Lechón, S. Banacloche, B. Corona, J. M. de Andrés	2023	0	70	5.2
Tracking and quantifying the cobalt flows in mainland China during 1994-2016: Insights into use, trade and prospective demand.	Zhenyang Chen, Lingen Zhang, Zhenming Xu	2019	41	26	5
Triple bottom line analysis of the Spanish solar photovoltaic sector: A footprint assessment	J. Zafrilla, Guadalupe Arce, M. Cadarso, C. Córcoles, Nuria Gómez, L. López, F. Monsalve, M. Tobarra	2019	19	78	4.9
Dynamic analysis of platinum material flows and stocks with hybrid MFA method aiming to carbon neutral targets of automotive industry in China	Yana Zhang, Yingying Liu, He Lv, Sha Chen, Sumei Li	2021	2	34	4.9
The Impact of Country Risks on the Dependence Patterns of International Cobalt Trade: A Network Analysis Method	Shuaiwei Shi, Qingru Sun, Zenglei Xi, Meiyi Hou, Jiaoyun Guo	2022	0	59	4.9
The evolution of the global cobalt and lithium trade pattern and the impacts of the low-cobalt technology of lithium batteries based on multiplex network	Liuguo Shao, Wenwen Kou, Hua Zhang	2022	3	45	4.9
Potential of urban cobalt mines in China: An estimation of dynamic material flow from 2007 to 2016	Yibo Wang, Jianping Ge	2020	15	109	4.8
Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages	Anqi Zeng, Wu Chen, Kasper Dalgas Rasmussen, Xuehong Zhu, M. Lundhaug, Daniel B. Müller, Juan Tan, J. Keiding, Litao Liu, Tao Dai, Anjian Wang, Gang Liu	2022	29	89	4.6
Cobalt Demand for Automotive Electrification in China: Scenario Analysis Based on the Bass Model	Qing Shi	2022	3	38	4.6

Title	Authors	Year	Citations	References	Similarity
The dragon awakens: Will China save or conquer concentrating solar power?	J. Lilliestam, Lana Ollier, S. Pfenninger	2019	6	29	4.5
Exploring potential opportunities for the efficient development of the cobalt industry in China by quantitatively tracking cobalt flows during the entire life cycle from 2000 to 2021.	Donghai Qiao, T. Dai, Gaoshang Wang, Yanling Ma, Hailong Fan, Tianming Gao, Bojie Wen	2022	1	48	4.5
Dynamic material flow analysis of critical metals for lithium-ion battery system in China from 2000–2018	Wenqiu Liu, Wei Liu, Xinxin Li, Yeye Liu, Abiodun Ogunmoroti, Muyang Li, Mengyan Bi, Zhaojie Cui	2021	32	38	4.5
How natural resources affect financial development development? Fresh evidence from top-10 natural resource abundant countries	J. Han, Chandrashekar Raghutla, Krishna Reddy Chittedi, Zhixiong Tan, M. Koondhar	2022	6	44	4.5
Socio-economic and environmental assessment of concentrating solar power systems	N. Caldés, Y. Lechón	2021	1	78	4.4
Assessment of cobalt recycling potential and environmental impact in China from 1994 to 2020.	Qiaoying Ma, Lilong Chen, Xin Li, Minxi Wang, Litao Liu	2022	0	32	4.4
Analysis of cobalt flows in mainland China: Exploring the potential opportunities for improving resource efficiency and supply security	Zhenyang Chen, Lingen Zhang, Zhenming Xu	2020	19	35	4.4
Does natural resource curse in finance exist in Africa? Evidence from spatial techniques	M. Nurmakhanova, Mohamed Elheddad, A. AlFar, Alloysius Egbulonu, M. Zaynul Abedin	2023	0	34	4.4
Analysis of long-term statistical data of cobalt flows in the EU	María Fernanda Godoy León, G. Blengini, J. Dewulf	2021	8	19	4.3

Table 4. 2. Analysis of Similarities of the Result 2.

