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A triple bottom line assessment of concentrated solar power generation in China and Europe 2020–2050

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ABSTRACT

Concentrated solar power (CSP) can be a flexible renewable resource on electric grids. Here we assess the direct and upstream socio-economic and environmental impacts of the projected deployment of CSP in China and Europe, using Input-Output Analysis. We first quantify the CSP experience curve, finding a learning rate of ~16%, and combine this with future projections for installed capacity from China's National Development and Reform Commission and the International Energy Agency. We find employment intensities of 4.2 and 2.3 person-year/GWh in China and Europe, respectively (higher than PV and wind). The carbon emission intensity of CSP is currently higher than alternatives but this gap may narrow through learning. Carbon intensities are estimated at 129.7 and 99.8 gCO2eq/kWh in 2020 (in China and Europe, respectively) and could drop to 40.4 and 31.1 gCO2eq/kWh by 2050 given the projected expansion. We discuss the importance of including both environmental and socio-economic dimensions when assessing the impact of energy technologies and provide context for the role of CSP in the energy transition.

1. Introduction

The transition to carbon free energy systems across the world is vital for the long-term stability of the planet's climate. There is increasing evidence that this would improve energy security and employment rates. While most energy system models identify wind and solar photovoltaics as comprising the largest component of energy systems there are other technologies that hold potential in certain market situations and specific regions. One such technology is concentrated solar power (CSP) which is based on collecting heat from the sun and running a heat engine. CSP can be integrated with thermal storage (by use of a medium to transfer heat) to provide dispatchable power services. Under some circumstances and locations this may improve the economic potential of CSP [1], enabling it to meet firm and peak demand over shorter time windows [2].

CSP capacity has increased by almost 750% in the last decade and is dominated by parabolic trough and solar tower technologies (both forms of CSP) [3]. Some estimates suggest CSP could comprise 12% of the global energy demand by 2050 [1,2]. Under IEA scenarios, cumulative installed CSP capacity could increase by 30% in Europe, and by more than 85% in China by 2050 (for the IEA's Current and New Projection scenarios) [4]. Under more ambitious scenarios, CSP is estimated to grow by more than 600% in Europe and 3000% in China between 2020 and 2050 meeting up to 1.5% and 5% of total installed capacity respectively in these two regions [4,5] (for the 450 IEA Scenario in Europe and the NDRC High RE Scenario in China). It is therefore essential to fully evaluate the environmental and socio-economic performance of CSP considering this potential growth.

Life Cycle Assessment (LCA) has been used in several studies to assess the impacts along the supply chain of CSP [1,6–11]. Likewise, Input-Output Analysis (IOA) has been used in Caldés et al. [12] and Corona et al. [13] with life cycle elements to evaluate the gross impacts of this technology. Note that most of the literature has focused on the USA and Europe, where much of the early development of the technology took place (see Table C3 and C5 in the Appendix). Only M. Zhang et al. [8] studied CSP in China, evaluating a pilot project. Given the importance of assessing the impact of CSP, our contribution to the literature is to expand the geographical and temporal assessment of CSP. We provide collated data for the structure of investment in CSP, expanding the applicability of the results. Here, China-specific data are used, providing specific values for this region [14–19]. Although China has not played a large role in CSP to date, it could be the global leader by 2030 since, as of 2021, it already produced 50% of global newly-built

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List of abbreviations

CSP	Concentrated solar power
GHG	Greenhouse gas
IEA	International Energy Agency
IOA	Input-Output analysis
LCA	Life Cycle Assessment
MRIO	multi-regional environmentally extended input-output
MR-IOT	multi-regional environmentally extended input-output table
NDRC	National Development and Reform Commission
O&M	Operations and maintenance
PV	Photovoltaics

CSP capacity [4]. We also provide impacts for Europe based primarily on data from Spain. Regarding the temporal aspects, while Viebahn et al. [1] considered the dynamic evolution of this technology, the assumptions used cover a short stretch of time (1984–1990) in the evolution of CSP. We base our study of future impacts on a much broader historical basis including data from 1985 to 2020.

The basis of this study is the application of learning rates to an Input-Output Analysis (IOA). We use a multi-regional environmentally extended input-output model (MRIO) to assess CSP in China and Europe, evaluating their social and environmental impact. CSP data are gathered from information available for different projects using solar tower and parabolic trough technology in both regions (we find very similar investment structures for the two types, see Methods below). The collated data for the distribution of CSP costs to the different economic sectors is presented in the Appendix (Table B5-B6) and may contribute to future studies. Costs for CSP have continued to decline. Moreover, in the coming decades, further important reductions are projected and this will impact future projects. To assess this, we review previous studies on learning curves of CSP and use an updated learning rate reflecting recent data to project the potential impacts of the growing installed capacity of CSP under four scenarios from the IEA and NDRC. For context, we compare our estimates for CSP with other renewable technologies from the literature.

2. Methods and data

We assess the historical impacts of CSP and project those impacts into the future. Here we describe the methods and data used. Subsection 2.1 presents the main features of the Environmentally Extended Input-Output model, which is used to calculate historical impacts. Subsection 2.2 discusses the characteristics of the experience curve, which is used to project future impacts. Finally, Subsection 2.3 concludes by describing the data sources and the process of collection and transformation.

