Concentrated Solar Power generation:
Triple bottom line assessment in Europe and China 2020-2050

Abstract

Concentrated Solar Power is one of the renewable energy technologies with the potential for satisfying the future energy demand in a sustainable way, mitigating climate change and reducing the current dependence on fossil fuels. Regarding the deployment of this technology, China and Europe are two regions playing a forefront role in the present and in the predicted future. In this study we assess the environmental and socio-economic impacts of the predicted expansion of Concentrated Solar Power generation. Using an Input-Output model, both the direct effects of these installations and their influence in other industries upstream are considered. In addition, this work studies the experience curve of this technology. It suggests a learning rate equal to 16%. This information is combined with the predicted cumulative installed capacity of concentrated solar power and other energy technologies from scenarios developed by the International Energy Agency and the National Development and Reform Commission. The results show how the development of this technology under different scenarios affects its performance assessing its potential as an alternative to produce electricity in the future. It is found that CSP employment intensity amounts to 2.28 jobs/GWh in Europe and 4.23 jobs/GWh in China. These CSP employment intensities are higher than other low carbon technologies intensities. In addition, this technology already presents lower carbon emissions than fossil fuels and it has the potential of reducing the gap with other low carbon technologies. It presents a carbon intensity of 99.76 gCO2eq/kWh in Europe and 129.65 gCO2eq/kWh in China. These values could further be reduced to 31.10 gCO2eq/kWh in Europe and 40.42 gCO2eq/kWh in China by 2050. This work stresses the importance of an integrated approach that considers environmental and socio-economic aspects when evaluating an energy technology and may provide important information about the potential role of CSP in the energy transition. In addition, these results can be used to emphasize the importance of investing on renewable energy technologies to gain experience, since the knowledge obtained during their deployment can be expected to improve their performance.

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Álvaro José Hahn Menacho

First Supervisor:
Dr. J.F. Dias Rodrigues – Leiden University (CML)
Second Supervisor:
Dr. P.A. Behrens – Leiden University (LUC)

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Abbreviations

CO_2eq	Carbon dioxide equivalent
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiation
EEIO	Environmentally Extended Input-Output
GHG	Greenhouse gases
HTF	Heat Transfer Fluid
IEA	International Energy Agency
IO	Input-Output
LR	Learning rate
MRIO	Multi regional Input-Output
NDRC	National Development and Reform Commission
NG	Natural Gas
PT	Parabolic Trough
ST	Solar Tower

1. Introduction

Global primary energy demand is expected to grow by more than one third between 2020 and 2050 (International Energy Agency, 2016; H. Lu et al., 2019; National Development and Reform Commission, 2015). At the same time, worldwide awareness of the importance of mitigating global warming has been increasing (H. Lu et al., 2019). In this context, it is essential to develop and implement renewable energy technologies in order to promote a transition to a clean energy system that can address environmental concerns while satisfying societal demands.

Concentrated Solar Power (CSP) is a renewable energy technology that can help achieve this goal. This promising technology concentrates sun radiation using reflecting heliostats. This energy is used as a heat source to run a conventional power plant cycle (Ko et al., 2018). The three most mature types of CSP plant technology are: (1) parabolic trough and Fresnel trough receiver, (2) solar tower and (3) Dish-Stirling systems (Koroneos et al., 2008). Figure 1 shows a representation of these three types.

The main advantage that this technology presents is the possibility of using solar irradiance as the heat source to generate electricity. Solar energy is used to produce steam, avoiding the need for burning fossil fuels. In addition, this alternative stands out when compared to other renewable technologies because of the possibility to operate them in a non-intermittent way. This technology can be integrated with thermal storage using molten salts or phase change materials. The energy can be extracted from the storage system when there is no sun radiation enough to keep the plant operating (Viebahn et al., 2011), which makes it possible to meet both peak and baseload demand (Estela et al., 2016).