Title	Authors	Year	Citations	References	Similarity
Assessing the sustainability impacts of concentrated solar power deployment in Europe in the context of global value chains	A. R. Gamarra, S. Banacloche, Y. Lechón, P. Del Río	2023	1	48	100
Socioeconomic and environmental impacts of bringing the sun to earth: A sustainability analysis of a fusion power plant deployment	S. Banacloche, A. R. Gamarra, Y. Lechón, C. Bustreo	2020	6	81	14.9
Assessment of the sustainability of Mexico green investments in the road to Paris	S. Banacloche, M. Cadarso, F. Monsalve, Y. Lechón	2020	11	84	12.3
Assessing dependence and governance as value chain risks: Natural Gas versus Concentrated Solar power plants in Mexico	A. R. Gamarra, Y. Lechón, Gonzalo Escribano, J. Lilliestam, L. Lázaro, N. Caldés	2022	4	54	10.8
Carbon capture penetration in Mexico's 2050 horizon: A sustainability assessment of Mexican CCS policy	S. Banacloche, Y. Lechón, A. Rodríguez-Martínez	2022	2	34	9.1
A comparison and methodological proposal for hybrid approaches to quantify environmental impacts: A case study for renewable energies.	A. R. Gamarra, Y. Lechón, S. Banacloche, B. Corona, J. M. de Andrés	2023	0	70	9.1
Triple bottom line analysis of the Spanish solar photovoltaic sector: A footprint assessment	J. Zafrilla, Guadalupe Arce, M. Cadarso, C. Córcoles, Nuria Gómez, L. López, F. Monsalve, M. Tobarra	2019	19	78	8.4
Code development for analyzing transient behaviors induced by the in-box LOCA of liquid blanket in hydrogen fusion energy systems	Z. Meng, Shichao Zhang, Zhibin Chen, Shisheng Wang, Changjian Wang	2019	3	35	7.6
Transient pressure propagation behavior in PbLi loop system triggered by in-box LOCA accident of DFLL blanket	Lin Chen, Shichao Zhang, Zhibin Chen, Z. Meng, Shisheng Wang, Neda Sahebi	2019	4	27	7.1
CFD simulation of pressure wave propagation in the helium coolant tube break accident of DFLL-TBM	Qian Sun, Tianji Peng, Zhiwei Zhou, Zhibin Chen, Shisheng Wang	2018	8	11	6.3

Title	Authors	Year	Citations	References	Similarity
Price Variance in Hybrid-LCA Leads to Significant Uncertainty in Carbon Footprints	A. Jakobs, Simon Schulte, S. Pauliuk	2021	3	52	6.1
Exploring solutions to achieve carbon neutrality in China: A comparative study of a large-scale Passive House district and a Green Building district in Qingdao	Fei Han, Yang Wang, W. Feist, Xinyun Cao, Zhengjie Yu, Binlei Song, H. Benli, Georgios Dermentzis	2022	1	38	6
Developing Indoor Temperature Profiles of Albanian Homes for Baseline Energy Models in Relation to Contextual Factors	Jonida Murataj, Rajat Gupta, F. Nicol	2022	1	67	6
Can a Greenhouse Gas Emissions Tax on Food also Be Healthy and Equitable? A Systemised Review and Modelling Study from Aotearoa New Zealand	C. Cleghorn, I. Mulder, Alex Macmillan, A. Mizdrak, Jonathan Drew, N. Nghiem, T. Blakely, C. Ni Mhurchu	2022	1	67	6
100% renewable electricity policies in U.S. cities: A mixed methods analysis of adoption and implementation	Leah C. Kunkel, Hanna L. Breetz, J. Abbott	2022	1	51	6
Assessing the Environmental-Health-Economic Co-Benefits from Solar Electricity and Thermal Heating in Ulaanbaatar, Mongolia	Hooman Farzaneh, Mehrnoosh Dashti, E. Zusman, So-Young Lee, D. Dagvadorj, Zifei Nie	2022	2	44	6
Lifting the veil on the correction of double counting incidents in hybrid life cycle assessment	Maxime Agez, G. Majeau-Bettez, M. Margni, A. Strømman, R. Samson	2019	14	64	5.9
Small-scale renewable power technologies are an alternative to reach a sustainable economic growth: Evidence from Spain	C. Ramos, A. García, Blanca Moreno, G. Díaz	2019	21	105	5.8
Assessing the three sustainability pillars through the Framework for Integrated Sustainability Assessment (FISA): Case study of a Solar Thermal Electricity project in Mexico	Irene Rodríguez-Serrano, N. Caldés, C. Rúa, Y. Lechón	2017	48	48	5.8
Comparing supply chains of platinum group metal catalysts in internal combustion engine and fuel cell vehicles: a supply risk perspective	Dengye Xun, Xin Sun, Zongwei Liu, F. Zhao, Han Hao	2022	1	49	5.8
Employment factors for wind and solar energy technologies: A literature review	L. Cameron, B. Zwaan	2015	130	32	5.7