2.1. Estimation of impact intensity of CSP

This work estimates the carbon emissions impact (ktCO2/M€) and employment impact (person-year/M€) of CSP using the method developed by Garrett-Peltier [20] and Behrens et al. [21]. We consider the impacts for both investment activities and Operations & Maintenance (O&M) activities. Both direct and indirect impacts within the economy are modelled linking the monetary flows related to CSP investments and O&M to the MRIO. This is done using the expression:

$$\Delta r = b' \cdot L \cdot \Delta y \tag{1}$$

where Δy is a stimulus vector including the investments or O&M expenditures for CSP allocated to different sectors in each region and has a length $n_R n_S$ - where n_R is the number of regions contained in the model and n_s is the number of economic sectors. L is the Leontief inverse matrix with sides of length $n_R n_S$, and describes the multiplier effect of one unit of final demand in any region and sector on the production of every region and sector taking into account intermediate use requirements along supply chains. b' is the intensity row vector with length $n_R n_S$ describing the direct carbon emissions (ktCO2) or contribution to employment (person-year) per unit of economic output (M€) of each sector and region. The result Δr is the overall environmental and social impacts of the stimulus vector representing CSP investments or O&M expenditures.

It is possible to identify key demand elements that contribute to total impacts by diagonalizing the stimulus vector with the following expression:

$$\Delta r = b' \cdot L \cdot diag(\Delta y) \tag{2}$$

The contribution analysis (Eq. (2)) returns a vector Δr in which each entry is the total impact (in GHG emissions or employment) that results from the purchase of the output of a particular sector from a particular region in the bundle that defines the CSP investment or O&M activities. In addition, it is also possible to identify key sectors where impacts occur by diagonalizing the intensity vector.

$$\Delta r = diag(b') \cdot L \cdot \Delta y \tag{3}$$

The hotspot analysis (Eq. (3)) returns a vector Δr in which each entry is the total impact (in GHG emissions or employment) that results from the activity of each particular sector from a particular region to satisfy the demand defined by the stimulus vector.

In order to assemble the stimulus vector we allocated different expenditures from microdata to MRIO sector and region categories. To assess the sensitivity of the results to this processing step we calculated the results for several combinations of two approaches: aggregating sectors to 19 rather than 200 and assuming that the construction of products is domestic rather than domestic and foreign. The result is four different assumptions which represent the different combinations of these two different approaches (see Table 1).

Table 1
Different assumptions used in the construction of the stimulus vector concerning regions and sectors.

Assumption	N° of sectors	Origin of products
1	19	Domestic only
2	200	Domestic only
3	19	Foreign and domestic
4	200	Foreign and domestic

Under assumptions 1 and 2 all goods and services that comprise the installation and O&M of CSP plants are provided domestically. Thus, initially considering as the stimulus a vector of purchases of length n_S with no regional detail (Δy^*), the full multiregional vector (Δy) is built according to the conditions below (Eqs. (4) and (5)):

$$\Delta y_i^r = \Delta y_i^* \quad \text{If} \quad r = t \tag{4}$$

$$\Delta y_i^r = 0 \quad \text{If} \quad r \neq t \tag{5}$$

where i is the sector index; r is a region index; and t is the index of the region of CSP plant installation (which we refer as to as target region).

Under assumptions 3 and 4 the stimulus vector contains demand of both domestic and foreign products. Then:

$$\Delta y_i^r = TS_i^r \cdot \Delta y_i^* \tag{6}$$

where TS gives the share of region r among all export regions in the purchases by the target region of product i. TS is computed as a ratio using total purchases as a proxy: the denominator is the sum of all purchases of product i in the target region across all intermediate and final demand categories. The numerator is the subset of those purchases that originate in region r. (Eqs (7) and (8)).

$$TS_i^r = \frac{Q_i^r}{\sum_s Q_i^s} \tag{7}$$

$$Q_i^r = \sum_j z_{i,j}^{r,t} + \sum_j y_{i,j}^{r,t} \tag{8}$$

where t is the target region index; $z_{i,j}^{r,t}$ is the flow from sector i in region r to sector j in region t (intermediate demand); and $y_{i,j}^{r,t}$ is the flow from sector i in region r to sector j in region t (final demand).

We use EXIOBASE v3.4, a Multi-Regional Environmentally Extended Input-Output Table (MR-IOT) covering 200 products and 49 regions. However, the structure of investments on CSP plants is built using microdata that allows the distinction between 19 sectors. The first option to deal with this issue is to aggregate the MR-IOT. The method to aggregate this MR-IOT is provided in Table B3 in the Supplementary Information and results in an MR-IOT of sides length 49 × 19 ($n_R n_S$) (Assumptions 1 and 3). The second alternative is to disaggregate the structure of investments. Table B4 in Appendix presents this stimulus vector of length 200 (n_s) with no regional detail. This is done using a rule of thumb as the data available was limited. The weight of the sectors not relevant for this technology is set to 0. Then, the weight is uniformly distributed amongst the corresponding sectors of the disaggregated vector. Results derived from this disaggregated stimulus vector (assumptions 2 and 4) are useful to evaluate the relevance of the level of aggregation (this evaluation is presented in Subsection 3.1). However, the main results are reported using assumptions 1 and 3 as we consider aggregating the MRIO table more robust than disaggregation of the stimulus vector.

2.2. Learning curves

To estimate future impact intensities, we use learning curves. These are usually defined for costs rather than intensities, so we first describe them in terms of costs and later make the translation to intensities. The application of learning rates to carbon emissions is a method widely present in the literature [1,22]. However, results derived from the application of the learning rate to employment intensity should be interpreted with caution since the process of learning is very different between, for example, installation and technical innovation. The learning curve is the mathematical relation between investment costs per unit of electricity generated and experience gained through technological development (Equation (9)). As a proxy for this experience gained through technological development, we use global cumulative installed capacity [23]:

$$C = C_0 \cdot n^b \tag{9}$$

In the preceding equation both C and C_0 are investment costs per unit of electricity generated, with C_0 being the cost of the first unit and C being the cost when global cumulative installed capacity is n. b is the experience index and is related to the learning rate (LR) as:

$$LR = 1 - 2^b \tag{10}$$

The learning rate is the rate at which costs decrease for each doubling of global cumulative installed capacity. In this study we use a one-factor learning curve where change of costs over time is explained by experience only. We consider that the learning rate is stable throughout the whole period under analysis and that all projects worldwide contribute to global installed capacity.

