Renewable and Sustainable Energy Reviews

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

--Manuscript Draft--

Manuscript Number:	RSER-D-22-01280R1
Article Type:	Original Research Article
Section/Category:	Solar Thermal
Keywords:	multiregional input-output analysis; Sustainability; concentrated solar thermal; cooperation projects; European Energy transition
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	Pablo del Río, PhD
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 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.
Suggested Reviewers:	Cristina de la Rua, PhD Researcher/Professor, Technische Universität München: Technische Universitat Munchen cristina.de-la-rua@tum.de PhD researcher, experienced in the assessment of renewable and sustainable energy systems
	Jorge Zafrilla, PhD Reseracher/Professor, Universidad de Castilla-La Mancha jorge.zafrilla@uclm.es PhD researcher and experience in research about economics of the renewable energies policy impact and sustainability assessments
	María Teresa García-Alvarez, PhD University of A Coruna: Universidade da Coruna mtgarcia@udc.es PhD researcher on Economics, experienced in the field of sustainability asssessment

	and indicators development
	Guadalupe Arce, PhD Researcher, University of Castilla-La Mancha Guadalupe.Arce@uclm.es She is wide-experienced in the application of EMRIO model for the tripple-bottom line approach and assessing sustainability of investments.

Response to Reviewers:

We thank the reviewers and the Editor for the comments and suggestions.

Responses fro the Reviewer #2
The paper is well written in a good structure. The subject is new and worth investigation. I have only two questions for the authors:
- The authors use data from 2011 and explain that this is a limitation of the study. I consider the assumption valid, however, EXIOBASE provides more recent data. Is there a specific reason to choose 2011?

Response:
Thanks for the comment. As the reviewer points out, there are later versions of the MRIOT EXIOBASE that include more recent years in their data series. However, the original EXIOBASE v3.4 data series ends in 2011. We used the 2011 data version for two main reasons. On the one hand, our data collection and research began in early 2018, prior to the release of the following versions mentioned above. On the other hand, although new developments have been made, the authors of these EXIOBASE versions advise caution in the use of these data. For example, the released version v3.8 offers data series until the year 2022 (including forecast data based on IMF), but the end years of the actual data points used are: 2015 for energy, 2019 for all GHG (non-fuel, non-CO2, now dropped from 2018), 2013 for material, 2011 for most others, land, water (1). Therefore, we believe that it was more consistent to keep the calculations and results using the original version of the database (data related to 2011).

Anyway, we have provided here a brief sensitivity analysis associated to the aforementioned decision of using the 2011 data. We compare the 2011 impact coefficients (GHG emissions, employment, value added) in key industries and countries (EXIOBASE v3.4, ixi) with those provided in the satellite accounts for the most recent year (EXIOBASE v3.8, ixi, year 2018), with the aim to assess if resulting figures would be different and if the results could be significantly distorted considering that advances in technology and efficiency have happened in the last decade. We have carried out a comparison exercise of the coefficients of the main indicators evaluated in our work: Employment rate, value added, GHG emissions and water consumption. The table shows the rates of change of the ten impact coefficients in the main industries and countries.

RegionSectorEmployment - change rateValue added - change rateGHG - change rateWATER - change rate
ESPManufacture of machinery and equipment n.e.c.-17.9%9.4%-52.5%-27.1%
ESPOther business activities-21.4%0.2%-2.6%-99.9%
ESPOther service activities-4.8%-0.1%14.9%-18.3%
/DEUManufacture of fabricated metal products, except machinery and equipment-9.0%-19.4%-30.0%-18.1%
ESPTerciary Sector, nec-11.7%-0.3%-39.9%-19.0%
ROWTerciary Sector, nec14.2%8.6%-5.7%-24.7%
ESPManufacture of glass and glass products-43.2%-2.9%-45.9%4.1%
ESPProduction of electricity by coal-39.5%-32.2%-13.6%-4.3%
WWLMining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.-100.0%-4.5%15.8%1.8%
ROWPrimary Sector, excluding mining and extraction activities-17.9%7.9%5.6%-22.0%
CHNPrimary Sector, excluding mining and extraction activities101.3%6.8%-34.6%-0.6%
Average of change ratio-25.1%-3.3%-15.4%-22.7%

(a better view of the data can be seen in the table of the MSWord document attached "Responses to Reviewers_VF" and in the SI Part E)

In general, employment rates are slightly reduced in Europe, moderately decreased in Spain, greatly decreased in Latin America, and greatly increased in China. Value added coefficients are decreased in general although there are some slight increases in Primary and Tertiary sectors in the ROW region and China. Environmental accounts are generally reduced in Europe, but with some increases in some sectors (the “Other services GHG” coefficient increases by 14% and the “Water consumption” coefficient increases by 4%). Slight increases are also observed in Latin America and the ROW region. In China, environmental coefficients are reduced, specially in terms of GHG emissions.

Although results can be affected by the observed changes, our conclusions reached using the 2011 IOT (and its satellite accounts) are, in general, robust.
Regarding value-added creation, our figures could be slightly overestimated and the differences among the scenarios are expected to be reduced as the VA factors are reduced in Europe and increased in China. However, the change is expected to be low.
As for employment, even with the changes in Europe, many jobs would be created in the key European sectors involved in scenarios S1 and S2, but much more of the estimated employment could leak to China in S3 (with rates of change in their coefficients above 100%). The environmental ratios would show a shift in favour of the S1 and S2 scenarios, where the main sectors involved would have reduced carbon and water intensity by becoming less polluting and/or efficient.

Pag. 24 Line.1-3
“In this regard, we have provided a brief analysis of the change in coefficients according to the latter release of the satellite accounts of EXIOBASE in the SI (PartE)”.

- I would consider the indicator water stress, instead of water consumption, as the authors want to capture the risk of desertification.
Response: Thank you for the suggestion. We have expanded the table in order to include both indicators (water consumption and water stress, which has been calculated by applying the AWARE method).
Pag. 15. Line 14. Table 6.

(1) Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., … Tukker, A. (2019). EXIOBASE 3.
https://doi.org/10.5281/ZENODO.3583071

Responses Reviewer #3: The main objective is to assess the economic, social and environmental sustainability impacts of CSP deployment in Spain and address the supply risks implications associated with those investments. The paper is well designed, with a robust methodology along with some variations that give a touch of novelty to the methods used. Furthermore, the proposed scenarios are plausible and close to real-life situations within the CSP GVC. The main manuscript has some form problems in its current version that need to be corrected in order to be published in RSER. My recommendation is that this paper has the potential to be published in RSER after a minor revision to improve the clarity of the article.

HIGHLIGHTS

*The first bullet point does not specify that CSP deployment would be in Spain. Please, try "CSP deployment in Spain will create…"
Response:Thank you for the suggestion. We have revised the sentence to specify that CSP deployment would be in Spain.
Pag. 1 Line 36.
Text: “CSP deployment in Spain will have socioeconomic benefits, mostly retained in Europe”

*The second bullet point would need to end with something like "…compared to other

energy sources".
Response:Thank you for the suggestion. We have revised the sentence and rephrased it to make its meaning clearer.
Pag. Lines 37-38.
Text: "CSP electricity has low silver extraction and carbon and water footprints compared to other energy sources".

INTRODUCTION

*Page 5, lines 1-12: Consider taking a look (and citing) at the works of Hahn Menacho et al. (2022) and Dejuán et al. (2022), which are valuable and recent references on MRIO models assessing different dimensions of the impacts of RES deployment in the EU.

These are the aforementioned references:

A.J. Hahn Menacho, J.F.D. Rodrigues, P. Behrens. (2022). A triple bottom line assessment of concentrated solar power generation in China and Europe 2020-2050. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2022.112677.

Dejuán, Ó., Portella-Carbó, F., & Ortiz, M. (2022). Economic and environmental impacts of decarbonisation through a hybrid MRIO multiplier-accelerator model. Economic Systems Research, 34(1), 1-21. https://doi.org/10.1080/09535314.2020.1848808

Response:Thank you for the relevant literature proposed. We believe that the references that you proposed are highly pertinent for our research. The research conducted by Menacho et al (2022) addresses the quantification of the employment and carbon intensities of CSP deployment considering the current fleet of CSP plants, and also the scenarios of deployment in Europe and China, taking into account the learning curve and cost reductions of CSP deployment (calculated under the assumptions of the IEA and the Chinese government). Although the CSP case studies present particularities, and are not directly comparable (configurations, technologies, etc.), the values have been included to compare the results obtained in the present research.

Dejuán et al (2022) analyse the impacts of decarbonisation policies (more renewable energy for electricity generation, electric vehicles car in transport, and heating for household consumption) in three energy intensive sectors (power sector, transport sector and households). They propose a methodology to model the changes the structure of production in different scenarios based on MRIO modelling assessing the impact on four economic and environmental variables (value added, employment, energy consumption, and emissions).

Pag. 5 Lines 5-6.
Text in the Introduction: "Research on wider sustainability impacts of renewables and decarbonisation policies can be found in the literature [27-30]". The reference number 30 is Dejuán et al (2022).

Pag. 5 Line. 11-15.
Text in the Introduction related to the work of Menacho et al: "Also in this line, recent work [34] 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 using a MRIO-based triple-bottom line approach".

MATERIAL AND METHOD
*Shouldn't it be "MaterialS and MethodS"?
Response: Thank you for the suggestion. We have changed the title of the section accordingly.
Pag. 5. Line 39.

*Page 7, lines 1-6: I agree with the authors' choice of EXIOBASE as the MRIO database because of its high sectoral disaggregation, especially in electricity production from different energy sources. However, the 2011 data seem rather old and, presumably, the GVCs and carbon intensities of CSP installations have changed since then. In this respect, it is worth acknowledging authors' effort to adjust the employment coefficients using a hybrid method based on previous literature data.

Response: Thanks for the valuable comment. As the reviewer points out, there are later versions of the MRIOT EXIOBASE that include more recent years in their data series. However, the original EXIOBASE v3.4 data series ends in 2011. We used the 2011 data version for two main reasons. On the one hand, our data collection and research began in early 2018, prior to the release of the following versions mentioned above. On the other hand, although new developments have been made, the authors of these EXIOBASE versions advise caution in the use of these data. For example, the released version v3.8 offers data series until the year 2022, but the end years of the actual data points used are: 2015 for energy, 2019 for all GHG (non-fuel, non-CO2, now dropped from 2018), 2013 for material, 2011 for most others, land, water (1). Therefore, we felt it was consistent to use the 2011 version for the calculation. Accordingly, we argued that it was consistent to keep the calculations and results using the original version of the database (data related to 2011).

(reviewer's commnet, cont.)
I wonder if authors know the IOTs forecasted by the EXIOBASE team for the years 2012-2022 (https://zenodo.org/record/4588235). I am not suggesting that authors should use these IOTs to re-estimate their results, but perhaps they can draw from them the most up-to-date satellite accounts and check whether the 2011 impact coefficients (GHG emissions, employment, value added) in key industries and countries are too outdated and significantly distort the results (considering that in the last decade there have been major advances in RES efficiency).

Response: In this regard, we have provided here a brief sensitivity analysis associated to the aforementioned decision of using the 2011 data (The analysis has also been included in the SI). We compare the 2011 impact coefficients (GHG emissions, employment, value added) in key industries and countries (EXIOBASE v3.4, ixi) with those provided in the satellite accounts for the most recent year (EXIOBASE v3.8, ixi, year 2018), with the aim to assess if resulting figures would be different and if the results could be significantly distorted considering that advances in technology and efficiency have happened in the last decade. We have carried out a comparison exercise of the coefficients of the main indicators evaluated in our work: Employment rate, value added, GHG emissions and water consumption. The table shows the rates of change of the ten impact coefficients in the main industries and countries.
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Pag. 24 Lines 1-3
Text: "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)".

*Pages 6-10: As far as I know, EXIOBASE does not include an individual sector for CSP electricity production. In which EXIOBASE sector is CSP production included? In case it is included in electricity production by PV, what implications does this have on the calculations? Are the GVCs of PV-electricity very similar to the GVCs of CSP-electricity? What are the main differences you would highlight in the materials and countries supplying these two technologies?

Response: Thank you for the comment. In fact, Exiobase includes the product "Production of electricity by solar thermal" and the industry "Production of electricity by solar thermal"(you can see this in Stadler et al (2018) (2). However, instead of using this product or industry for our analysis, we build a demand vector for this technology using our cost data and the particular origin of the different components investigated in the three scenarios. This allowed us to assess the differences between collaborative approaches versus pure domestic approaches to reach the renewable targets as well as the impact of a higher Chinese participation in the solar thermal investments in Spain.

