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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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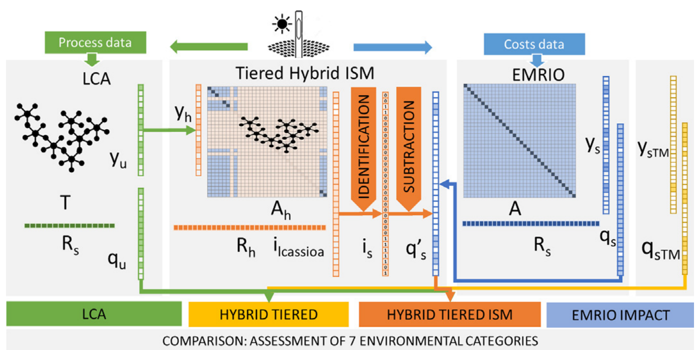
## HIGHLIGHTS

- 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 be 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 MRIOTs 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 MRIOT 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 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. Therefore, the main weakness of the approach is the sectoral aggregation, meaning 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). 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 MRIO), 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 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 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 particularsector. 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 the 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 sensoring 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, $CO_2$ 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 Electrica 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),

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

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 $CO_2$ 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:

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

where $q_s$ represents the total sustainability impact (kg of $CO_2$, 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 $CO_2$e (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 $NO_x$, $SO_2$, 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 to 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 MRIO 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, $m^3$, 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 MRIO. 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 insumes (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 MRIO 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 MRIO). 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 $CO_2$e/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 $CO_2$e/MWh. Whitaker et al. (2013) evaluated a 106-MW power tower concentrating solar power plant

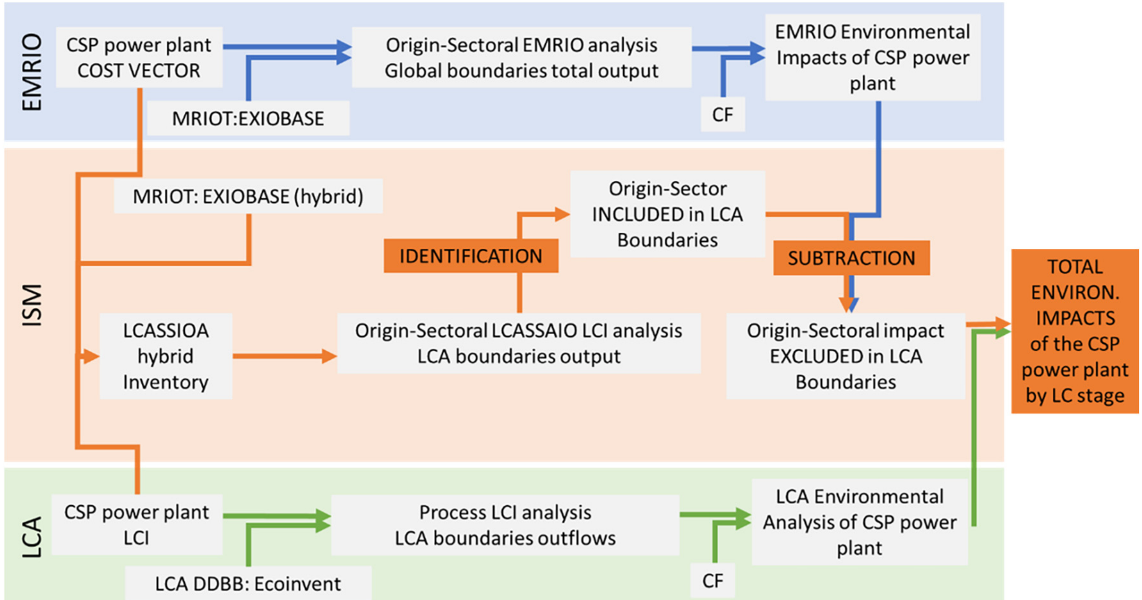


**Fig. 1.** Methodological scheme of the LCA, EMRIO and ISM. CF: Environmental impact characterization factors.

over its life cycle obtaining 37 kg $CO_2$e/MWh emissions, and the review provided in UNECE (2021) found an average value of 21.7 kg $CO_2$e/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 $CO_2$e/MWh which means that 82 % of the $CO_2$e 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 $CO_2$e/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 $CO_2$e/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 $CO_2$e 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 $CO_2$e associated with extraction and production of a portion of materials, compensating the emissions produced in the recycling processes. The $CO_2$e results obtained for the DEOL stage are similar in every method, with differences lower than 1 kg $CO_2$e/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