Estimates of learning rates in the literature consider two different independent variables, electricity generated and installed capacity, with the dependent variable being the cost of the independent variable [23]. In this study we use installed capacity as the independent variable (n in Eq. (9)) and investment cost per unit of generated electricity as the dependent variable (C in Eq. (9)). This is because we are able to derive our model from the installation of the facility using investment shares.

2.3. Data

CSP data are gathered from information available for different projects using solar tower and parabolic trough technology in two regions, China and Europe [12–15,17–19,24–26], from which production recipes (Table B1-B4 in Appendix) where assembled. We found very similar investment structures for the two technologies and for both locations (see Methods below). In addition, we find that the relative proportion of investments between sectors in the production recipe remains constant over time (Table B6 in Appendix). To obtain European values we follow this method and run the model with MRIO data from EXIOBASE for specific European countries that are suitable for potential deployment of large-scale of CSP (Spain, Italy, Greece). While this naturally does not include all European nations, we report the findings as those from Europe as a whole. This is similar to reporting findings for the US though CSP is very regional within the country (which also has several distinct electricity grids). We argue that this is appropriate given that the single market acts to homogenise the costs and tariffs across Europe and that there is a large policy drive to integrate electricity markets across Europe and enable them via long-distance transmission [27]. Additionally, we assume that future projects installed from 2020 to 2050 include thermal storage capacity. This hypothesis is supported by current trends in CSP development (8 of 9 CSP plants reviewed in this study included it).

We study two differentiated phases in the life cycle of CSP plants: (1) manufacturing of equipment and installation, and (2) operation and maintenance (O&M). We assume a lifespan of 25 years [13] for a CSP plant. O&M costs are set to 3.17% of total investment costs (Table B6 in Appendix). Dismantling is not considered due to a lack of data and an expectation that this will have a small impact [1].

Once future intensities are calculated using learning rates, these are compared to other technologies using data from Yuan et al. [22] which used a similar method to estimate approximate costs of other technologies including solar and wind. The two life cycle phases – installation and O&M – are used in sub-section 3.1 to model the total impacts of CSP. However, in sub-section 3.3, we focus on the installation when evaluating the future impacts of CSP and how it compares to other low carbon technologies only, not comparing O&M costs. Data for installation were more robust than for O&M, as shown in Table 6 of the Appendix. Also, the ratio of O&M costs to total costs is similar for the different low carbon technologies considered (Table C6 of the Appendix).

We use the monetary MRIO EXIOBASE v3.4 for 2011 and all the monetary flows are converted to $€_{2011}$ [28,29]. Data for the learning curve was gathered from SolarPACES [3]. Then, it was complemented with data from Lilliestam & Thonig [30] and other publications and reports (full list available in the supplementary information). As in Lilliestam et al. [31], results are obtained considering only CSP projects with a capacity of 10 MW or higher. Projects under construction are included. Those "announced" or "under development" are not. Yearly values are obtained as the average of all plants entering operation in that year. Monetary data are converted to US dollars. This is done by taking the average exchange rate [28] of the year in which the project entered into operation and then deflated to 2019 [29]. We apply the same learning rate obtained evaluating costs over time ($\$_{2019}$/MW) to the impacts (impact/$€_{2011}$). Data for the future cumulative installed capacity were collected from the IEA [4] and the NDRC [5] and linear extrapolation was used to extend projections for a short period up to 2050 where scenarios ended at 2040. This data collection process was carried out from February to April 2020.

Table 2
Life cycle carbon emissions and employment impacts associated with CSP projects in China and Europe. Reference year:2020.

Impact	Value	Unit	China	Europe
GHG	Average	gCO_2eq/kWh	129.7	99.8
	Range	gCO_2eq/kWh	53.9–181.4	26.0–182.6
Employment	Average	person-year/GWh	4.2	2.3
	Range	person-year/GWh	2.9–4.6	1.2–3.4

3. Results

3.1. Impacts of CSP

Carbon emissions and impacts on employment associated with CSP plants in China and Europe show a broad range (see Table 2). Life cycle emissions are 53.9–181.4 gCO_2eq/kWh for Chinese plants and 26.0–182.6 6 gCO_2eq/kWh for those in Europe. For employment, we find 2.9–4.6 person-year/GWh in China and 1.2–3.4 person-year/GWh in Europe. In comparison to fossil technologies, CSP presents positive values for employment creation and carbon emissions (Table C2-C5 in Appendix). In 2020, CSP in China has a carbon intensity that is 81% smaller than gas. However, CSP is not as competitive against other low carbon technologies. In 2020, the carbon intensity of installation of CSP per GW capacity installed in China (4.29 MtCO2/GW) is 238% higher than that of solar PV (1.27 MtCO2eq/GW) and 225% higher than that of wind (1.32 MtCO2eq/GW). These results for CSP are in a similar range as other IO [12,13,32,33] and LCA analyses [1,7,8,11,34,35].