Regarding the comparison of the associated impacts of the GVCs of PV power production in Spain and those of CSP we refer the reviewer to the work of Banacloche et al. (2020) (3) that applied the same methodology presented in the present research to both technologies. Substantial differences were found. In summary, the comparison between the deployment hypothetically solar plants based on the main CSP technologies (which are CR and PT) and PV (plus battery storage) technologies showed that economic indicators (value added and employment) scores of the PV plus battery system are higher (since the investments are much higher) but only outside Europe as both socioeconomic impacts in Europe are reduced in the PV plus battery case in comparison with CSP. Environmental and social impacts are also much higher in PV than in CSP although, also in this case, outside Europe.

As for the material analysis, ongoing research is being developed by the authors of this paper.

*Pages 8. Table 2: Table 2 is difficult to read. Please consider separating the rows with lines to easily establish correspondence between the third and fourth columns.
Response: Thank you for the suggestion. Lines separating each cell have been added.

Pag. 9 Line 1. Table 2.

*Pages 8-9. Table 2 and Figure 1: I think the name of the first environmental indicator, "Climate Change", is imprecise; shouldn't it be called "GHG emissions"? Authors are aware that "climate change" is a very broad term that cannot be reduced to a single indicator measured in CO2eq, although GHG emissions are the main cause of climate change.
Please, change the name of this indicator in table 2, figure 1 and throughout the article.
Response: Thank you for the comment. We agree with you. We have replaced the name of the indicator by the more precise term “GHG emissions”.

Pages 11. L2: "we used our own data with reference costs to 2016". Do authors apply any deflation method to make the costs vector compatible with the prices of the 2011 MRIO tables?
Response: Thank you for the comment.
First we have identified an error, the correct reference year of the data costs is 2018. We used the data on cost from the MUSTEC consortium and the disaggregation by components from the SAM tool. Then, we used the Industrial producer price index provided by Eurostat for the period (2011-2018) to deflate the costs to 2011 prices. We have included the text below in order to clarify this point.

Pag. 11. Lines 4-5.
Text: “Then, the Industrial Producer Price Index provided by Eurostat for the period (2011-2018) were used and the costs were deflated to 2011 prices”

RESULTS

*Pages 11. Lines 48-49: "Findings per CSP technology indicated that CR technology creates more employment". Shouldn't it be "… creates more value added"?
Response: Thank you. We agree. We have made changes accordingly.
Pag. 11 Lines 38-39.

*Pages 12. Table 2: Table 2 is a bit chaotic. Too many rows, the subtotal (9th row) is not equal to the sum of the previous rows. Please, redesign the table to improve clarity and correspondences of subtotals and totals with the previous groups of rows.
Response: Thank you. We assume that you are referring to Table 3 instead of Table 2 (which does not include any number). We have included a bold font, separating lines between groups of rows of the table, and a different indent. Totals and subtotals are located in order to facilitate the interpretation focused on distinguishing European from non-European impacts, as well as distinguishing the impact of upstream value chain (upstream, manufacturing) from the overall impact. We hope that you find that the new design of table is clearer.

Pag. 11-12. (Table 3). In addition, the rest of tables of results (Tables 4-8) have been modified (formatted) in order to clarify the subtotals.

*Pages 14. Figure 3: Although the comparisons presented in Figure 3 are very interesting, I recommend removing this chart from the main manuscript and placing it in the SI, considering that these results are not obtained by the calculations presented in this article. It would also be useful to attach Annex I of reference 42 so that the label numbers in Figure 3 make sense and the reader can refer to the sources of these estimates.
Response: Thank you for the suggestion. We have made changes accordingly. We have taken the figure and the list of references to the SI Part D and we have referred to it in the main text.

Pag. 13. Lines 33-35.
“Figure 9 in the SI (PartD) shows some results of the employment created per installed capacity (MW) by different renewable energy technologies, including CSP, found in the literature.”

*Pages 14: How do authors estimate GHG emissions impacts in gCO2/kWh? According to the introduction and methods section, the main goal of the article is to estimate the direct and indirect impacts of the investment and O&M stages of a CSP

project. I expect the units of the results to be gCO2 or gCO2/kW; but didn't expect to see results in gCO2/kWh. Is this measure related to the electricity produced by the CSP plant per year? How do you arrive to kWh numbers in sections 3.2.1 and 3.2.2?
Response: Thank you for the comment.
First, we quantified the expected total electricity production (kWh) along the whole life (25 years) of the CSP power plants under study considering the technical specifications (yield, location, Direct Normal Irradiation, etc.) per type of technology (PT, CR). In the SI (Table 2. Technical parameters defining plants configurations obtained from SAM analysis), the annual net production and lifelong years are provided. Using this total electricity production, we have calculated the impacts per kWh generated, which is a very useful indicator to compare our results with others in the literature.

*Pages 17-20: I really liked the analysis on Risk supply (figures 4 and 5) and the summary of sustainability impacts (Tables 7 and 8). Well done. Although the impact estimation sections are interesting, I believe the main methodological and thematic novelty of this article lies in the analysis of GVC vulnerability and supply risk associated with CSP deployment. In case the article is rejected in this journal (or receives a major revision), I encourage authors to give more prominence to results related to vulnerability and supply risks. The vulnerability of GVCs and the challenge of RES to secure the supply of scarce minerals and materials are very striking issues today.
Response: We appreciate your positive and encouraging comment on the supply risk analysis presented in the research. Although this is an essential part of the sustainability analysis, we think that the extension dedicated to the impact in this paper is balanced with the rest of impacts being assessed. However, further research related to this aspect is the matter of an ongoing article and it is stated as a future line of research. We have added a sentence in this sense in the section 3.6 ("Main limitations and assumptions").

Pag. 24. Lines 7-9.
Text: "Further research on the supply risks associated to the GVC of the CSP and renewables deployment focused on material requirements and resource constraints should be addressed"

*Page 22. Table 9: Caption and labels in table 9 are quite ambiguous. For instance, the reader can't know what the fifth column "Impact" refers to. Please, use a more precise title for the table (cumulative impacts in 2050 for 39-100 GW of CSP) and provide more details in the labels.
Response: Thank you for the comment. We assume you refer the Table 11. Changes have been made following your advice. We have added some separating lines and reformulated titles in order to improve the clarity of the table.
Pag. 22. Line 1. Table 11.

(1) Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., … Tukker, A. (2019). EXIOBASE 3. https://doi.org/10.5281/ZENODO.3583071

(2) Stadler K, Wood R, Bulavskaya T, Södersten C-J, Simas M, Schmidt S, et al. EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. J Ind Ecol 2018;22:502–15. https://doi.org/10.1111/jiec.12715.

(3) Banacloche S, Gamarra AR, Tellez F, Lechon Y. Sustainability assessment of future CSP cooperation projects in Europe. Deliverable 9.1 MUSTEC project. Spain: 2020.

From: Ana R. Gamarra, MSc
Spanish Ministry of Science & Innovation
CIEMAT (Research Center on Energy, Environment & Technology)
Energy Dpt. - Energy Systems Analysis Unit

To: Editors - Renewable & Sustainable Energy Reviews Journal

Subject: Responses to Minor revision/Cover letter

Madrid, October 2nd 2022

Dear Editors,

After the corresponding review of the manuscript considering the Reviewers' comments (minor revision) we have resubmitted the full-length paper entitled *Assessing the sustainability impacts of concentrated solar power deployment in Europe in the context of global value chains*. We thank the editor and reviewers the pertinent and enriching comments and suggestions. We hope you find the responses and undertaken modifications appropriate.

Our research aims to identify the potential socioeconomic, social and environmental impacts associated with the future deployment of concentrated solar power (CSP) projects in Spain, taking into account the global CSP value chain. We propose and evaluate a set of plausible scenarios considering the two main CSP technologies, and three alternative origins of component supply. Our results help to enlarge the body of knowledge on the benefits of CSP deployment in Europe, as well as to address relevant questions for policy makers. Thus, our results suggest focusing energy policy strategies on strengthening the local and European CSP industry through cooperative mechanisms that ensure contribution to energy security, dispatchability and flexibility in the European electricity mix, while promoting employment and economic growth and thus a more sustainable energy system.

The research is an outcome of the project MUSTEC project resulting of the collaboration between a multidisciplinary team of authors dedicated to research in different areas of renewable energy. The project received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No.764626 (MUSTEC). Some of the results included in the paper have been addressed in the corresponding deliverable. In addition, this research takes part of the research conducted in the framework of my Doctoral Thesis development.

Authors of the research paper are: Ana R. Gamarra[a,b*]; Santacruz Banacloche[a]; Yolanda Lechon[a] and del Río, Pablo[c].

[a] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT). Energy Systems Analysis Unit. Avda. Complutense n. 40, 28040, Madrid (Spain).

[b] Universidad Politécnica de Madrid. C/José Gutiérrez Abascal, s/n. Madrid (Spain)

[c] Consejo Superior de Investigaciones Científicas (CSIC), Institute for Public Policies and Goods (IPP). C/Albasanz 26-28, 28037, Madrid (Spain)

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http://rdgroups.ciemat.es/web/ase
www.ciemat.es

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the paper. All of the authors have approved the paper submission to the journal and confirm it has not been published previously nor is it being considered by other peer-reviewed journal.

Hence, it is requested that the research paper including the revision carried out following the reviewer's suggestions may be finally considered for publication.

With warm regards,

Ana,

**Corresponding author contact and address: e- mail: anarosa.gamarra@ciemat.es. Tel. 0034.346.64.45. CIEMAT. E1. P0. D45. Av. Complutense, s/n 28040 Madrid, Spain.*
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Responses to the Reviewers and/or Editors' comments:

Reviewer #2: The paper is well written in a good structure. The subject is new and worth investigation. I have only two questions for the authors:
- The authors use data from 2011 and explain that this is a limitation of the study. I consider the assumption valid, however, EXIOBASE provides more recent data. Is there a specific reason to choose 2011?

Response:
Thanks for the comment. As the reviewer points out, there are later versions of the MRIOT EXIOBASE that include more recent years in their data series. However, the original EXIOBASE v3.4 data series ends in 2011. We used the 2011 data version for two main reasons. On the one hand, our data collection and research began in early 2018, prior to the release of the following versions mentioned above. On the other hand, although new developments have been made, the authors of these EXIOBASE versions advise caution in the use of these data. For example, the released version v3.8 offers data series until the year 2022 (including forecast data based on IMF), but the end years of the actual data points used are: 2015 for energy, 2019 for all GHG (non-fuel, non-CO2, now dropped from 2018), 2013 for material, 2011 for most others, land, water[1]. Therefore, we believe that it was more consistent to keep the calculations and results using the original version of the database (data related to 2011).

Anyway, we have provided here a brief sensitivity analysis associated to the aforementioned decision of using the 2011 data. We compare the 2011 impact coefficients (GHG emissions, employment, value added) in key industries and countries (EXIOBASE v3.4, ixi) with those provided in the satellite accounts for the most recent year (EXIOBASE v3.8, ixi, year 2018), with the aim to assess if resulting figures would be different and if the results could be significantly distorted considering that advances in technology and efficiency have happened in the last decade. We have carried out a comparison exercise of the coefficients of the main indicators evaluated in our work: Employment rate, value added, GHG emissions and water consumption. The table shows the rates of change of the ten impact coefficients in the main industries and countries.

Region	Sector	Employment - change rate	Value added - change rate	GHG - change rate	WATER - change rate
ESP	Manufacture of machinery and equipment n.e.c.	-17.9%	9.4%	-52.5%	-27.1%
ESP	Other business activities	-21.4%	0.2%	-2.6%	-99.9%
ESP	Other service activities	-4.8%	-0.1%	14.9%	-18.3%
/DEU	Manufacture of fabricated metal products, except machinery and equipment	-9.0%	-19.4%	-30.0%	-18.1%
ESP	Terciary Sector, nec	-11.7%	-0.3%	-39.9%	-19.0%
ROW	Terciary Sector, nec	14.2%	8.6%	-5.7%	-24.7%
ESP	Manufacture of glass and glass products	-43.2%	-2.9%	-45.9%	4.1%
ESP	Production of electricity by coal	-39.5%	-32.2%	-13.6%	-4.3%

[1] Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., … Tukker, A. (2019). EXIOBASE 3. https://doi.org/10.5281/ZENODO.3583071

WWL	Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.	-100.0%	-4.5%	15.8%	1.8%
ROW	Primary Sector, excluding mining and extraction activities	-17.9%	7.9%	5.6%	-22.0%
CHN	Primary Sector, excluding mining and extraction activities	101.3%	6.8%	-34.6%	-0.6%
	Average of change ratio	-25.1%	-3.3%	-15.4%	-22.7%

In general, employment rates are slightly reduced in Europe, moderately decreased in Spain, greatly decreased in Latin America, and greatly increased in China. Value added coefficients are decreased in general although there are some slight increases in Primary and Tertiary sectors in the ROW region and China. Environmental accounts are generally reduced in Europe, but with some increases in some sectors (the "Other services GHG" coefficient increases by 14% and the "Water consumption" coefficient increases by 4%). Slight increases are also observed in Latin America and the ROW region. In China, environmental coefficients are reduced, specially in terms of GHG emissions.