Title	Authors	Year	Citations	References	Similarity
Towards energy transition in Tunisia: Sustainability assessment of a hybrid concentrated solar power and biomass plant.	S. Banacloche, I. Herrera, Y. Lechón	2020	12	57	5.6
A triple bottom line assessment of concentrated solar power generation in China and Europe 2020–2050	A.J. Hahn Menacho, João F. D. Rodrigues, P. Behrens	2022	1	28	5.6
Reducing carbon emissions in aquaculture: Using Carbon Disclosures to identify unbalanced mitigation strategies	Alienor Jue Hammer, Charles Millar, S. Hennige	2022	1	50	5.6
Analysis of material flow among multiple phases of cobalt industrial chain based on a complex network	Meng Liu, Huajiao Li, Jinsheng Zhou, Sida Feng, Yanli Wang, Xingxing Wang	2022	1	37	5.6
The threshold effect of HDI on the relationship between financial development and oil revenues	Taghi Ebrahimi Salari, Ali Akbar Naji Meidani, Zeinab Shabani Koshalshahi, Amir Abbas Ajori Ayask	2022	1	41	5.6
Where have all the funds gone? Multiregional input-output analysis of the European Agricultural Fund for Rural Development	F. Monsalve, J. Zafrilla, M. Cadarso	2016	28	55	5.5
Hybridization of complete PLCA and MRIO databases for a comprehensive product system coverage	Maxime Agez, Richard Wood, M. Margni, A. Strømman, R. Samson, G. Majeau-Bettez	2020	13	46	5.5
Oil boom, a blessing for Mexico?	R. Sánchez	1983	2	2	5.5
Status of the EU test blanket systems safety studies	D. Panayotov, Y. Poitevin, I. Ricapito, M. Zmitko	2015	9	6	5.4
Numerical simulation of airflow characteristics during the loss of vacuum accident of CFETR	Youyou Xu, Songlin Liu, Xuebin Ma, Xiaoman Cheng, K. Jiang, Xiaokang Zhang	2018	9	21	5.4
Implementing hybrid LCA routines in an input–output virtual laboratory	Man Yu, T. Wiedmann	2018	21	79	5.4

Title	Authors	Year	Citations	References	Similarity
Deployment of renewable energy: Economic effects on the Croatian economy	Damira Keček, Davor Mikulić, Željko Lovrinčević	2019	45	33	5.3
Employment creation in EU related to renewables expansion	P. Fragkos, Leonidas Paroussos	2018	71	15	5.3
Safety regulatory framework for hydrogen fusion reactors in China	Xinyuan Shen, Zhibin Chen, Zhen Wang, Haixia Wang, Shanqi Chen, Daochuan Ge, Chao Chen, Jieqiong Jiang, Liqin Hu, Jie Yu, Yican Wu	2019	12	18	5.3
¿La acción climática destruye empleos? Efectos del objetivo de los 2 °C del Acuerdo de París en el empleo	Guillermo Montt, Kirsten S. Wiebe, Marek Harsdorff, Moana Simas, Antoine Bonnet, Richard D. Wood	2018	1	32	5.2
Employment creation potential of renewable power generation technologies: A life cycle approach	Hiroki Hondo, Yue Moriizumi	2017	61	36	5.2
Employment effects of renewable electricity deployment. A novel methodology	Margarita Ortega, P. Río, Pablo Ruiz, C. Thiel	2015	47	30	5.2
Emissions burden shifting in global value chains – winners and losers under multi-regional versus bilateral accounting	M. Cadarso, F. Monsalve, Guadalupe Arce	2018	18	73	5.2
L'action pour le climat, une action contre l'emploi? Évaluation des conséquences du scénario à 2 °C sur l'emploi	Guillermo Montt, Kirsten S. Wiebe, Marek Harsdorff, Moana Simas, A. Bonnet, Richard Wood	2018	1	41	5.2
Correcting remaining truncations in hybrid life cycle assessment database compilation	Maxime Agez, Elliot Muller, Laure Patouillard, Carl-Johan Södersten, Anders Arvesen, M. Margni, R. Samson, G. Majeau-Bettez	2021	2	49	5.1