When examining the different life cycle phases, installation impacts see 0.9–2.7 $ktCO_2eq$/M€ and 47.8–71.0 person-year/M€ in China and 0.7–1.1 $ktCO_2eq$/M€ and 26.0–53.4 person-year/M€ in Europe (see Figs. 2 and 3) (see Fig. 1). For O&M, results range between 0.9–3.1 $ktCO_2eq$/M€ and 42.6–76.4 person-year/M€ in China and 0.6–3.8 $ktCO_2eq$/M€ and 19.5–48.5 person-year/M€ in Europe. The level of impacts in Europe strongly increases with an increased reliance on imported components (Assumptions 1 and 2 against 3 and 4). The reverse is true for China.

3.2. Historical evolution and learning rate of CSP

We find a learning rate of 16% with a reasonable fit ($R^2 = 0.85$) between 1985 and 2020 (see Fig. 4). This value is higher than previous estimates (Table C1 in Appendix) potentially due to recent data covering new CSP plants [36–38]. As there is a similar trend for parabolic trough projects and plants with thermal storage, we assume the same learning rate for all forms of CSP.

3.3. Outlook for impacts of CSP

We now combine this learning rate with the values computed for 2020 installation impacts. We show the projected investment intensities for CSP installation in Figs. 5 and 6. We find a curve which describes a learning rate of 16%. This curve would show a development of investments costs from 0.82 $€_{2011}$/kWh in 2020 to 0.21 $€_{2011}$/kWh in 2050 for IEA 450 and NDRC scenarios. These scenarios present a CSP penetration rate of ~ 5%. Under them, the carbon impact of CSP installation in 2050 (0.7–1.6 MtCO2/GW) is comparable to that of nuclear (0.9–1.3

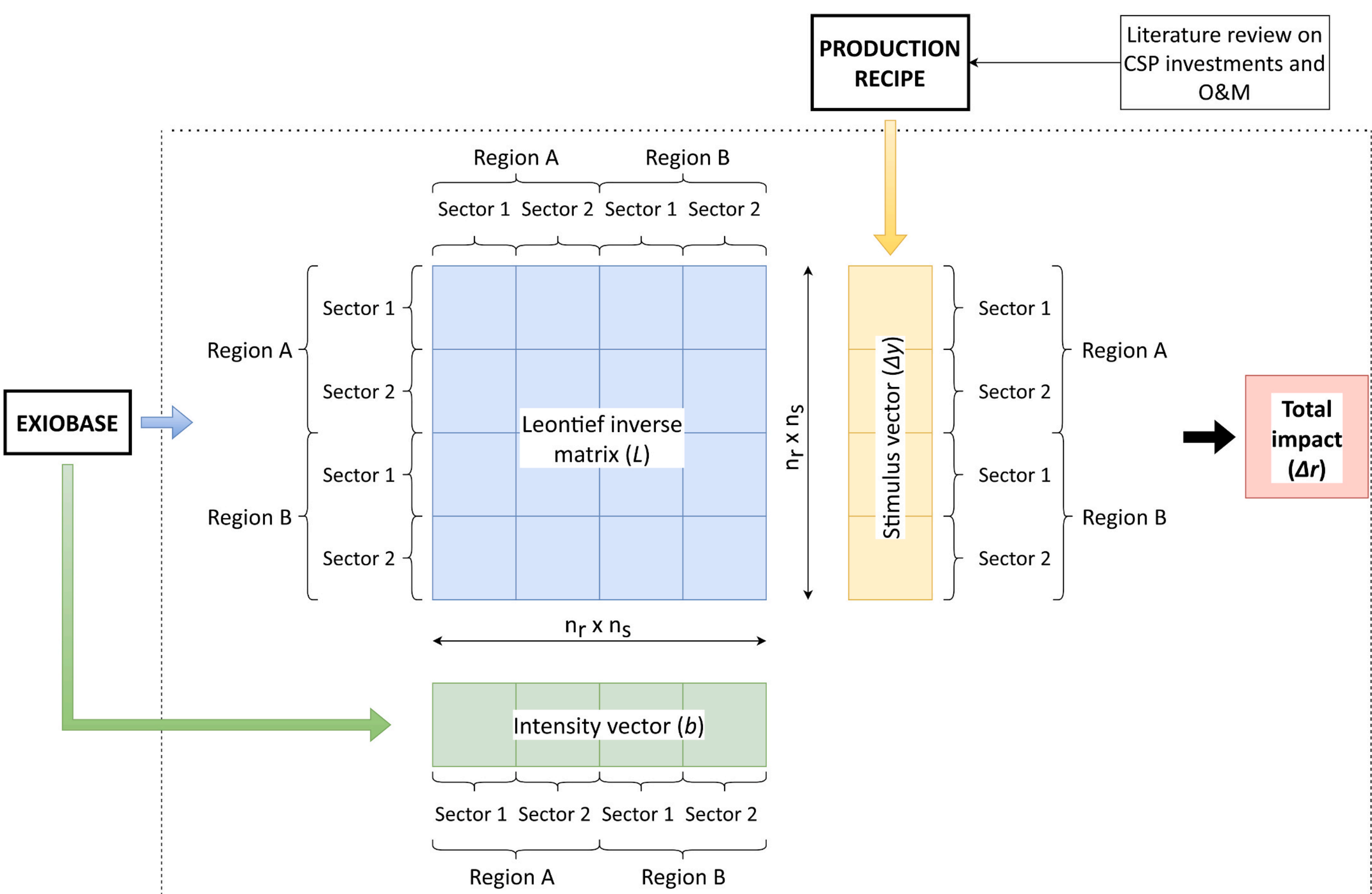

Fig. 1. Conceptual outline of the method used to calculate the total impact of CSP. Each element in the figure is described mathematically in the text. The matrices are colour coded with blue representing the transactions between sectors for a unit of output per sector, green the environmental or employment intensities per different sector, and yellow the final demand required per sector.