Although results can be affected by the observed changes, our conclusions reached using the 2011 IOT (and its satellite accounts) are, in general, robust.
Regarding value-added creation, our figures could be slightly overestimated and the differences among the scenarios are expected to be reduced as the VA factors are reduced in Europe and increased in China. However, the change is expected to be low.
As for employment, even with the changes in Europe, many jobs would be created in the key European sectors involved in scenarios S1 and S2, but much more of the estimated employment could leak to China in S3 (with rates of change in their coefficients above 100%). The environmental ratios would show a shift in favour of the S1 and S2 scenarios, where the main sectors involved would have reduced carbon and water intensity by becoming less polluting and/or efficient.

Pag. 24 Line.1-3
"In this regard, we have provided a brief analysis of the change in coefficients according to the latter release of the satellite accounts of EXIOBASE in the SI (PART E)".

- I would consider the indicator water stress, instead of water consumption, as the authors want to capture the risk of desertification.

Thank you for the suggestion. We have expanded the table in order to include both indicators (water consumption and water stress, which has been calculated by applying the AWARE method).
Pag. 15. Line 14. Table 6.

Manuscript No.: RSER-D-22-01280
Title: Assessing the sustainability impacts of concentrated solar power deployment in Europe in the context of global value chains

Responses to the Reviewers and/or Editors' comments:

Reviewer #3: The main objective is to assess the economic, social and environmental sustainability impacts of CSP deployment in Spain and address the supply risks implications associated with those investments. The paper is well designed, with a robust methodology along with some variations that give a touch of novelty to the methods used. Furthermore, the proposed scenarios are plausible and close to real-life situations within the CSP GVC. The main manuscript has some form problems in its current version that need to be corrected in order to be published in RSER. My recommendation is that this paper has the potential to be published in RSER after a minor revision to improve the clarity of the article.

HIGHLIGHTS

* The first bullet point does not specify that CSP deployment would be in Spain. Please, try "CSP deployment in Spain will create..."
Thank you for the suggestion. We have revised the sentence to specify that CSP deployment would be in Spain.
Pag. 1 Line 36.
Text: “*CSP deployment in Spain will have socioeconomic benefits, mostly retained in Europe”*

* The second bullet point would need to end with something like "...compared to other energy sources".
Thank you for the suggestion. We have revised the sentence and rephrased it to make its meaning clearer.

Pag. Lines 37-38.
Text: “CSP electricity has low silver extraction and carbon and water footprints compared to other energy sources”.

INTRODUCTION

* Page 5, lines 1-12: Consider taking a look (and citing) at the works of Hahn Menacho et al. (2022) and Dejuán et al. (2022), which are valuable and recent references on MRIO models assessing different dimensions of the impacts of RES deployment in the EU.

These are the aforementioned references:

A.J. Hahn Menacho, J.F.D. Rodrigues, P. Behrens. (2022). A triple bottom line assessment of concentrated solar power generation in China and Europe 2020-2050. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2022.112677.

Dejuán, Ó., Portella-Carbó, F., & Ortiz, M. (2022). Economic and environmental impacts of decarbonisation through a hybrid MRIO multiplier-accelerator model. Economic Systems Research, 34(1), 1-21. https://doi.org/10.1080/09535314.2020.1848808

Thank you for the relevant literature proposed. We believe that the references that you proposed are highly pertinent for our research. The research conducted by Menacho et al (2022) addresses the quantification of the employment and carbon intensities of CSP deployment considering the current fleet of CSP plants, and also the scenarios of deployment in Europe and China, taking into account the learning curve and cost reductions of CSP deployment (calculated under the assumptions of the IEA and the Chinese government). Although the CSP case studies present particularities, and are not directly comparable (configurations, technologies, etc.), the values have been included to compare the results obtained in the present research.

Dejuán et al (2022) analyse the impacts of decarbonisation policies (more renewable energy for electricity generation, electric vehicles car in transport, and heating for household consumption) in three energy intensive sectors (power sector, transport sector and households). They propose a methodology to model the changes the structure of production in different scenarios based on MRIO modelling assessing the impact on four economic and environmental variables (value added, employment, energy consumption, and emissions).

Pag. 5 Lines 5-6.
Text in the Introduction: *"Research on wider sustainability impacts of renewables and decarbonisation policies can be found in the literature [27-30]". The reference number 30 is* Dejuán et al (2022).

Pag. 5 Line. 11-15.
Text in the Introduction related to the work of Menacho et al: "Also i*n this line, recent work [34] 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 using a MRIO-based triple-bottom line approach".*

MATERIAL AND METHOD
* Shouldn't it be "MaterialS and MethodS"?
Thank you for the suggestion. We have changed the title of the section accordingly.
Pag. 5. Line 39.

* Page 7, lines 1-6: I agree with the authors' choice of EXIOBASE as the MRIO database because of its high sectoral disaggregation, especially in electricity production from different energy sources. However, the 2011 data seem rather old and, presumably, the GVCs and carbon intensities of CSP installations have changed since then. In this respect, it is worth acknowledging authors' effort to adjust the employment coefficients using a hybrid method based on previous literature data.

Thanks for the valuable comment. As the reviewer points out, there are later versions of the MRIOT EXIOBASE that include more recent years in their data series. However, the original EXIOBASE v3.4 data series ends in 2011. We used the 2011 data version for two main reasons. On the one hand, our data collection and research began in early 2018, prior to the release of the following versions mentioned above. On the other hand, although new developments have been made, the authors of these EXIOBASE versions advise caution in the use of these data. For example, the released version v3.8 offers data series until the year 2022, but the end years of the actual data points used are: 2015 for energy, 2019 for all GHG (non-fuel, non-CO2, now dropped from 2018), 2013 for material, 2011 for most others, land, water[2]. Therefore, we felt it

[2] Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., Tukker, A. (2019). EXIOBASE 3. https://doi.org/10.5281/ZENODO.3583071

was consistent to use the 2011 version for the calculation. Accordingly, we argued that it was consistent to keep the calculations and results using the original version of the database (data related to 2011).

(reviewer's commnet, cont.)
I wonder if authors know the IOTs forecasted by the EXIOBASE team for the years 2012-2022 (https://zenodo.org/record/4588235). I am not suggesting that authors should use these IOTs to re-estimate their results, but perhaps they can draw from them the most up-to-date satellite accounts and check whether the 2011 impact coefficients (GHG emissions, employment, value added) in key industries and countries are too outdated and significantly distort the results (considering that in the last decade there have been major advances in RES efficiency).

In this regard, we have provided here a brief sensitivity analysis associated to the aforementioned decision of using the 2011 data (The analysis has also been included in the SI). We compare the 2011 impact coefficients (GHG emissions, employment, value added) in key industries and countries (EXIOBASE v3.4, ixi) with those provided in the satellite accounts for the most recent year (EXIOBASE v3.8, ixi, year 2018), with the aim to assess if resulting figures would be different and if the results could be significantly distorted considering that advances in technology and efficiency have happened in the last decade. We have carried out a comparison exercise of the coefficients of the main indicators evaluated in our work: Employment rate, value added, GHG emissions and water consumption. The table shows the rates of change of the ten impact coefficients in the main industries and countries.

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In general, employment rates are slightly reduced in Europe, moderately decreased in Spain, greatly decreased in Latin America, and greatly increased in China. Value added coefficients are decreased in general although there are some slight increases in Primary and Tertiary sectors in the ROW region and China. Environmental accounts are generally reduced in Europe, but with some increases in some sectors (the "Other services GHG" coefficient increases by 14% and the "Water consumption" coefficient increases by 4%). Slight increases are also observed in Latin America and the ROW region. In China, environmental coefficients are reduced, specially in terms of GHG emissions.

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Pag. 24 Lines 1-3
Text: "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)".

* Pages 6-10: As far as I know, EXIOBASE does not include an individual sector for CSP electricity production. In which EXIOBASE sector is CSP production included?
In case it is included in electricity production by PV, what implications does this have on the calculations? Are the GVCs of PV-electricity very similar to the GVCs of CSP-electricity? What are the main differences you would highlight in the materials and countries supplying these two technologies?

Thank you for the comment. In fact, Exiobase includes the product "Production of electricity by solar thermal" and the industry "Production of electricity by solar thermal"(you can see this in Stadler et al (2018)[3]). However, instead of using this product or industry for our analysis, we build a demand vector for this technology using our cost data and the particular origin of the different components investigated in the three scenarios. This allowed us to assess the differences between collaborative approaches versus pure domestic approaches to reach the renewable targets as well as the impact of a higher Chinese participation in the solar thermal investments in Spain.

Regarding the comparison of the associated impacts of the GVCs of PV power production in Spain and those of CSP we refer the reviewer to the work of Banacloche et al. (2020)[4] that applied the same methodology presented in the present research to both technologies. Substantial differences were found. In summary, the comparison between the deployment hypothetically solar plants based on the main CSP technologies (which are CR and PT) and PV (plus battery storage) technologies showed that economic indicators (value added and employment) scores of the PV plus battery system are higher (since the investments are much higher) but only outside Europe as both socioeconomic impacts in Europe are reduced in the PV plus battery case in comparison with CSP. Environmental and social impacts are also much higher in PV than in CSP although, also in this case, outside Europe.

As for the material analysis, ongoing research is being developed by the authors of this paper.

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[3] Stadler K, Wood R, Bulavskaya T, Södersten C-J, Simas M, Schmidt S, et al. EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. J Ind Ecol 2018;22:502–15. https://doi.org/10.1111/jiec.12715.
[4] Banacloche S, Gamarra AR, Tellez F, Lechon Y. Sustainability assessment of future CSP cooperation projects in Europe. Deliverable 9.1 MUSTEC project. Spain: 2020.

* Pages 8. Table 2: Table 2 is difficult to read. Please consider separating the rows with lines to easily establish correspondence between the third and fourth columns.
Thank you for the suggestion. Lines separating each cell have been added.
Pag. 9 Line 1. Table 2.

* Pages 8-9. Table 2 and Figure 1: I think the name of the first environmental indicator, "Climate Change", is imprecise; shouldn't it be called "GHG emissions"? Authors are aware that "climate change" is a very broad term that cannot be reduced to a single indicator measured in CO2eq, although GHG emissions are the main cause of climate change.
Please, change the name of this indicator in table 2, figure 1 and throughout the article.
Thank you for the comment. We agree with you. We have replaced the name of the indicator by the more precise term “GHG emissions”.

Pages 11. L2: "we used our own data with reference costs to 2016". Do authors apply any deflation method to make the costs vector compatible with the prices of the 2011 MRIO tables?
Thank you for the comment.
First we have identified an error, the correct reference year of the data costs is 2018. We used the data on cost from the MUSTEC consortium and the disaggregation by components from the SAM tool. Then, we used the Industrial producer price index provided by Eurostat for the period (2011-2018) to deflate the costs to 2011 prices.
We have included the text below in order to clarify this point.

Pag. 11. Lines 4-5.
Text: “Then, the Industrial Producer Price Index provided by Eurostat for the period (2011-2018) were used and the costs were deflated to 2011 prices”

RESULTS

* Pages 11. Lines 48-49: "Findings per CSP technology indicated that CR technology creates more employment". Shouldn't it be "... creates more value added"?
Thank you. We agree. We have made changes accordingly.
Pag. 11 Lines 38-39.

* Pages 12. Table 2: Table 2 is a bit chaotic. Too many rows, the subtotal (9th row) is not equal to the sum of the previous rows. Please, redesign the table to improve clarity and correspondences of subtotals and totals with the previous groups of rows.
Thank you. We assume that you are referring to Table 3 instead of Table 2 (which does not include any number). We have included a bold font, separating lines between groups of rows of the table, and a different indent. Totals and subtotals are located in order to facilitate the interpretation focused on distinguishing European from non-European impacts, as well as distinguishing the impact of upstream value chain (upstream, manufacturing) from the overall impact. We hope that you find that the new design of table is clearer.