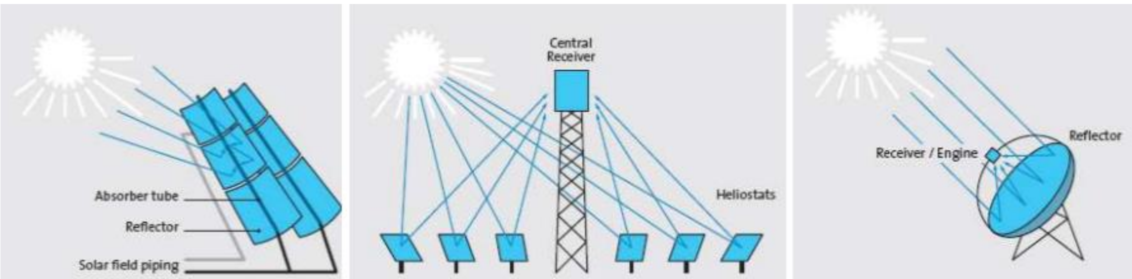


Figure 1. Representation of the different types of CSP plant. From left to right: parabolic trough, solar tower and dish system. Retrieved from Koroneos et al. (2008).

CSP generation increased by almost 750% in the last decade. The potential for CSP is great and it is suggested that it could meet up to 12% of the global energy demand (Estela et al., 2016; Viebahn et al., 2011). Considering this expected growth, it becomes crucial to fully assess the performance of this technology. As the energy system is a major economic sector, the economic consequences of energy production projects have attracted the attention of researchers for a long time (Ram et al., 2020). In addition, in the energy transition context, it has become a key aspect to evaluate and clearly quantify the system-wide environmental and social impacts from energy systems when modelling the energy market of the future (Ram et al., 2020).

This work studies the performance of CSP plants regarding sustainability, assessing its potential as a renewable energy technology in the future energy market. In order to estimate the sustainability of this technology, the approach chosen bears the triple-bottom-line in mind: Economy, Environment and Society. Here, the evolution of CSP costs is analysed and linked to GHG emissions and job creation, providing a fully integrated perspective of this technology.

1.1. Knowledge gap

Considering the importance of producing electricity in a sustainable way, this research aims at contributing to the assessment of the potential of CSP plants as an important source of renewable energy in the energy transition. Several studies (Aden et al., 2010; Klein & Rubin, 2013; Ko et al., 2018; Koroneos et al., 2008; Lamnatou & Chemisana, 2017; Viebahn et al., 2011; M. Zhang et al., 2012) have used Life Cycle Assessment (LCA) to estimate the impacts along the CSP supply chain. In addition, Caldés et al. (2009) and Corona et al. (2016) use IO analyses with Life Cycle thinking to assess the gross effects of these projects. However, all the previous studies limit the base of their calculations to the characteristics of a certain existing plant, none of them being a commercial plant situated in China. Although China did not play a relevant role regarding CSP in the past, it makes half of global newly-built capacity and could be the world leader by 2030. In addition, Viehbahn et al. (2011) is the only one also considering the dynamic evolution of CSP plants. However, the assumptions they use are built considering a very short period of the deployment of this technology. It can be said that the applicability of the existing results presents certain geographical, temporal and technological limits.

In light of the above paragraph, there exists the need to further collect information about CSP to better understand how the evolution of this technology may affect its performance and its comparison with other alternatives. Costs for CSP have already declined, but further significant reductions are expected in the next decades. This will influence the impacts associated with these installations. To answer this, this work reviews the existing studies about the CSP learning rate. Furthermore, a Multi-regional Environmentally Extended Input-Output Model will be built with the aim of assessing the environmental and socio-economic impacts of CSP plants in Europe and China. This IO model is based on information about several CSP plants using parabolic trough and solar tower technology. In addition, the location of the different plants ensures the applicability of the results to the two regions studied. Finally, it can be highlighted that the key feature of this work is its dynamic approach, which evaluates the potential improvements in CSP technology when comparing it to other alternatives.