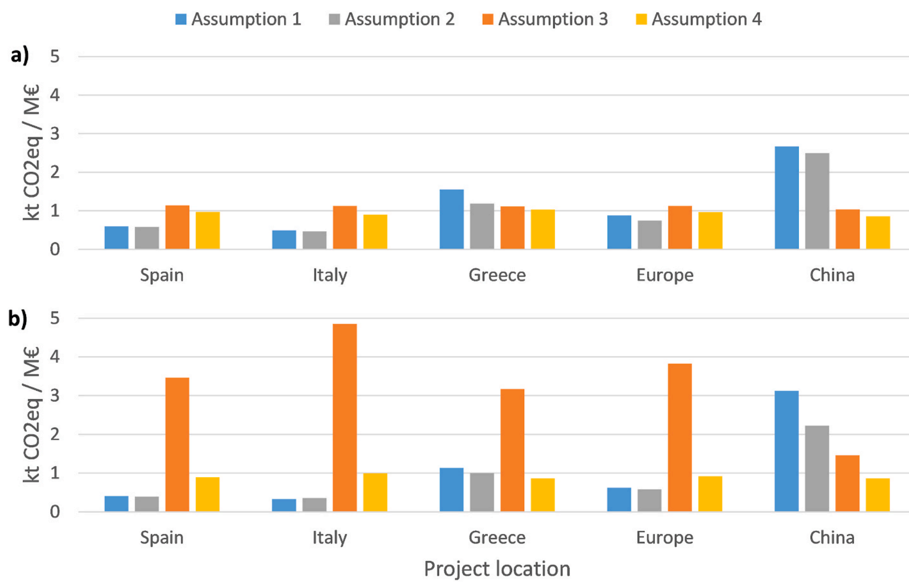

Fig. 2. Total carbon impact per investment cost (M€ of 2011). Reference year: 2020. (a) Installation impacts (b) O&M impacts. Assumptions refer to Table 1. Supplementary data: Tables C9-C10 in Appendix.

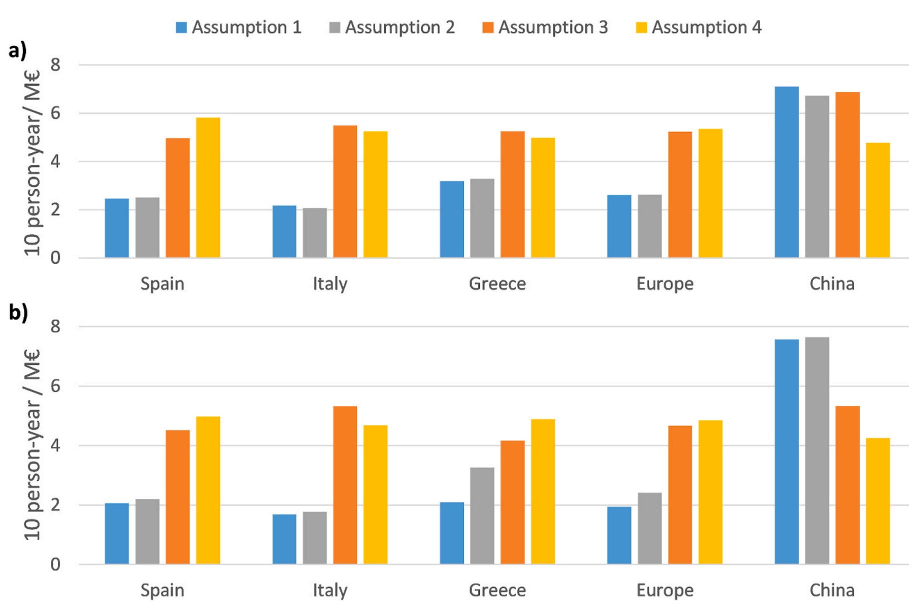

Fig. 3. Total employment impact per investment cost (M€ of 2011). Reference year: 2020. (a) Installation impacts (b) O&M impacts. Assumptions refer to Table 1. Supplementary data: Tables C11-C12 in Appendix.

MtCO2/GW). By 2050, the difference between the carbon intensity of CSP and those of wind (0.9 MtCO2eq/GW) and solar (0.8 MtCO2eq/GW) is expected to narrow from 225% and 238% to 54% and 76% under the NDRC scenario. Regarding job creation, CSP installation intensity is also reduced (28.3–53.8 person-year/MW). In the IEA-Current and IEA-New scenarios, both of which see a slower adoption of CSP, the technology experiences only one doubling of cumulative capacity. As a result, we find much slower cost reductions for these scenarios. It must be noted that developing CSP would bring job creation opportunities since its employment intensity is higher than comparable technologies. Increased cumulative installed capacity would foster job creation. While the net economic impacts of this are uncertain (although our analysis implies more jobs these may be less well paid), this could have an influence on political decision-making (see Figures C2-C5 in Appendix).

We do not address O&M impacts for these future scenarios. This is supported by the ratio of O&M cost to total costs, which is similar for the different low carbon technologies considered (Table C6 in Appendix), and by the data for the installation phase of the life cycle, which is more robust than for the second phase (Table B6 in Appendix). The goal of this sub-section is to point out the CSP improvement potential since this technology is in an early stage of its deployment compared to other low carbon technologies. Its goal is not to produce the most accurate prediction of the future impacts of these technologies.