Table 4. 3. Analysis of Similarities of the Result 3.

Title	Authors	Year	Citations	References	Similarity
A comparison and methodological proposal for hybrid approaches to quantify environmental impacts: A case study for renewable energies.	A. R. Gamarra, Y. Lechón, S. Banacloche, B. Corona, J. M. de Andrés	2023	0	70	100
Price Variance in Hybrid-LCA Leads to Significant Uncertainty in Carbon Footprints	A. Jakobs, Simon Schulte, S. Pauliuk	2021	3	52	15.7
Lifting the veil on the correction of double counting incidents in hybrid life cycle assessment	Maxime Agez, G. Majeau-Bettez, M. Margni, A. Strømman, R. Samson	2019	14	64	14.5
Hybridization of complete PLCA and MRIO databases for a comprehensive product system coverage	Maxime Agez, Richard Wood, M. Margni, A. Strømman, R. Samson, G. Majeau-Bettez	2020	13	46	12
Implementing hybrid LCA routines in an input–output virtual laboratory	Man Yu, T. Wiedmann	2018	21	79	11.6
Correcting remaining truncations in hybrid life cycle assessment database compilation	Maxime Agez, Elliot Muller, Laure Patouillard, Carl-Johan Södersten, Anders Arvesen, M. Margni, R. Samson, G. Majeau-Bettez	2021	2	49	10.5
Uncertainty Implications of Hybrid Approach in LCA: Precision versus Accuracy.	Jessica Perkins, S. Suh	2019	25	32	10.2
A or I-A? Unifying the computational structures of process- and IO-based LCA for clarity and consistency	R. Heijungs, Y Yang, K.Z. Zhang, P.K. Kannan, Hung-Suck Park	2022	0	56	10
Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues.	G. Majeau-Bettez, A. Strømman, E. Hertwich	2011	246	38	9.7
Integrated hybrid life cycle assessment and contribution analysis for CO2 emission and energy consumption of a concentrated solar power plant in China	Ruixiong Li, Haoran Zhang, Huanran Wang, Qingshi Tu, Xuejun Wang	2019	23	46	9.2

Title	Authors	Year	Citations	References	Similarity
Unified Theory of Allocations and Constructs in Life Cycle Assessment and Input-Output Analysis	G. Majeau-Bettez, Richard Wood, A. Strømman	2014	54	64	9.1
Assessing the sustainability impacts of concentrated solar power deployment in Europe in the context of global value chains	A. R. Gamarra, S. Banacloche, Y. Lechón, P. Del Río	2023	1	48	9.1
Guidelines for application of deepened and broadened LCA Deliverable D 18 of work package 5 of the CALCAS project Authors	B. Weidema	2010	6	49	8.9
Comparative Study of Different Hybrid Life Cycle Assessment Methodologies Applied to Biomass-based Chemical Production	Yuqing Luo, Robert M. O’Dea, Thomas H. Epps, M. Ierapetritou	2021	1	19	8.8
Hybrid life cycle inventory methods – A review	R. Crawford, P. Bontinck, A. Stephan, T. Wiedmann, Man Yu	2018	177	153	8.7
Improving the integrated hybrid LCA in the upstream scope 3 emissions inventory analysis	Chia-Ho Lee, Hwong-wen Ma	2012	28	23	8.7
Truncation Error Estimates in Process Life Cycle Assessment Using Input-Output Analysis	H. Ward, L. Wenz, J. Steckel, J. Minx	2018	30	60	8.7
A model for streamlining and automating path exchange hybrid life cycle assessment	A. Stephan, R. Crawford, P. Bontinck	2018	33	81	8.7
The EPiC database: Hybrid embodied environmental flow coefficients for construction materials	R. Crawford, A. Stephan, F. Prideaux	2021	6	60	8.6
The role of services and capital in footprint modelling	D. Vivanco	2020	7	45	8.6
Chapter for CALCAS deliverable D 18 , 2009 “ Guidelines for applications of deepened and broadened LCA ” Hybrid approaches combining IOA and LCA 1		2009	0	49	8.5