Pag. 11-12. (Table 3). In addition, the rest of tables of results (Tables 4-8) have been modified (formatted) in order to clarify the subtotals.

* Pages 14. Figure 3: Although the comparisons presented in Figure 3 are very interesting, I recommend removing this chart from the main manuscript and placing it in the SI, considering that these results are not obtained by the calculations presented in this article. It would also be useful to attach Annex I of reference 42 so that the label numbers in Figure 3 make sense and the reader can refer to the sources of these estimates.

Thank you for the suggestion. We have made changes accordingly. We have taken the figure and the list of references to the SI Part D and we have referred to it in the main text.

Pag. 13. Lines 33-35.

"Figure 9 in the SI (PartD) shows some results of the employment created per installed capacity (MW) by different renewable energy technologies, including CSP, found in the literature."

* Pages 14: How do authors estimate GHG emissions impacts in gCO2/kWh? According to the introduction and methods section, the main goal of the article is to estimate the direct and indirect impacts of the investment and O&M stages of a CSP project. I expect the units of the results to be gCO2 or gCO2/kW; but didn't expect to see results in gCO2/kWh. Is this measure related to the electricity produced by the CSP plant per year? How do you arrive to kWh numbers in sections 3.2.1 and 3.2.2?

Thank you for the comment.

First, we quantified the expected total electricity production (kWh) along the whole life (25 years) of the CSP power plants under study considering the technical specifications (yield, location, Direct Normal Irradiation, etc.) per type of technology (PT, CR). In the SI (Table 2. Technical parameters defining plants configurations obtained from SAM analysis), the annual net production and lifelong years are provided. Using this total electricity production, we have calculated the impacts per kWh generated, which is a very useful indicator to compare our results with others in the literature.

* Pages 17-20: I really liked the analysis on Risk supply (figures 4 and 5) and the summary of sustainability impacts (Tables 7 and 8). Well done. Although the impact estimation sections are interesting, I believe the main methodological and thematic novelty of this article lies in the analysis of GVC vulnerability and supply risk associated with CSP deployment. In case the article is rejected in this journal (or receives a major revision), I encourage authors to give more prominence to results related to vulnerability and supply risks. The vulnerability of GVCs and the challenge of RES to secure the supply of scarce minerals and materials are very striking issues today.

We appreciate your positive and encouraging comment on the supply risk analysis presented in the research. Although this is an essential part of the sustainability analysis, we think that the extension dedicated to the impact in this paper is balanced with the rest of impacts being assessed. However, further research related to this aspect is the matter of an ongoing article and it is stated as a future line of research. We have added a sentence in this sense in the section 3.6 ("Main limitations and assumptions").

Pag. 24. Lines 7-9.

Text: "Further research on the supply risks associated to the GVC of the CSP and renewables deployment focused on material requirements and resource constraints should be addressed"

* Page 22. Table 9: Caption and labels in table 9 are quite ambiguous. For instance, the reader can't know what the fifth column "Impact" refers to. Please, use a more precise title for the table (cumulative impacts in 2050 for 39-100 GW of CSP) and provide more details in the labels.

Thank you for the comment. We assume you refer the Table 11. Changes have been made following your advice. We have added some separating lines and reformulated titles in order to improve the clarity of the table.

Pag. 22. Line 1. Table 11.

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

Gamarra, A.R.[1,2*], *Banacloche, S.*[1]; *Lechon, Y.*[1]; *del Río, P.*[3]

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[2] Universidad Politécnica de Madrid. C/José Gutiérrez Abascal, s/n. Madrid (Spain)
[3] Consejo Superior de Investigaciones Científicas (CSIC), Institute for Public Policies and Goods (IPP). C/Albasanz 26-28, 28037, Madrid (Spain)

* corresponding author: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT). Energy Systems Analysis Unit. Avda. Complutense n. 40, 28040, Madrid (Spain); anarosa.gamarra@ciemat.es

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.

Keywords: multiregional input-output analysis; sustainability; concentrated solar thermal; cooperation projects; European energy transition.

Highlights

- CSP deployment in Spain will ~~create value added and employment~~have socioeconomic benefits, mostly retained in Europe
- CSP electricity has low silver extraction and carbon and water footprints compared to other energy sources~~CSP electricity has a low carbon and water footprints, and silver extraction~~
- Chinese penetration in the European CSP market worsens the sustainability of plants
- The best sustainability performance occurs in the European cooperative scenario
- There are tradeoffs between the sustainability impacts driven by the CSP investments

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Word Count: ~~9783~~ 9970 words excluding title, author names and affiliations, keywords, abbreviations list, table/figures captions, acknowledgements, supplementary information, data availability and references.

List of abbreviations, units and nomenclature

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_{WGIix} ~~**Dg wgix**~~	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 CO_2, employees, etc.),
$\hat{f}$	Impact vector (e.g. employees/EUR or kg of pollutants/EUR), and
FISA	Framework for Integrated Sustainability Assessment
FTE	Full-time equivalent
g CO_2 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 CO_2	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 Maintenanace
OECD	Organisation for Economic Cooperation and Development
PEF	Product environmental~~enviroenmntal~~ f~~F~~ootprint
PSNV	Political Stability and No violence
PT	Parabolic through
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_{xc}	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

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 c~~C~~limate c~~C~~hange aspiring to be a neutral continent by 2050, through investing in environmentally-friendly technologies and decarbonizing the energy sector [4]. The EU targets for~~towards~~ 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 constrains 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 ~~installations~~ 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 ~~fully~~. 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]~~[27–29].~~. 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 [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 ~~analyzed~~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~~of those~~ 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, ~~we~~ the research departs from the FISA framework [34], and enhance it to also consider supply risks along the value chain. Then, ~~we apply~~ 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, ~~we assess~~ 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].

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

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

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2.1. EMRIO model

The methodology followed in this work is based on input-output analysis (IOA) [40][2]. It is based on symmetrical tables called input-output tables (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:

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

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 CO_2 emitted by a specific sector and year per unit of output produced by such specific sector. ~~Equation 2 expresses the calculation of the method of~~ The extension is calculated as follows:

$$F = \hat{f} \cdot (I - A)^{-1} \cdot y_{CSP} \tag{2}$$

Where F represents the total sustainability impact (kg. of CO_2, 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~~considers~~ 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.

Table 1. Type of results that are obtained from the IOA, their formulation and meaning.

Impact	Formulation	Meaning

[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].

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

EXIOBASE3 [42] has been used as the MRIOT. Therefore, ~~we assume that~~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~~we work with aggregated sectors from 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 ~~we would~~ desireable. Nevertheless, indirect effects are not negligible at all and must be considered.

As a solution regarding the specific case of employment, a ~~we follow a~~ hybrid approach is followed by using the industry figures for direct employment (using data from the literature and from consultations with industry, firm COBRA[3]) recalculating the indirect employment using the ratio indirect/direct or employment multipliers ~~that we obtain~~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 ~~recently~~ published [33]. ~~We refer the reader to this paper f~~For the methodological details ~~s~~refer to this paper. In the present study, ~~we assess~~ the dependence and the level of governance along

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

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the supply chain are assessed considering the total demand as well as silver extraction, which will be~~is considered~~ 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 ~~we apply a~~ diversity metric known as Entropy (E) is used. The entropy metric has been used and studied as an indicator of diversity in several disciplines, ~~from physics to ecology, and more recently to~~including economics ~~in a publication by the European Central Bank~~ [45], environmental studies [46] and~~the and~~ other contributions in the scientific literature [47,48]~~, and environmental studies [48]. T~~. The entropy is calculated according to:

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

Where P_{xc} is the share of the contribution by~~of~~ 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, ~~we use~~ the six-composite Worldwide Governance Indicators [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).[4]

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 ~~we add 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.

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

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*.

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

[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.

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].

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	~~Climate change~~Greenhouses gases emissions (GHG emissions)	Gg CO_2 eq
		Water consumption	Mm^3 of blue and green water
		Silver extraction	Mg of silver
Social	SHDB	Sweatfree wage	Medium risk hours
		Child labour	Medium risk hours
Supply risks	WGI	Risk on supply of total goods and services	Non-dimensional
		Risk on supply of silver	Non-dimensional

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, ~~climate change~~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 de~~s~~carboni~~s~~zation 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 ~~on supply~~ 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).

Figure 1 synthesizes the adapted FISA application in this paper[5]. 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.

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[5] This has ~~been~~ previously been applied in the EU-funded MUSTEC project. https://www.mustec.eu/

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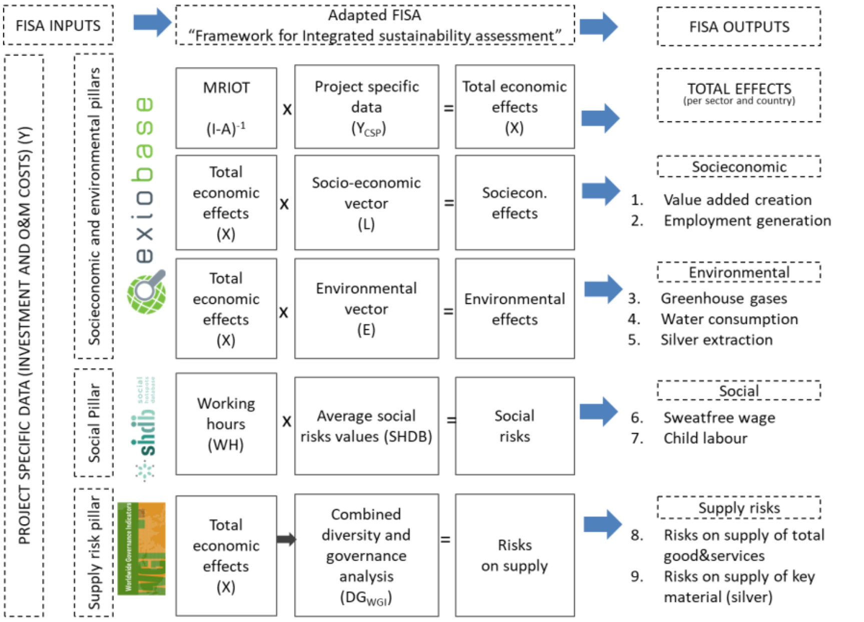

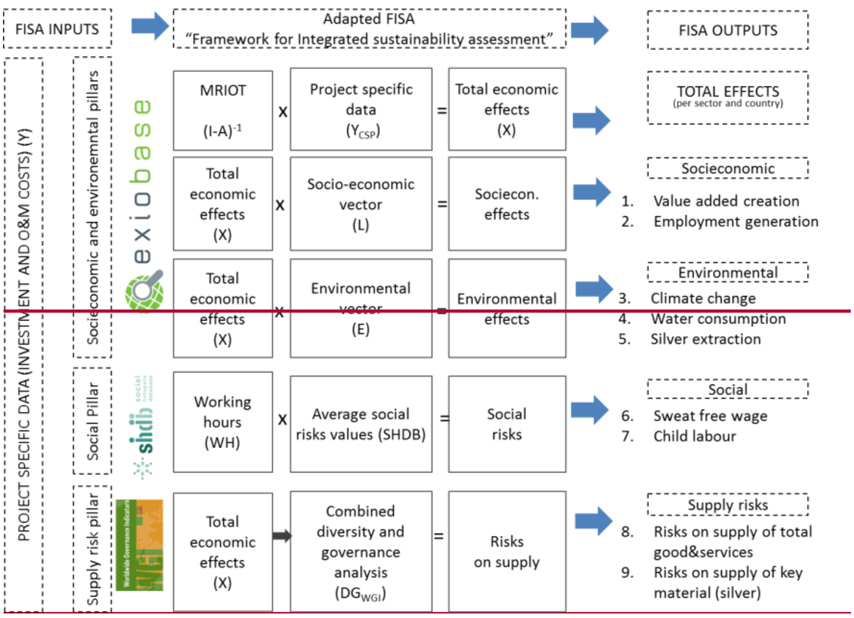

Figure 1. Adapted Framework for Integrated sustainability assessment (FISA).