4. Discussion

A main driver for future CSP deployment over other renewable generation types is to provide dispatchability of electricity [2,39,40]. This may be seen as a necessary trade-off with the higher carbon intensities for CSP when compared to other low-carbon technologies [22]. Under the slightly higher learning rate found here than previously reported in the literature (Table C1 in Appendix), the CSP carbon impact

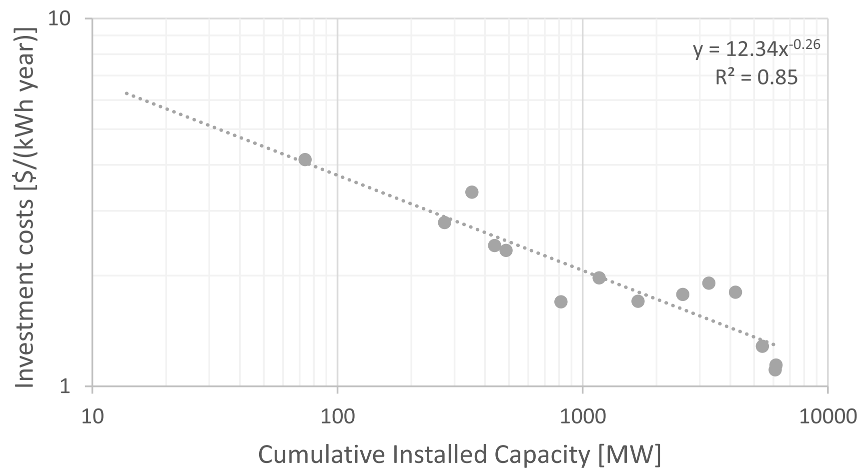

Fig. 4. In log-log space, CSP costs development and learning curve. Monetary unit is 2019 US$. Each data point is the average of all projects which entered operation in that year.

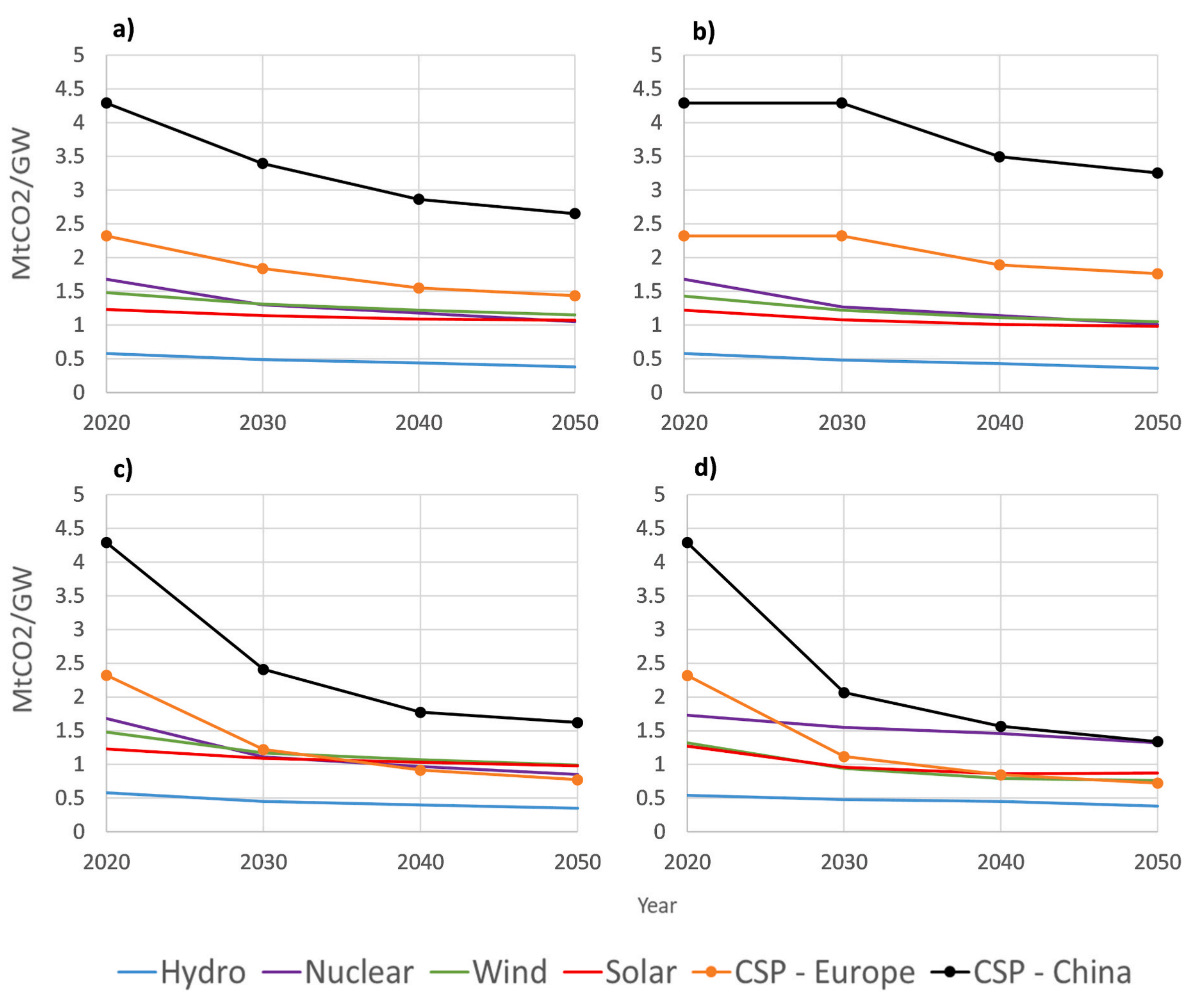

Fig. 5. Carbon intensity evolution under different scenarios. This evolution is dependent on the global cumulative installed capacity development of each energy technology in each scenario. (a) IEA Current scenario (b) IEA New (c) IEA 450 (d) NDRC High RE Scenario. CSP results are obtained from the values calculated in this work. Other energy technologies results are obtained from the values in Yuan et al. [22]. Table C7 in Appendix presents supplementary data.