Title	Authors	Year	Citations	References	Similarity
Regional Research Institute West Virginia University Resource Document Series LCA Methodologies an Annotated Bibliography	Xueting Zhao	2015	0	52	8.5
Input–Output and Hybrid LCA	Shinichiro Nakamura, K. Nansai	2016	24	165	8.4
Guidelines for application of deepened and broadened LCA	T. Ekvall, R. Heijungs	2009	144	57	8.4
When Do Allocations and Constructs Respect Material, Energy, Financial, and Production Balances in LCA and EEIO?	G. Majeau-Bettez, Richard Wood, E. Hertwich, A. Strømman	2016	25	110	8.3
An environmental assessment tool designed for the calculation of life cycle emissions from companies, municipalities and organizations	Christian Solli, H. N. Larsen, J. Pettersen	2009	0	41	8.3
Approaches to correct for double counting in tiered hybrid life cycle inventories	A. Strømman, G. Peters, E. Hertwich	2009	105	23	8.2
Evaluating the environmental performance of a university	O. Baboulet, M. Lenzen	2010	89	33	8.2
The impact of value engineering on embodied greenhouse gas emissions in the built environment: A hybrid life cycle assessment	Man Yu, M. Robati, Philip Oldfield, T. Wiedmann, R. Crawford, A. A. Nezhad, D. Carmichael	2020	21	94	8.1
Improving the uptake of hybrid life cycle assessment in the construction industry	P. Bontinck, R. Crawford, A. Stephan	2017	11	18	8.1
Towards an Automated Approach for Compiling Hybrid Life Cycle Inventories	R. Crawford, P. Bontinck, A. Stephan, T. Wiedmann	2017	26	35	8
A comment on "Functions, commodities and environmental impacts in an ecological-economic model"	G. Peters, E. Hertwich	2006	54	15	7.9

Title	Authors	Year	Citations	References	Similarity
Hybrid life cycle assessment at the neighbourhood scale: The case of Ydalir, Norway	C. Lausset, R. Crawford, H. Brattebø	2022	1	46	7.9
Decomposition of integrated hybrid life cycle inventories by origin and final-stage inputs	Soo Huey Teh, T. Wiedmann	2018	3	22	7.8
Environmental Assessment of the Agricultural Sector	Azra Alikadic	2013	0	105	7.7
Towards a comprehensive hybrid life cycle inventory for Chilean building materials	V. Bunster, R. Crawford, P. Bontinck, A. Stephan, W. Bustamante	2018	0	50	7.6
Application of hybrid life cycle approaches to emerging energy technologies--the case of wind power in the UK.	T. Wiedmann, S. Suh, K. Feng, M. Lenzen, A. Acquaye, K. Scott, J. Barrett	2011	234	58	7.6
Embodied and Life Cycle Carbon Assessment of Buildings in Latin America: State-of-the-Art and Future Directions	Francesco Pomponi, L. Campos	2018	6	30	7.5
Hybrid life cycle assessment (LCA) does not necessarily yield more accurate results than process-based LCA	Y Yang, K.Z. Zhang, P.K. Kannan, R. Heijungs, R. Heijungs, M. Brandão	2017	63	12	7.4
Generalized Make and Use Framework for Allocation in Life Cycle Assessment	S. Suh, B. Weidema, J. Schmidt, R. Heijungs	2010	150	82	7.4
Hybrid life-cycle assessment for robust, best-practice carbon accounting	Cara Kennelly, M. Berners-Lee, C. N. Hewitt	2019	17	77	7.4