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 ~~representability~~ of the results. A detailed explanation on data sources and methodological details on the treatment of data are~~is~~ provided in the SI-Part B. Anyway, some

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methodological aspects should be highlighted. First, for the specific case of the molten salts supplied by Chile, ~~as this country is not individually included in EXIOBASE3,~~ 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 employment using the employment multipliers obtained in the IOA. Third, two characterization methods have~~has~~ been used for the environmental impacts: the ~~climate change~~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.

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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 ~~conducting~~ 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 2,353 kWh/m^2/year.

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The costs have been obtained from the System Advisor Model (SAM) [59] developed by NREL. For the cost inputs, ~~we used our~~ own data with reference costs to 2018~~6~~ 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 [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 ~~cost~~ investment costs~~s~~ data is included in the SI, Part C. The ~~O&M~~ disaggregation of O&M costs regarding the CR technology come from [34]. In the case of PT, data were obtained from [61].

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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, ~~we assume that~~ 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 [63]

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and [34]. 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, ~~we directly provide~~ the results per sustainability dimension are provided~~and present them,~~ 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 1 shows the results of our calculations on the value added creation (direct and indirect) for the whole project. Findings per CSP technology indicate~~d~~ that CR technology creates more ~~employment~~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.

Table 1. 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*
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).

3.1.2. Employment creation

Similarly to the value added effects, the CR technology leads to better results regarding the employment effects in terms of employment (Table 2). 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~~is~~ highest in the case of CR plants and ~~is quantified in~~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~~n~~ 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 (Figure 2).

Table 2. 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*
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).

Labour costs on the operation and the installation of the CSP plant are provided by [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 1,733 (*PT*) and 1,933 (*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 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 2,044 (*PT*) and 2,698 (*CR*) FTE in *S1* and *S2* (10.2 and 13.5 versus 13 FTE/MW reported by the company COBRA), and 2,177 (*PT*) and 2,874 (*CR*) FTE under *S3* (10.9 and 14.4 FTE/MW, respectively).

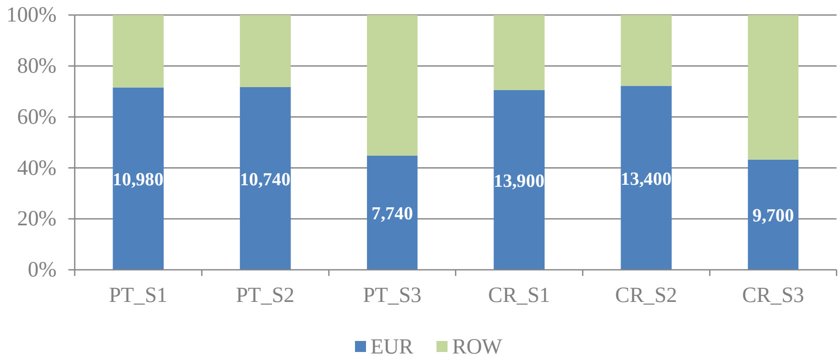

Figure 2. Share of European and non-European (ROW) employment creation in the different scenarios. Numbers indicate the employees engaged.

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 *manufacturing 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. Figure 9 in the SI (~~Figure 3~~Part D) shows some results from the literature on ~~of~~ employment creation per installed capacity (MW) for~~of~~ different renewable energy technologies, including CSP. ~~, per installed capacity (MW) found in the literature.~~ 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.

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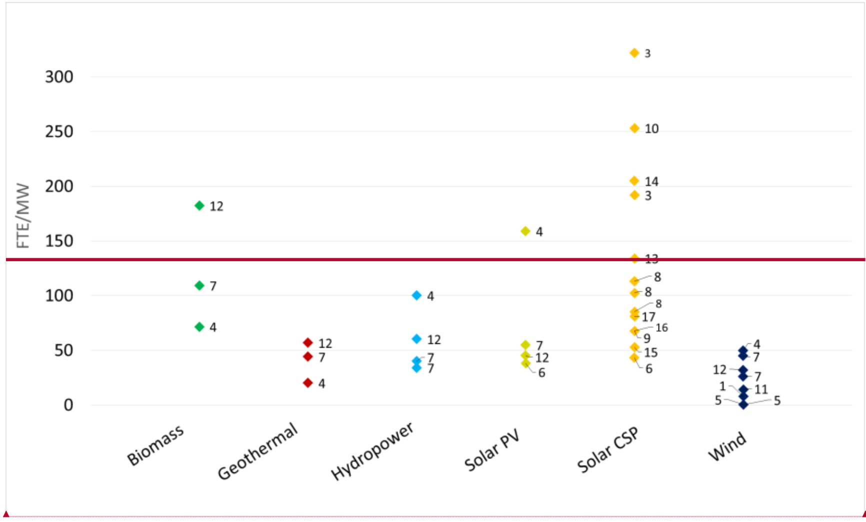

~~Figure 3. Comparison of employment values between different renewable energy technologies found in the literature from IOA studies and industry reports. Sources are listed in Appendix Table A1 from [43].~~

3.2. *Environmental impacts*

3.2.1. ~~*Climate change*~~*GHG emissions*

According to our calculations, total GHG emissions of CSP range from 15 to 28 g CO_2 eq/kWh, which are in line with the life cycle analysis literature (22 - 30 g CO_2 eq/kWh [65,66]). The input-output literature provides a broader range of results. Table 3 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.

Table 3. Total (~~,~~both direct and indirect)~~,~~ GHG emissions in Gg of CO_2 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
European	***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

[6] CSP ~~has~~shows lower ~~climate change~~ carbon emissions ~~impacts~~ than crystalline silicon PV (~~,~~with GHG emissions of around 45 g CO_2 eq/kWh [80]), higher emissions than those of wind energy (with GHG emissions of around 11 CO_2 eq/kWh [81]), and similar emissions than~~to~~ geothermal ~~is~~ (33.6 g CO_2 eq/kWh [66]). GHG emissions associated to CSP investments and operation are much lower than those of fossil technologies [82].

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*
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).

The deployment of this CSP power plant will increase European GHG emissions by around 162-238 Gg of CO_2eq 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 CO_2 decoupling from economic growth in Europe.

The sectors producing the largest GHG impacts are the *mining of 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 CO_2 emissions, is also a relevant contributor of CO_2 emissions especially in China but also in Spain and Germany. This source of emissions will be reduced as these countries move towards a decarbonised~~n~~ energy transition~~ committed to decarbonisation~~.

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.

Table 4. Total, both direct and indirect, water consumption in Mm^3, ~~(Investment and O&M Stages)~~and ~~. Last row shows the~~ results of the ~~total~~ water scarcity weighed in Mm^3 of water deprived.~~(AWARE method)~~

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
European	***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	***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*
Indirect	*17.0*	*15.9*	*28.6*	*19.4*	*15.2*	*29.7*

Direct plant	6.2	6.2	6.2	2.6	2.6	2.6
Total	**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
European	***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 plant	483	483	483	204	204	204
Total (Mm3 deprived water)	**1,390**	**1,306**	**1,731**	**1,254**	**961**	**1,565**
Total (l deprived water/kWh)~~Total water weighted (l/kWh)~~	**661,390**	**621,306**	**821,731**	**471,253**	**36961**	**591,565**

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

The w~~W~~ater 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~~is~~ responsible for the overall results on water impacts ~~results~~. 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.

3.2.3. *Silver extraction*

The values of ~~extraction of~~ silver extraction range between 4.7 (PT_S2) and 8.1 (CR_S3) Mg (Table 5) 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 ~~fabrication~~ 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.

Table 5. 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
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**
Direct	1.42	1.31	1.34	2.34	1.21	2.44
Indirect	3.64	3.37	3.58	5.70	3.85	5.69
~~Total~~	~~5.1~~	~~4.7~~	~~4.9~~	~~8.0~~	~~5.1~~	~~8.1~~
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).

3.3. Social impacts: sweatfree wage and child labour

Although direct investments are mostly made with European components and services, intermediate~~s~~ 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. 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.

Table 6. 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
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
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.[illegible]5
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
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).

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 ~~are the S1~~ 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 supply.

When applying the combined indicator of diversity and governance (DG_{WGIix}), it is possible to consider which are the key actors quantitatively (Figure 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.

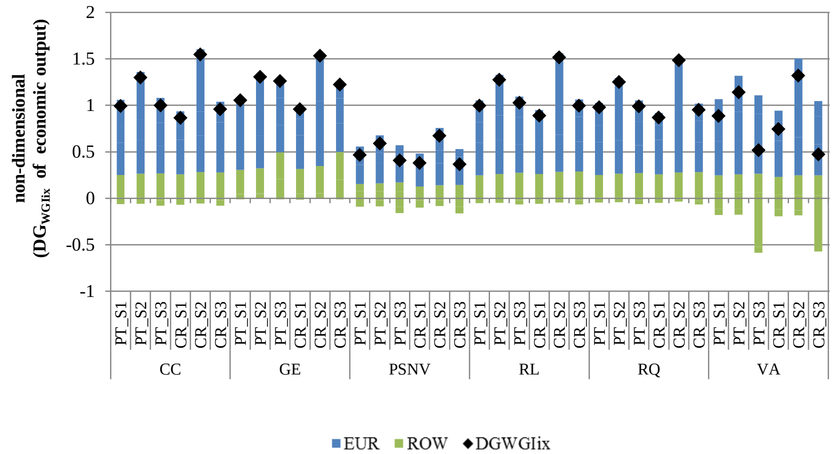

Figure 3. Combined diversity and governance indicator for the analysis of the total output per each governance indicator, disaggregated per ~~by~~ region (EUR and ROW), for the scenarios assessed.

The combined indicator of supply risk has also been applied to silver extraction along the value chain (Figure 4~~5~~). 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~~n~~ 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).

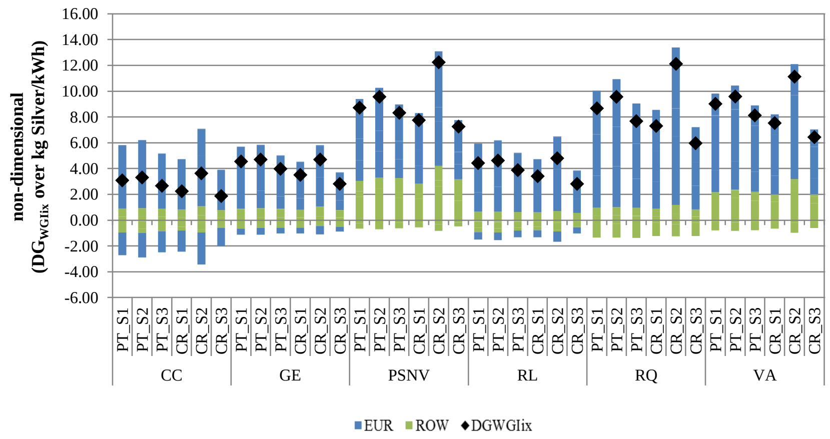

Figure 4~~5~~. Combined diversity and governance indicator of the silver extraction per unit of power produced for each governance criterion, disaggregated per~~by~~ region (EUR and ROW), for the scenarios assessed.

3.5. *Synthesis of sustainability impacts and key findings*

The following tables summarize the sustainability impacts for the two CSP technologies (Table 7) and for the different scenarios (Table 8). 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, ~~also~~ 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.

Table 7. Comparative sustainability impacts across technologies (parabolic trough and central receiver).

SUSTAINABILITY IMPACTS		PARABOLIC TROUGH*	CENTRAL RECEIVER
Economic	Value added	=	>

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	Employment	=	>
Environmental	GHG emissions	=	<
	Water consumption	=	<
	Silver extraction	=	>
Social	Sweatfree wage	=	=
	Child labour	=	<
Supply risk	Risk on supply of total goods and services	=	<=
	Risk on supply of silver	=	<=

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

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),~~ and~~ 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.

Table 8. Comparative sustainability impacts across scenarios (S1, S2, S3).

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

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

~~Cooperation~~ 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 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 CO_2 eq (4-7 g CO_2 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,

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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~~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~~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.

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 to 100 GW. Table 9 shows the relative importance of the impacts of the deployment of ~~this cumulative installed capacities~~these cumulative installed capacities ~~deployment~~. 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 ~~the~~ 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 CO_2 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~~of~~ 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.

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Table 9. Estimation of European impacts ~~estimation~~ in relative terms for the scenarios (scenarios with low and high values of each impact).