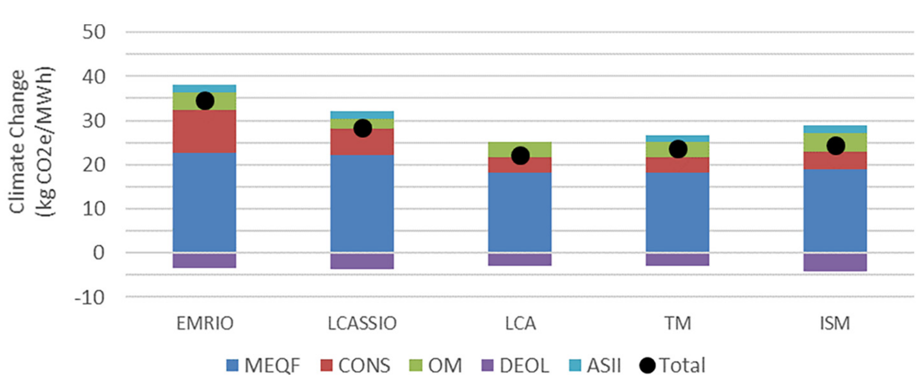


**Fig. 2.** Climate Change impact by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying five methods of quantification.

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 $CO_2$e/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 disperse 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 América 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*

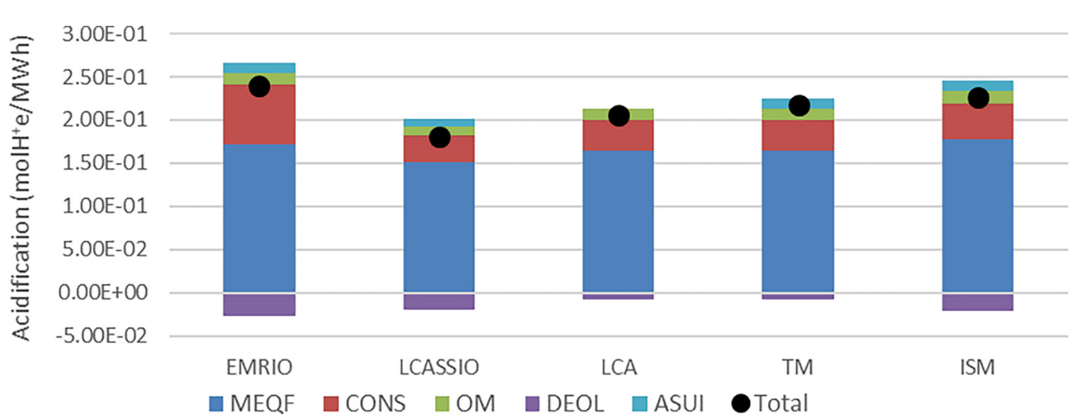


**Fig. 3.** Acidification impact by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying five methods of quantification.