of installation may be lower than nuclear for some scenarios with high CSP penetration rates. Furthermore, the gap between PV and wind and CSP also narrows. In regard to employment, the contribution to job creation per GW of CSP installed capacity could be expected to decrease too. Nevertheless, it remains the largest of all the energy technologies considered. In addition, integrating CSP with thermal storage may

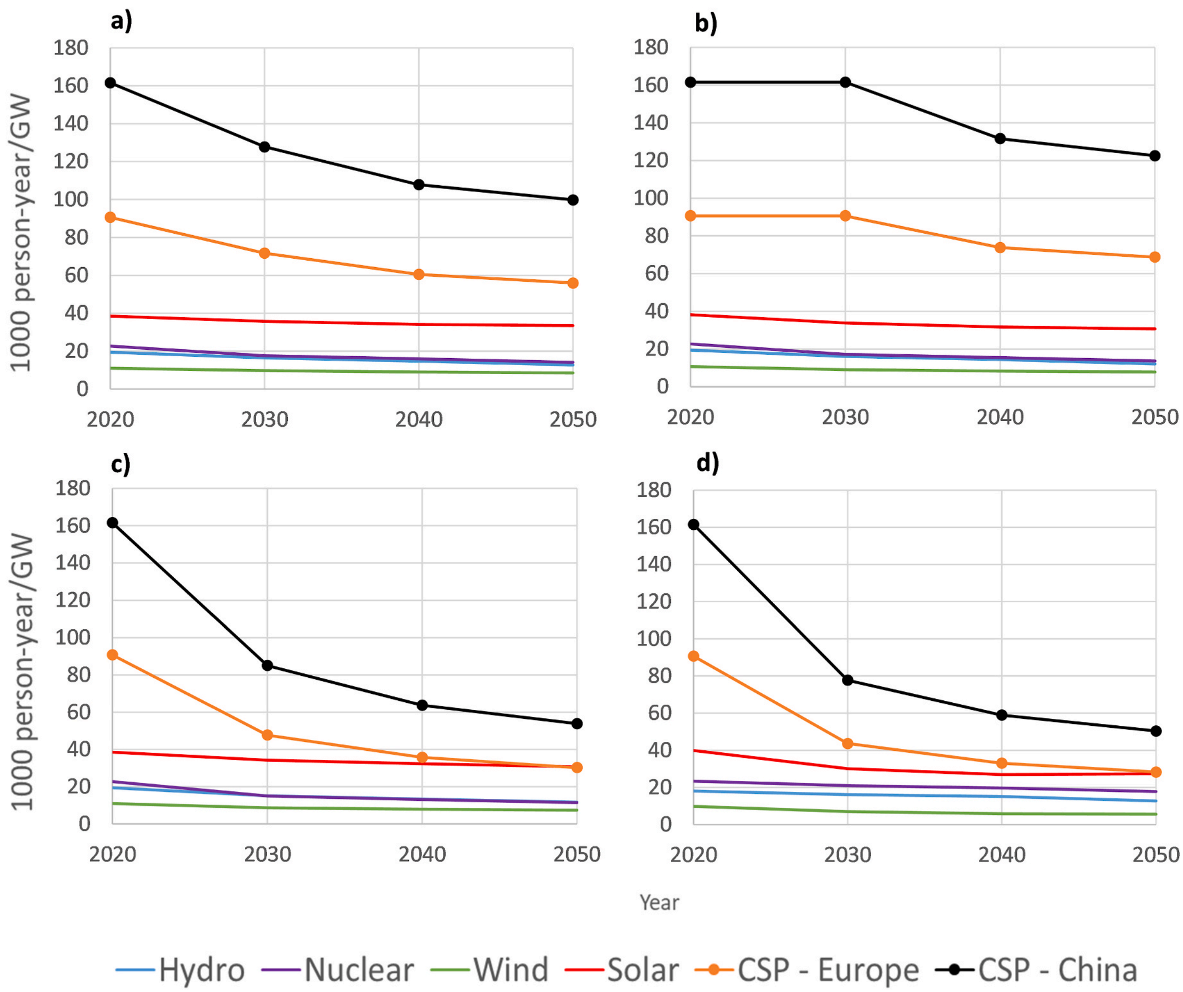

Fig. 6. Employment intensity evolution under the different scenarios evaluated. This evolution is dependent on the global cumulative installed capacity development of each energy technology in each scenario. (a) IEA Current scenario (b) IEA New (c) IEA 450 (d) NDRC High RE Scenario. CSP results are obtained from the values calculated in this work. Other energy technologies results are obtained from the values in Refs. [22,32,33]. Table C8 in Appendix presents supplementary data.