~~Impact~~Sustainability impact	Scenario		Total impact in Europe of 200MW	Impact per MW	Cumulative CSP deployment	Total impact for the cumulative CSP deployment	Annual impact	Overall European impact	Source	Relative impact
	~~Scenario~~		~~/MW~~							
GHG emissions			Gg $CO_{2eq.}$	Gg $CO_{2\,eq}$/MW ~~Gg~~	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	4,237	[74]	0.02%
	High	PT_S1	238	1.19	100,000	119	4			0.09%
Water consumption			Mm^3	Mm^3	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	Mg	Mg	Gg of silver ~~extraction~~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	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	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%

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 900-950 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 ~~a~~ 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 CO_2 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 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 ~~also at the~~ 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, ~~we identify~~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 la~~t~~ter 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, ~~we assess~~ 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~~200~~MW in the next renewable energy auction, which will be ~~being~~ conducted on October 25th~~April~~ 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, ~~we take into account~~ 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.

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4. Conclusions

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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, ~~in~~ 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~~200~~ 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~~Germany~~ firms manufacture the key components.

Our findings suggest focusing energy policy strategies on~~in~~ 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.

Acknowledgements

We thank the MUSTEC's consortium members for the contributions and insights as well as to Felix Téllez, researcher at the CIEMAT-PSA (http://www.psa.es/es/index.php), for the provided data on CSP power plant technical features and performance under the scenarios assessed.

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Funding information

The research is an outcome of the project MUSTEC project. The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 764626 (MUSTEC).

Supplementary Information

The Supplementary Information provided consists of three main sections: Part A. CR and PT technologies description and technical data of plants; Part B. Data sources; and Part C. Share of costs data. Part D. Employment values of the renewable energy technologies from the literature. and Part E. Analysis of the change in the coefficients in the satellite accounts.

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Data Availability

Related datasets can be found at https://zenodo.org/record/3964021#.YiZKg9XMJpg, an open-source online data repository hosted at ZENODO [60].

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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.

Keywords: multiregional input-output analysis; sustainability; concentrated solar thermal; cooperation projects; European energy transition.

Highlights

- CSP deployment in Spain will have socioeconomic benefits, mostly retained in Europe
- CSP electricity has low silver extraction and carbon and water footprints compared to other energy sources
- Chinese penetration in the European CSP market worsens the sustainability of plants
- The best sustainability performance occurs in the European cooperative scenario
- There are tradeoffs between the sustainability impacts driven by the CSP investments

Word Count: 9970 words excluding title, author names and affiliations, keywords, abbreviations list, table/figures captions, acknowledgements, supplementary information, data availability and references.

List of abbreviations, units and nomenclature

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
$\mathbf{DG_{WGIix}}$	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 CO_2, employees, etc.),
$\hat{f}$	Impact vector (e.g. employees/EUR or kg of pollutants/EUR), and
FISA	Framework for Integrated Sustainability Assessment
FTE	Full-time equivalent
g CO_2 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 CO_2	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 through
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
$\boldsymbol{P_{xc}}$	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
$\boldsymbol{WGI_{ic}}$	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
$\boldsymbol{x}$	total production
$\boldsymbol{y}$	and the demand
$\boldsymbol{y_{CSP}}$	Cost vector for each stage (investment or O&M)
$(\boldsymbol{I}-\boldsymbol{A})^{-1}$	Leontief inverse matrix

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 constrains 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 [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].

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][2]. It is based on symmetrical tables called input-output tables (IOTs), which consist of the inputs required to

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

[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

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 CO_2 emitted by a specific sector and year per unit of output produced by such specific sector. The extension is calculated as follows:

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

Where F represents the total sustainability impact (kg. of CO_2, 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.

Table 1. Type of results that are obtained from the IOA, their formulation and meaning.

Impact	Formulation	Meaning
Direct impact	$(\hat{f} \cdot y_{CSP})$	Final demand of goods and services due to the CSP power plant, distinguishing between domestic direct effects and non-domestic direct effects.
Indirect impact	$(F - \hat{f} \cdot y_{CSP})$	Intermediate outcomes that will occur in order to meet changes in the final demand (distinguishing between domestic and non-domestic indirect effects).

display the distribution in monetary values of the production of one sector over the rest of the sectors (outputs) [79].

Multiplier effect	$(\frac{F}{\hat{f} \cdot y_{CSP}})$:	Change in the total impact as a result of changes in the final demand for goods or services described.

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 COBRA[3]) 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:

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

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

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 Indicators [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).[4]

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 = 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].

Table 2. Socioeconomic, environmental social and supply risk indicators covered in the present research. FTE: full-time equivalent ([52])

Impact	Database	Indicator	Units

[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.

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
		Silver extraction	Mg of silver
Social	SHDB	Sweatfree wage	Medium risk hours
		Child labour	Medium risk hours
Supply risks	WGI	Risk on supply of total goods and services	Non-dimensional
		Risk on supply of silver	Non-dimensional

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).

Figure 1 synthesizes the adapted FISA application in this paper[5]. 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.

[5] This has previously been applied in the EU-funded MUSTEC project. https://www.mustec.eu/

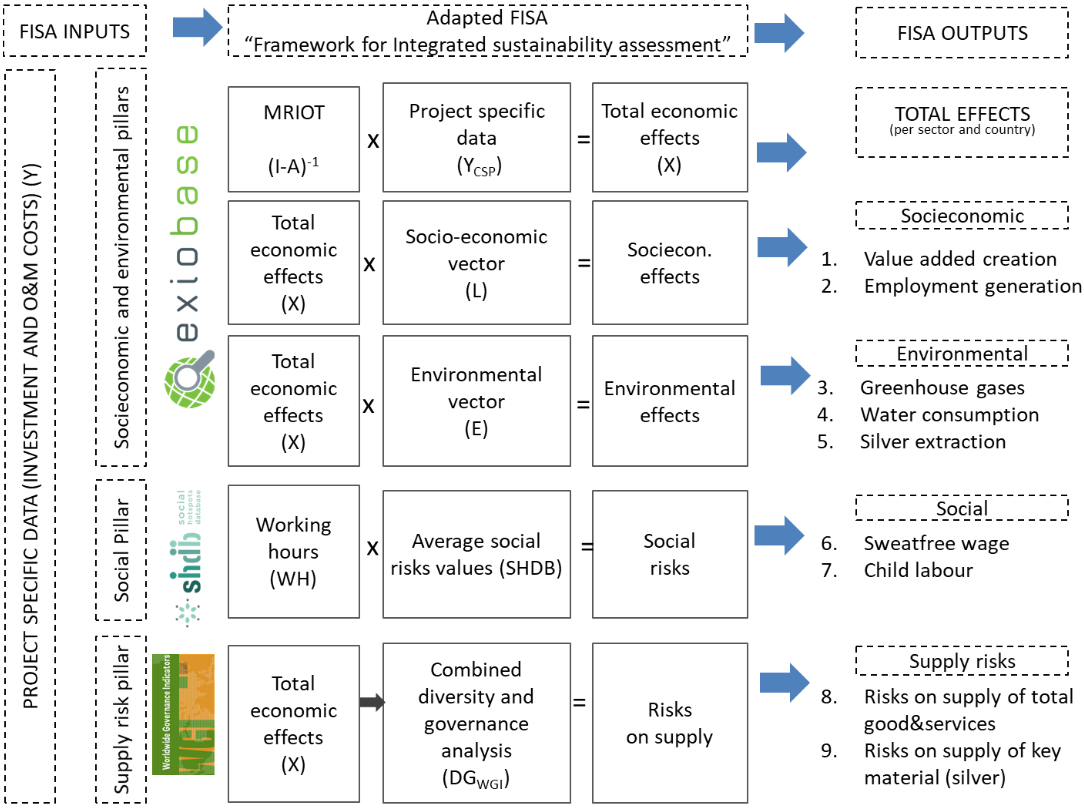

Figure 1. Adapted Framework for Integrated sustainability assessment (FISA).

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 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 2,353 kWh/m^2/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 [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 [34]. In the case of PT, data were obtained from [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 [63] and [34]. 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 1 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.

Table 1. 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*
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).

3.1.2. Employment creation

Similarly to the value added effects, the CR technology leads to better results regarding the employment effects in terms of employment (Table 2). 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 (Figure 2).

Table 2. 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*
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).

Labour costs on the operation and the installation of the CSP plant are provided by [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 1,733 (*PT*) and 1,933 (*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 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 2,044 (*PT*) and 2,698 (*CR*) FTE in *S1* and *S2* (10.2 and 13.5 versus 13 FTE/MW reported by the company COBRA), and 2,177 (*PT*) and 2,874 (*CR*) FTE under *S3* (10.9 and 14.4 FTE/MW, respectively).

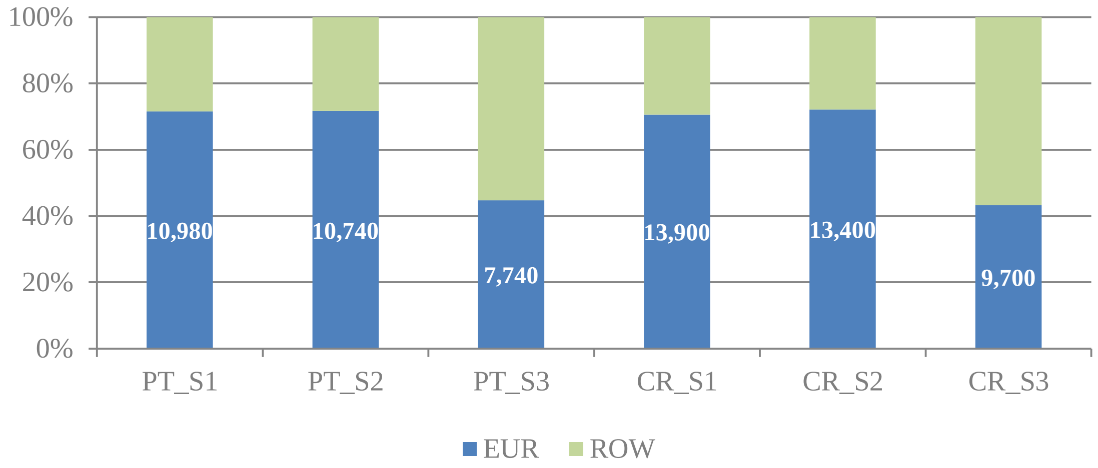

Figure 2. Share of European and non-European (ROW) employment creation in the different scenarios. Numbers indicate the employees engaged.

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 *manufacturing 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. Figure 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 CO_2 eq/kWh, which are in line with the life cycle analysis literature (22 - 30 g CO_2 eq/kWh [65,66]). The input-output literature provides a broader range of results. Table 3 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.

Table 3. Total (both direct and indirect) GHG emissions in Gg of CO_2 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
European	***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*
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).

The deployment of this CSP power plant will increase European GHG emissions by around 162-238 Gg of CO_2eq 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 CO_2 decoupling from economic growth in Europe.

The sectors producing the largest GHG impacts are the *mining of 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 CO_2 emissions, is also a relevant contributor of CO_2 emissions

[6] CSP has lower carbon emissions than crystalline silicon PV (with GHG emissions of around 45 g CO_2 eq/kWh [80]), higher emissions than those of wind energy (with GHG emissions of around 11 CO_2 eq/kWh [81]), and similar emissions than geothermal (33.6 g CO_2 eq/kWh [66]). GHG emissions associated to CSP investments and operation are much lower than those of fossil technologies [82].

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.

Table 4. Total, both direct and indirect, water consumption in Mm^3, and results of the water scarcity weighed in Mm^3 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
European	***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***
Direct	*0.7*	*0.7*	*0.9*	*0.1*	*0.1*	*0.6*
Indirect	*17.0*	*15.9*	*28.6*	*19.4*	*15.2*	*29.7*
Direct plant	**6.2**	**6.2**	**6.2**	**2.6**	**2.6**	**2.6**
Total	**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
European	***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 plant	483	483	483	204	204	204
Total (Mm3 deprived water)	**1,390**	**1,306**	**1,731**	**1,254**	**961**	**1,565**
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).

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.

3.2.3. Silver extraction

The values of silver extraction range between 4.7 (PT_S2) and 8.1 (CR_S3) Mg (Table 5) 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.

Table 5. 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
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**
Direct	1.42	1.31	1.34	2.34	1.21	2.44
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).

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. 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.

Table 6. 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
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 of which	***56.06***	***52.86***	***66.74***	***65.30***	***52.60***	***68.73***
Direct	0.74	0.73	3.70	0.97	0.88	1.19
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 of which	***123.18***	***118.03***	***271.49***	***143.31***	***118.92***	***271.50***
Direct	0.50	0.50	42.35	0.20	0.20	34.27
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).