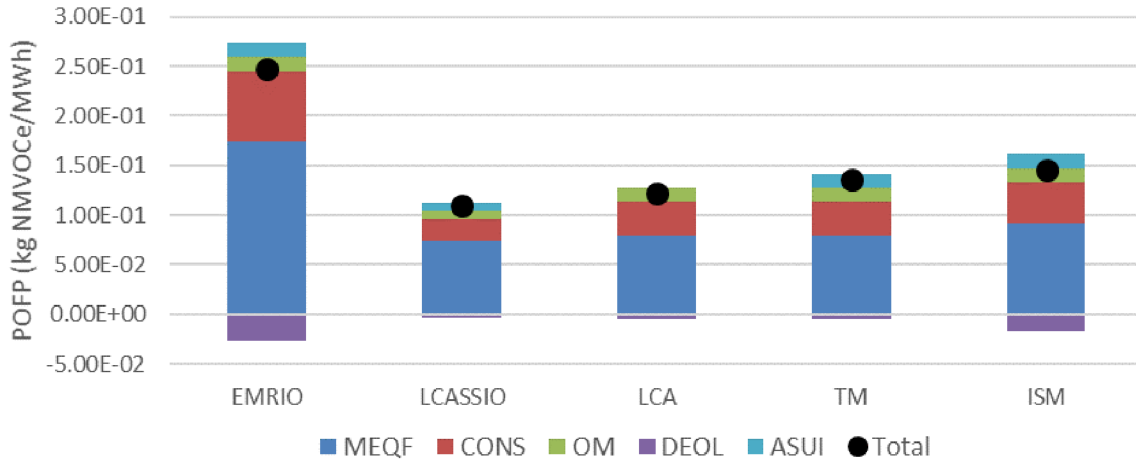


**Fig. 4.** Photochemical ozone formation potential impact by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying five methods of quantification.

*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

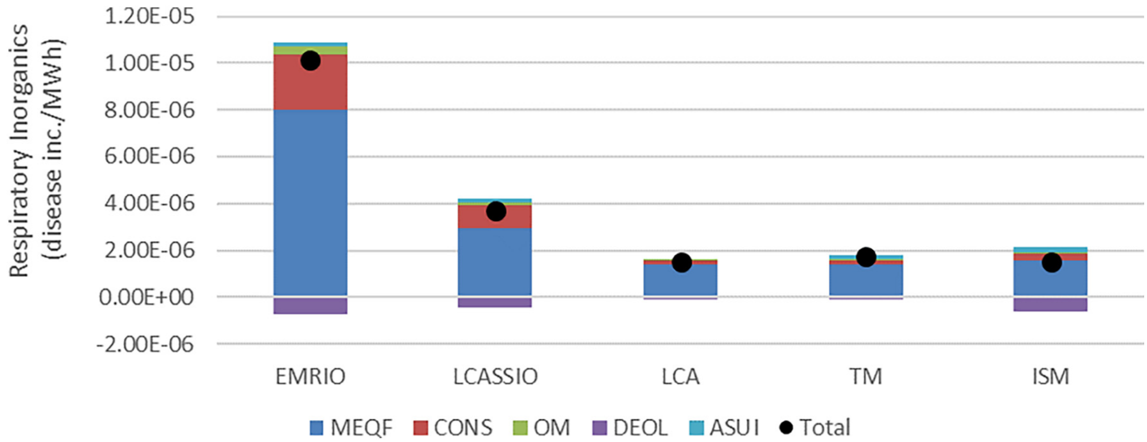


**Fig. 5.** Respiratory inorganics impact by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying five methods of quantification.

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 $m^3$/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 | EMRIO | 0.78 | 0.34 | 1.66 | −0.27 | 0.15 | 2.66 |
| ($m^3$/MWh) | 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 |
| Water depletion | EMRIO | 40.04 | 18.37 | 128.45 | −12.00 | 8.12 | 182.97 |
| ($m^3$ depriv. /MWh) | 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 $m^3$ 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