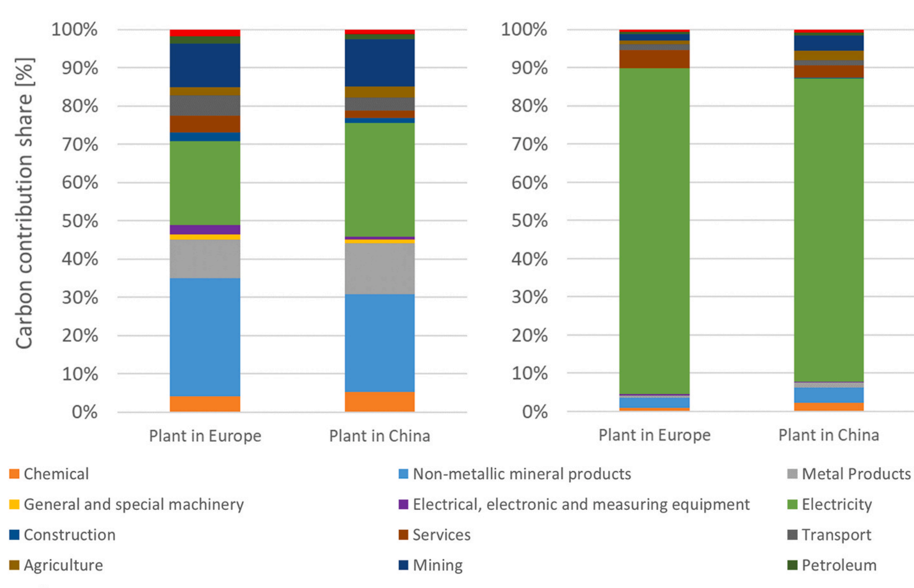

Fig. 7. Sectoral analysis of life cycle carbon impacts of CSP plants: On the left, installation; on the right, O&M. Supplementary data: Tables C17-C18 in Appendix.

improve the economic potential of the technology by enabling it to meet firm and peak demand (if regulators and/or markets incentivise such operating modes). CSP has the potential to increase grid stability and dispatchability services as installed variable renewable energy sources continue to grow. CSP technology may also be used in novel applications including desalination, process heat and hybridisation with heat from biomass or fossil fuels [2]. According to innovation theory, these applications may offer niche markets which provide an opportunity to improve performance, increase learning, drive down costs, and ultimately incentivise further deployment into other, often larger, markets [40].

Despite the complementarity with other renewable sources, in the absence of strong capacity incentives, direct competition from PV power can be identified as a barrier delaying the deployment of CSP [40]. In addition, coupling PV and lithium-ion batteries would also offer competition for dispatchable electricity. Carbon intensities for these hybrid energy systems have been found to be only slightly higher than that of PV and still lower than that of CSP [41–43]. However, studies on the future of these two solar energy technologies with storage find CSP to be economically preferable as it offers bigger storage capacities and greater efficiencies [44,45]. In order to push costs down through more extensive deployment further government support may be necessary to make this technology competitive. However, some authors point out that cost reductions for CSP have been lower than initially expected [31,40]. We find a slightly higher learning rate and a larger potential opportunity for CSP than previously thought, but that is only relevant if the technology is supported while manufacturing scale factors drive the cost down and if the higher learning rates found here are maintained into the future.

The findings in this work associate CSP deployment with positive socio-economic and environmental impacts. This more optimistic perspective for this technology is also found in recent work suggesting the potential for a long-term and large-scale deployment of CSP [1,2,39,40,46–48]. Regarding the learning rate, we only consider the endogenous technical change resulting from the experience gained as global cumulative capacity increases. Deployment of new low carbon technologies will affect the environmental performance of the electricity system resulting in negative feedback on the CSP carbon intensity. It is important as "Electricity" was identified by the hotspot analysis (Fig. 7) and contribution analysis (Tables C13-C20 in Appendix) as one of the sectors contributing the most in CSP installation. This is also true for other renewable technologies.

The high employment intensity of CSP has been used as an argument for political support in CSP developments. Nevertheless, this employment intensity is caused by higher investment costs. Increased costs for electricity could result in negative net effects on the economy. A net approach to the calculation of the effects of CSP in China and Europe from 2020 to 2050 might bring a deeper understanding of the implications of its deployment. Still, positive net calculations were found in Corona et al. [13]. Furthermore, it must be noted that our environmental analysis focuses on climate impacts and does not include other environmental impact categories relevant for CSP such as water use and landscape [40].

5. Conclusion

We find that carbon and employment intensities for CSP are greater than those for other low carbon technologies. However, CSP already presents beneficial carbon impacts compared to fossil technologies. CSP has the potential to drop significantly in price since it is in an initial stage of its development yet. Carbon intensity associated with the installation of CSP could drop to the same level as nuclear for those scenarios with a high penetration rate of this technology. The gap between CSP impacts and other renewable energy technologies such as wind and solar PV could also narrow dramatically. The carbon intensity of CSP is found to be 129.7 gCO_2eq/kWh (China) and 99.8 gCO_2eq/kWh (Europe). In regard to employment intensity, CSP gross effects are also found to be higher in China than in Europe (4.2 and 2.3 person-year/GWh). Investment costs would be reduced from 0.82 $€_{2011}$/kWh in 2020 to 0.21 $€_{2011}$/kWh in 2050 for scenarios with high CSP penetration rates (e.g. NDRC). By 2050, for these scenarios, CSP carbon intensity is estimated to be 40.4 gCO_2eq/kWh in China and 31.1 gCO_2eq/kWh in Europe; and job intensity is estimated to be 1.3 person-year/GWh in China and 0.7 person-year/GWh in Europe. According to these results, CSP plants would present positive impacts on carbon emissions reduction and employment creation in the energy transition. We find a higher CSP learning rate than previous estimates. This difference is due to recent technological developments and the inclusion of operational aspects in the calculation of the experience curve. Moreover, we provide collated data for the distribution of CSP costs to the different economic sectors, particularly providing China-specific values, which can be of interest for future studies. Note that while much of the past research has focused on the USA and Europe, where CSP early development took place, it is China that is predicted to be instrumental in the next phase of the development of CSP.

Credit author statement

Hahn Menacho: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Rodrigues**: Conceptualization, Methodology, Writing- Reviewing and Editing; **Behrens**: Methodology, Writing- Reviewing and Editing

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112677.

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