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 supply.

When applying the combined indicator of diversity and governance (DG_{WGIix}), it is possible to consider which are the key actors quantitatively (Figure 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.

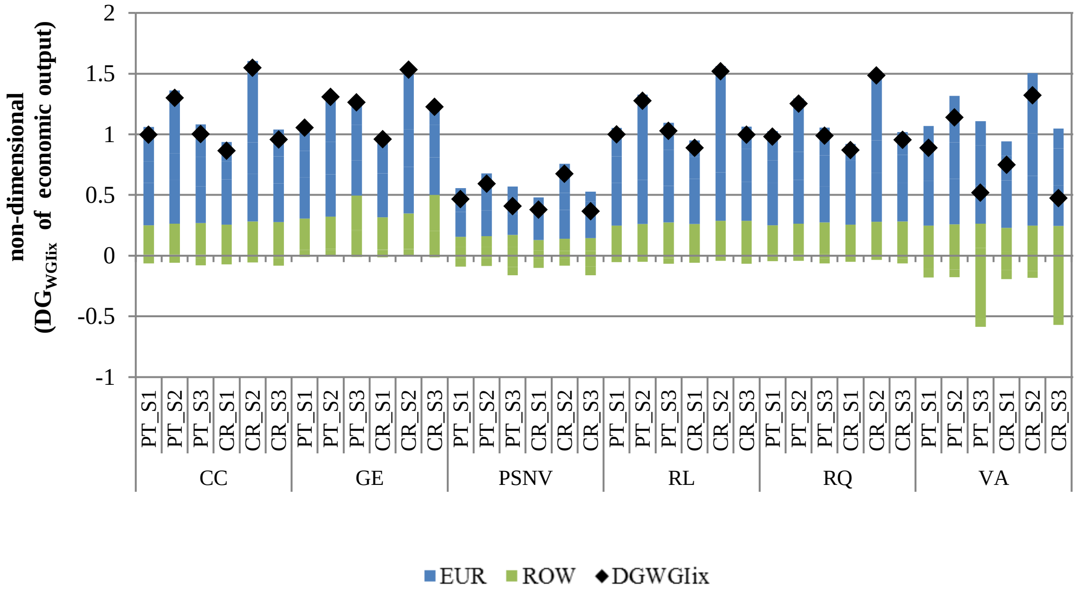

Figure 3. Combined diversity and governance indicator for the analysis of the total output per each governance indicator, disaggregated per region (EUR and ROW), for the scenarios assessed.

The combined indicator of supply risk has also been applied to silver extraction along the value chain (Figure 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).

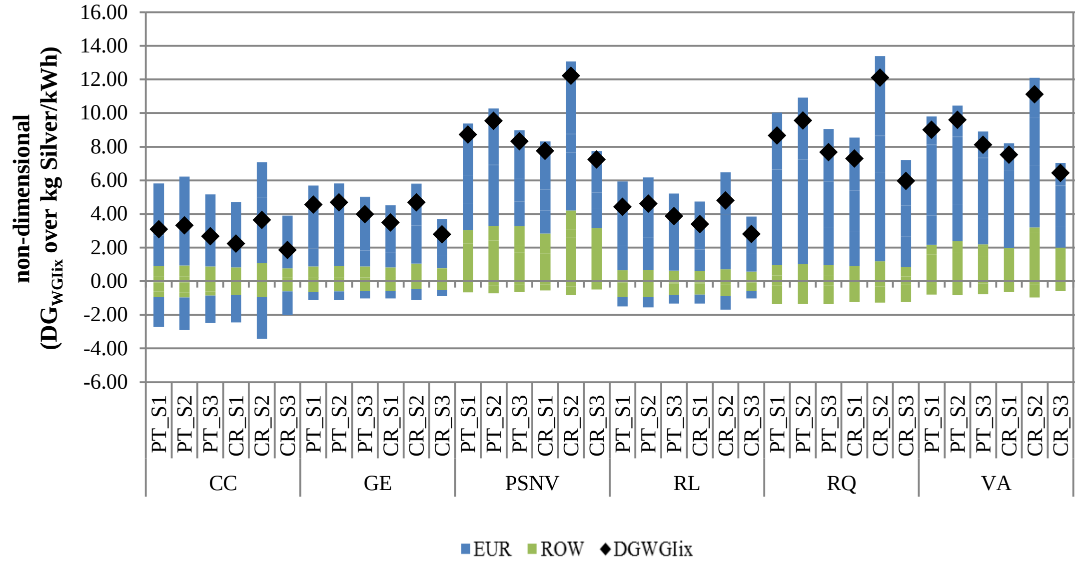

Figure 4. Combined diversity and governance indicator of the silver extraction per unit of power produced for each governance criterion, disaggregated per region (EUR and ROW), for the scenarios assessed.

3.5. Synthesis of sustainability impacts and key findings

The following tables summarize the sustainability impacts for the two CSP technologies (Table 7) and for the different scenarios (Table 8). 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.

Table 7. Comparative sustainability impacts across technologies (parabolic trough and central receiver).

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

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

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.

Table 8. Comparative sustainability impacts across scenarios (S1, S2, S3).

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

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

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 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 CO_2 eq (4-7 g CO_2 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.

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 to 100 GW. Table *9* 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 CO_2 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.

Table 9. 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 200MW	Impact 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	4,237	[74]	0.02%
	High	PT_S1	238	1.19	100,000	119	4			0.09%
Water consumption			Mm^3	Mm^3	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	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	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	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%

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 900-950 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 CO_2 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 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 220MW 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.

Acknowledgements

We thank the MUSTEC's consortium members for the contributions and insights as well as to Felix Téllez, researcher at the CIEMAT-PSA (http://www.psa.es/es/index.php), for the provided data on CSP power plant technical features and performance under the scenarios assessed.

Funding information

The research is an outcome of the project MUSTEC project. The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 764626 (MUSTEC).

Supplementary Information

The Supplementary Information provided consists of three main sections: Part A. CR and PT technologies description and technical data of plants; Part B. Data sources; and Part C. Share of costs data. Part D. Employment values of the renewable energy technologies from the literature. and Part E. Analysis of the change in the coefficients in the satellite accounts.

Data Availability

Related datasets can be found at https://zenodo.org/record/3964021#.YiZKg9XMJpg, an open-source online data repository hosted at ZENODO [60].

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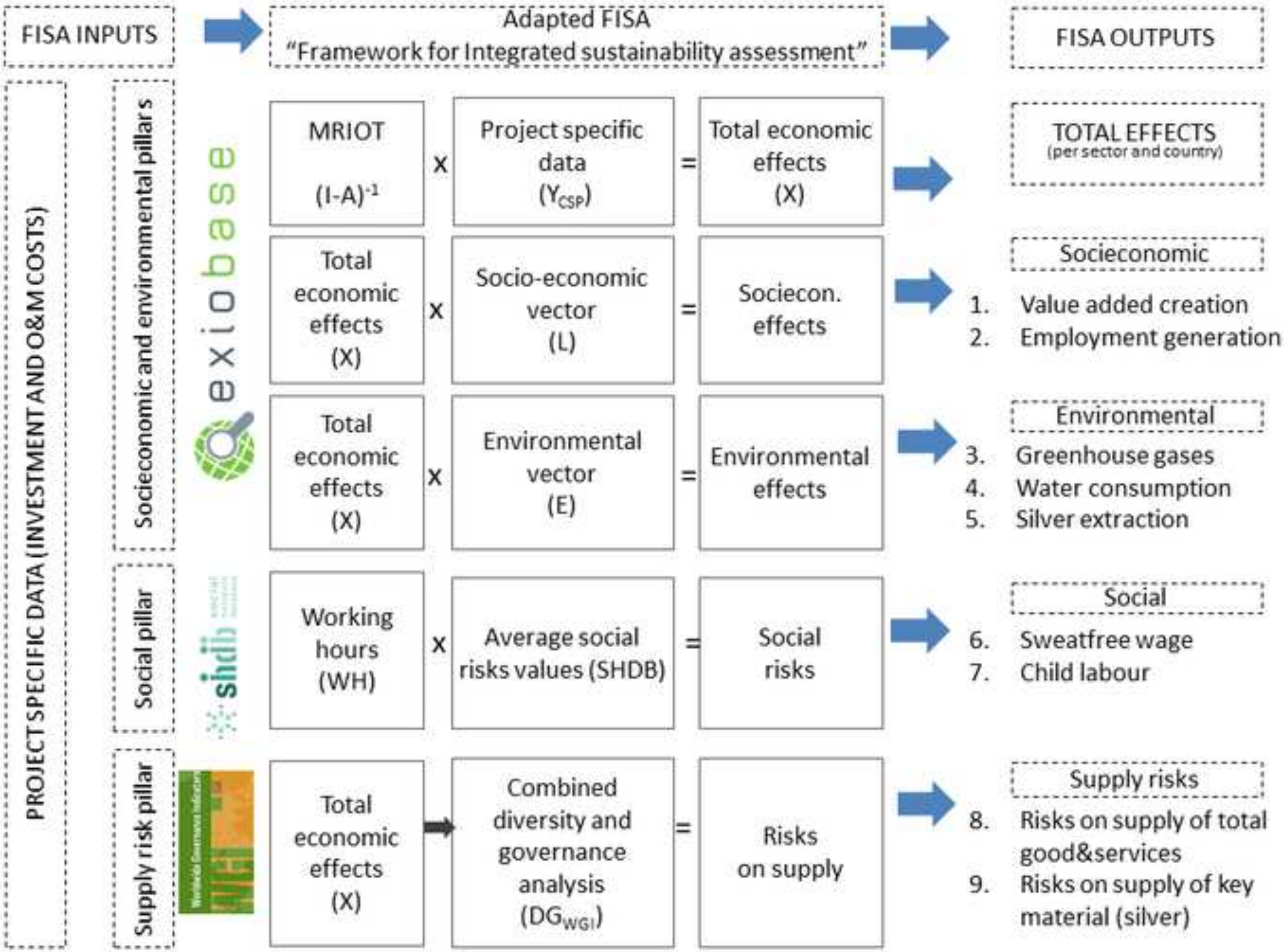
Figure 1 vf



FISA INPUTS
Adapted FISA
"Framework for Integrated sustainability assessment"
FISA OUTPUTS
PROJECT SPECIFIC DATA (INVESTMENT AND O&M COSTS)
Socioeconomic and environmental pillars
exiobase
MRIOT
(I-A)-1
x
Project specific data
(YCSP)
=
Total economic effects
(X)
TOTAL EFFECTS
(per sector and country)
Total economic effects
(X)
x
Socio-economic vector
(L)
=
Sociecon. effects
Socieconomic
1. Value added creation
2. Employment generation
Total economic effects
(X)
x
Environmental vector
(E)
=
Environmental effects
Environmental
3. Greenhouse gases
4. Water consumption
5. Silver extraction
Social pillar
shdb
Working hours
(WH)
x
Average social risks values (SHDB)
=
Social risks
Social
6. Sweatfree wage
7. Child labour
Supply risk pillar
Total economic effects
(X)
Combined diversity and governance analysis
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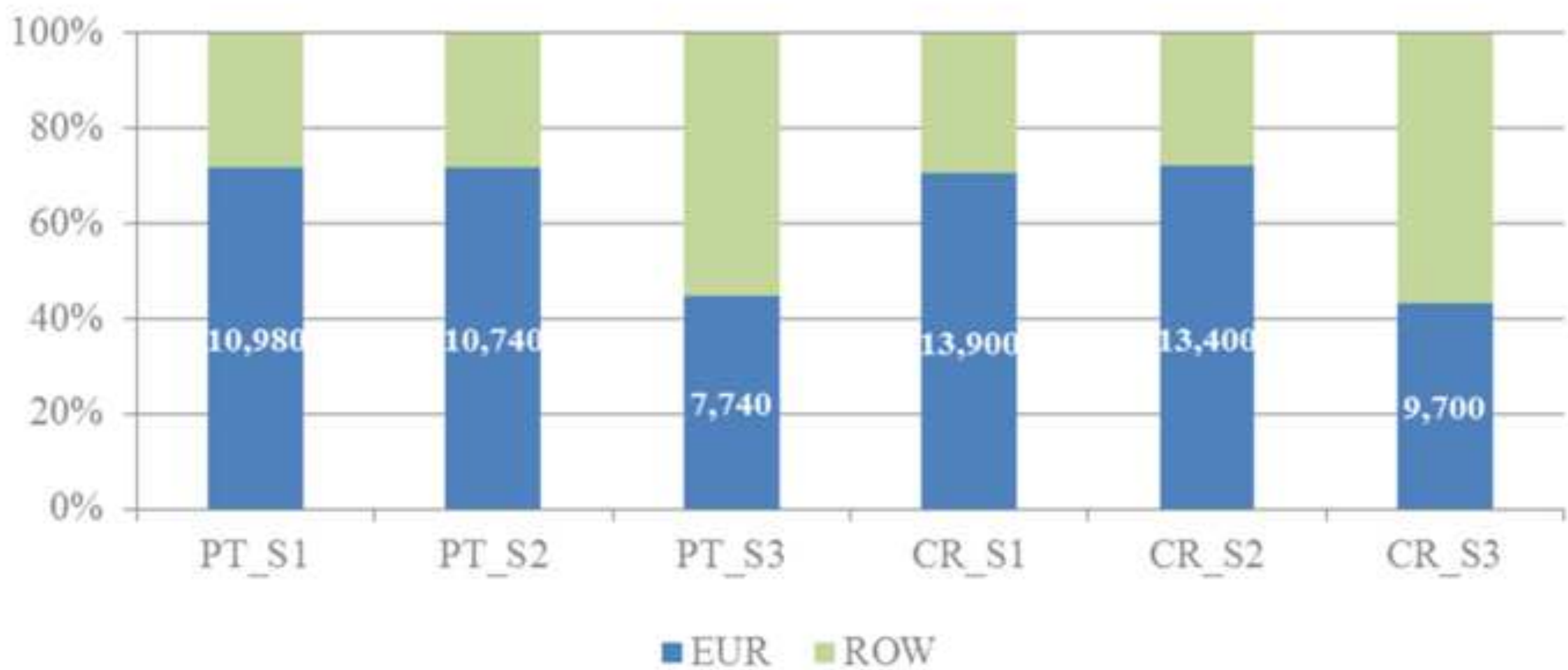
Risks on supply
Supply risks
8. Risks on supply of total good&services
9. Risks on supply of key material (silver)