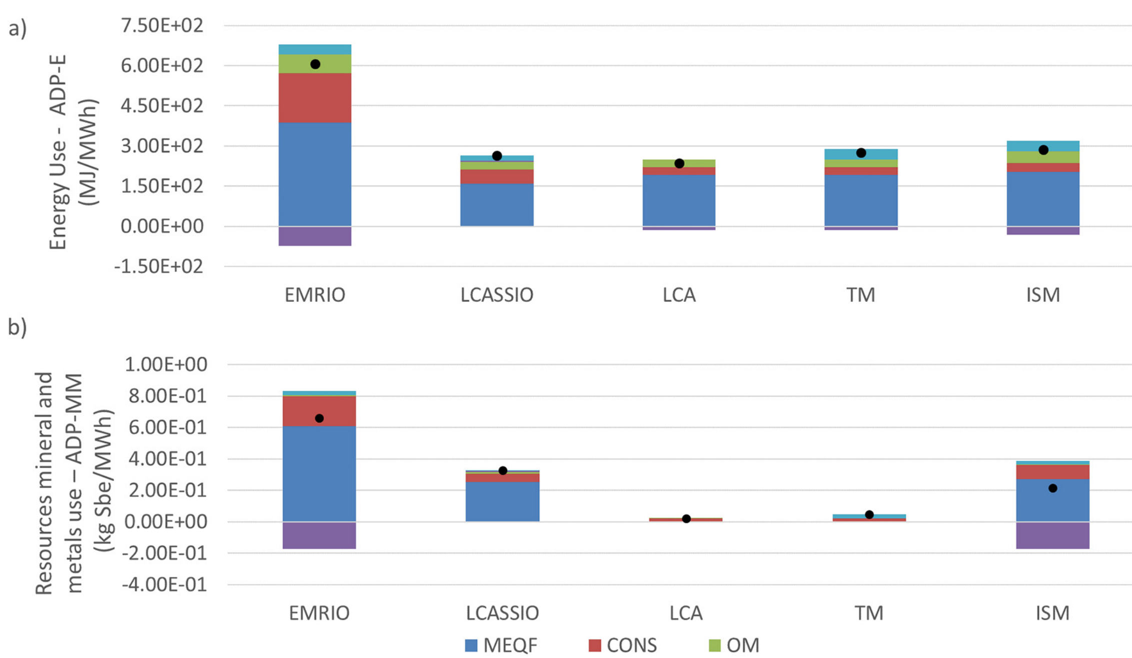


**Fig. 6.** Energy use (ADP-E) on the top (a) and mineral and metals use (ADP-MM) on the bottom (b) by stage of the Life Cycle of a 100 MW CSP tower power plant, by applying five methods of quantification.

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

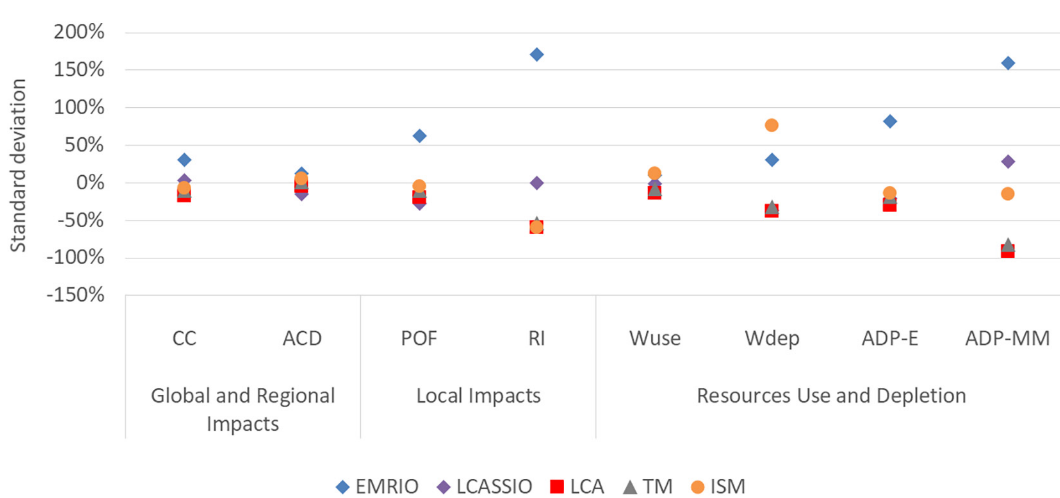


**Fig. 7.** Dispersion of the results obtained by each of the approaches in the assessment of the different environmental impact categories.

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 $CO_2e$/kWh for CSP in the present study, and carbon footprint of renewables in the LCA literature is 8 to 83 g $CO_2e$/kWh for photovoltaics (PV), hydropower from 6 to 147 g $CO_2e$/kWh, and wind 7 and 23 g $CO_2e$/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 socieconomic 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 tired 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 $CO_2e$/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 REmaining (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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