Figure 2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CR_S2
CR_S3
EUR
ROW

Figure 3

Click here to access/download;Figure;figure3.TIF

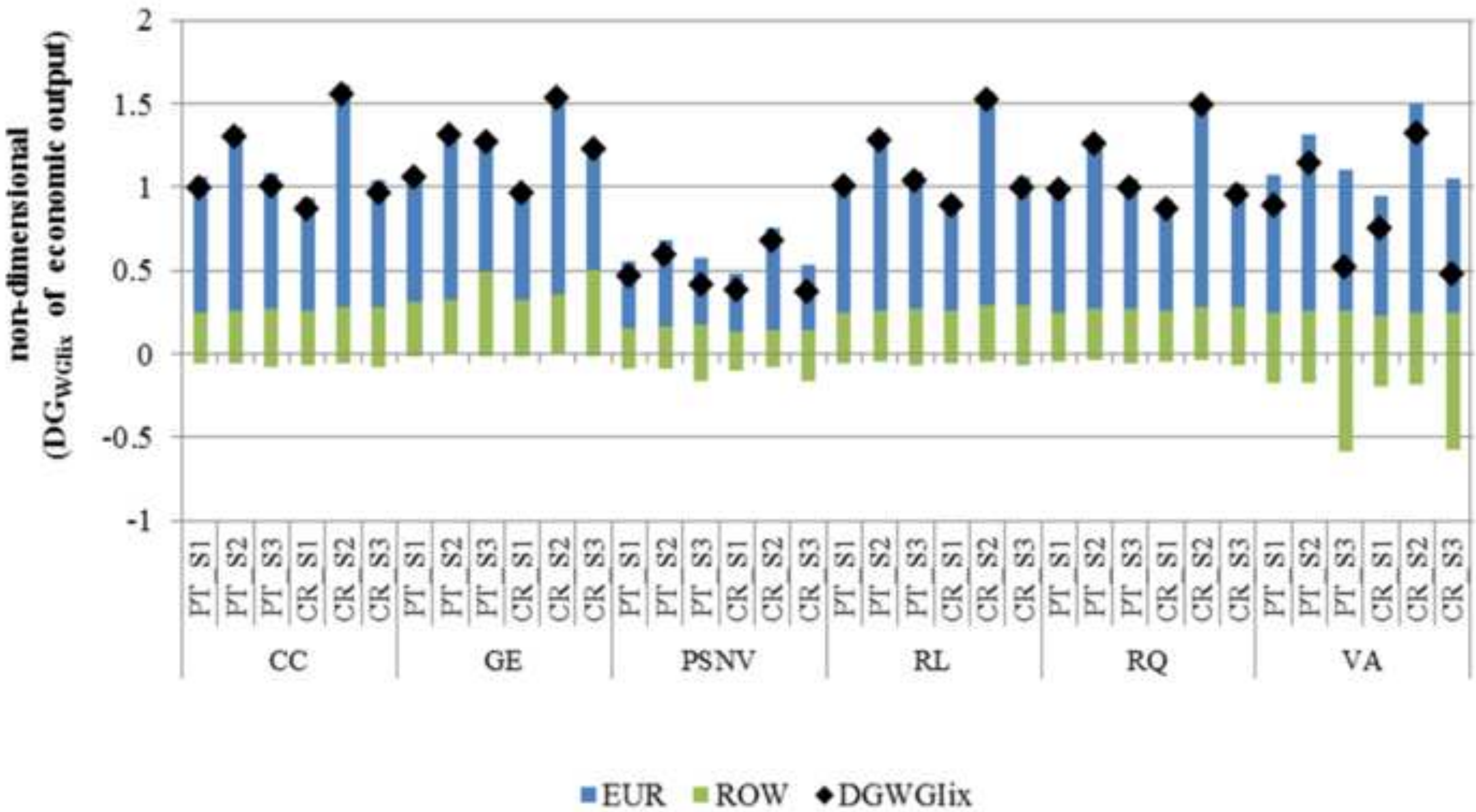

Figure 4

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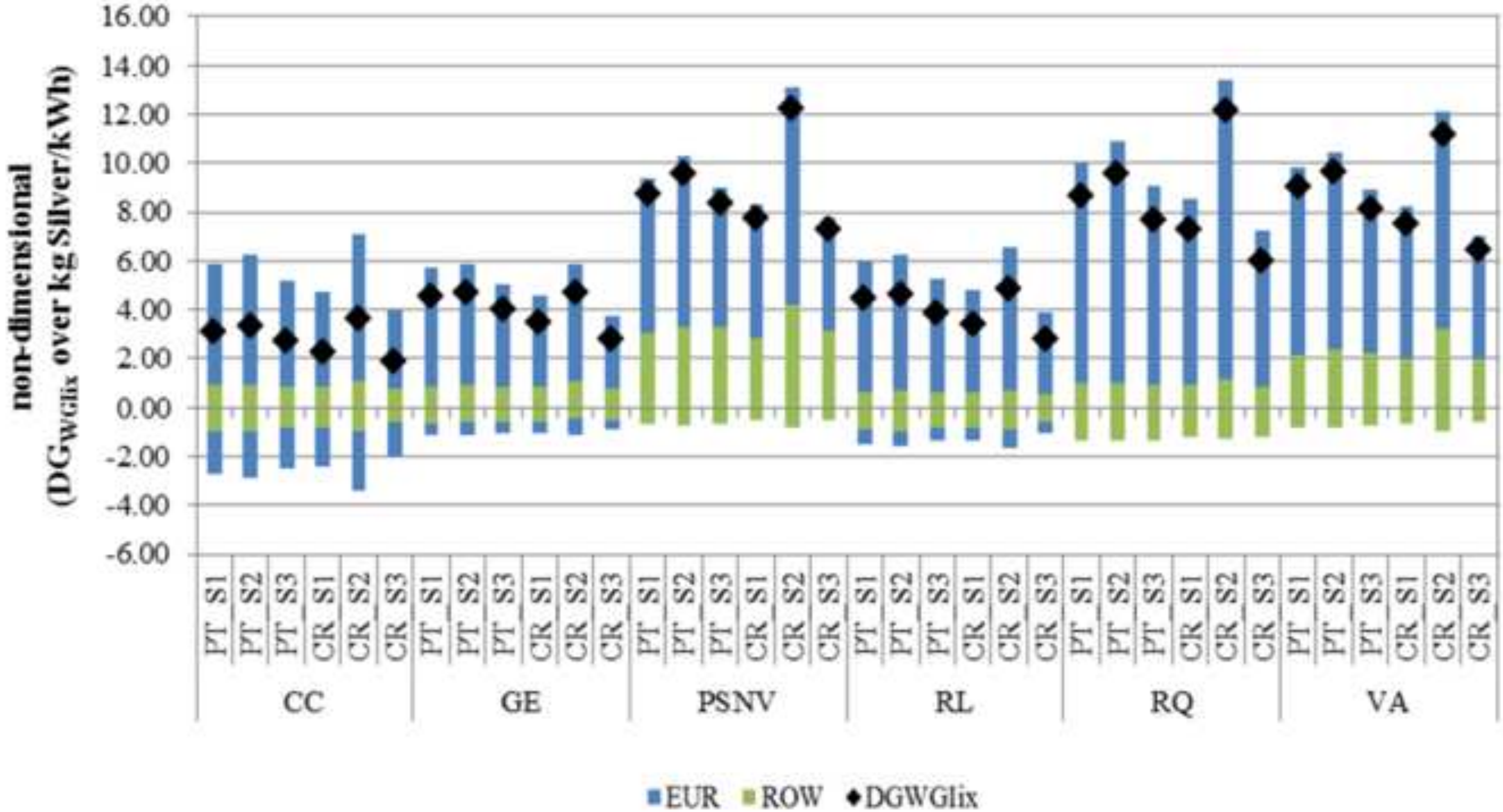

Highlights

- CSP deployment in Spain will have socioeconomic benefits, mostly retained in Europe
- CSP electricity has low silver extraction and carbon and water footprints compared to other energy sources
- Chinese penetration in the European CSP market worsens the sustainability of plants
- The best sustainability performance occurs in the European cooperative scenario
- There are tradeoffs between the sustainability impacts driven by the CSP investments

RSER Checklist table

Item	**Check**	**Notes**
Article type	Full-length article (9783 words)	words excluding title, author names and affiliations, keywords, abbreviations list, table/figures captions, acknowledgements, supplementary information, data availability and references
Manuscript	The manuscript is a single MS Word file	
Cover letter	The one page Cover letter has been dated and addressed to the Editors. The letter includes: • Title paper, key findings and why novel and meets the journal scope, • Article type • Details relating to elements of the work already published • The details of funding agencies etc. • Provide a declaration of interest, • List any recommended reviewers, • The corresponding author must sign the Cover letter as the person held responsible for all aspects of the paper during and after the publication process	
Layout of paper	The elements/headings listed below appears in the paper (in order): • Title • Author details • Abstract • Highlights • Keywords • Word Count • List of abbreviations including units and nomenclature • 1.0 Introduction • 2.0 Material and methods • 3.0 Results and discussion • 4.0 Conclusion • Acknowledgements • Supporting information • List of References	Before the references sections we have include the supporting information (SI) description.
English, grammar and syntax	Yes, English grammar and syntax have been checked.	
Title	Yes, the title has been checked and adhered to GFA. The title does not include acronyms or abbreviations.	

Item	Check	Notes
Author names and affiliations	Yes, author's names and affiliations checked and adhered to GFA.	
Corresponding author	The corresponding author has been denoted in the article by an asterix superscript (*) beside their name and a footnote.	
Highlights	These have been inserted as requested in the article and uploaded as a separate file	
Graphical abstract	A graphical abstract is not provided	
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Referencing style	Yes, referencing style has been checked and adhered to RSER preferred style. All references mentioned in the Reference List are cited in the text, and vice versa.	The reference styling and template has been managed with using Mendeley.
Single column	Yes, checked. The article has been submitted in a one column format	
Logos/emblems, etc.	There is no logos in the paper	
Embed graphs, tables and figures/other images in the main body of the article	Yes, images checked, all images appear embedded in the main body of the article	
Figures/Graphs/other images	Yes, images captions checked	
Tables	Yes, tables captions checked	
Line numbering	Yes, checked and adhered to GFA files without line numbers	
Acknowledgements	Yes, we read guidance on Acknowledgements in GFA and included according to them.	
Ethics in Publishing	Yes, all the authors checked carefully by all the authors named on the paper	
Ethical Statement		

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☒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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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.