1.2. Research questions

This study will determine the environmental and socio-economic impacts of CSP plants in Europe and China. In addition, it is assessed how the evolution of this technology under different scenarios will affect its performance. This information can be useful to evaluate the potential of this technology as an alternative to produce electrify in the energy transition context. The main research question of this thesis is therefore:

What are the expected and potential environmental and socio-economic impacts of Concentrated Solar Power (CSP) in China and Europe 2020-2050?

To structure the report and answer the main research question, the following sub-questions are presented:

1. What is the historical and expected evolution of CSP penetration rate and performance?
2. What is the production recipe and supply chain structure of the existing CSP projects?
3. What is the predicted environmental and socio-economic impact of CSP plants?
4. How do these impacts compare to other technologies?

5. What are the main drivers and barriers influencing the potential deployment of this technology?

The first two sub-questions constitute the data collection phase. After processing the information about the existing CSP plants, the answer to the first sub-question will bring the learning rate of this technology. The answer to the second sub-question will provide the needed information about how the investments on CSP plants are distributed to the different sectors in the economy. The third sub-question guides the analysis part where the impacts of CSP plants are derived from the EEIO model. Then, sub-question 4 will yield a dynamic comparison between the results for CSP from the model built in this thesis and the results for other energy technologies obtained from the literature. Finally, the last sub-question brings a discussion about the potential role that CSP may play in the energy transition. This discussion will be based on the answers to the previous sub-questions and a review of the existing literature.

2. Methodology

This chapter describes the methodologies and tools used to assess the environmental and socio-economic impact of CSP plants. In addition, the different energy scenarios from the IEA and the NDRC are introduced. They will be used to evaluate the future evolution of the cumulative installed capacity of different energy technologies. Then, this section concludes describing the characteristics of the experience curve and the Environmentally Extended Input-Output (EEIO) model used in this work.

This research studies the impacts of CSP plants taking a dynamic approach. This is done building on the methodology developed in Yuan et al. (2018). Firstly, an EEIO model provides an assessment of the carbon intensity and job creation intensity related to the economic performance of CSP plants. Then, the concept of learning curves is used to evaluate the future impact of this technology. This will be used to assess how the performance evolves as cumulative installed capacities increases. This approach emphasizes the importance of the knowledge gained during the deployment of one technology to increase its competitiveness.

This work aims at expanding the period covered in the existing literature when building the learning curves. Many new CSP were installed in recent years (National Renewable Energy Laboratory, n.d.). Hence, any effort to collect data for this technology may provide a better understanding of it, gaining insight on the long-term view of its future (Samadi, 2018). Furthermore, adding environmental considerations when working with the learning curves will complement the existing knowledge about the environmental impacts related to the production of electricity in CSP plants.

Finally, this technology is compared with the predicted performance of other low carbon energy technologies. The results for the CSP performance will be compared with the data obtained from similar studies about other technologies. The performance of the different technologies will be evaluated under different scenarios as they are also expected to evolve depending on the cumulative installed capacity. Information about the future evolution of the cumulative installed capacity of different energy technologies is retrieved from the International Energy Agency (International Energy Agency, 2016) and the National Development and Reform Commission (National Development and Reform Commission, 2015). Four different scenarios are evaluated: IEA – Current Scenario, IEA – New, IEA – 450 and NDRC – High RE. Specific information about these scenarios can be found in Table 9-11, in Appendix A.

Regarding the scope of this research, it is defined as follows:

- Spatial scope: Europe and China
- Temporal scope: 2020 - 2050
- Technological scope: Solar Tower and Parabolic Trough

Considering the existing number of operating CSP plants in these two regions, this spatial scope ensures available data for this research (National Renewable Energy Laboratory, n.d.). In addition, the expected growth in electricity production from CSP plants in China and Europe provides relevance to the results here obtained (International Energy Agency, 2019). Furthermore, the economy structure of these two regions is expected to be relatively different. Then, comparing the performance of CSP plants in each region may provide a better understanding of this technology.

Regarding the temporal scope, this period is considered to comprise the energy transition in both regions. This election is also consistent with the future scenarios studied and provided by the two institutions considered.

Finally, this research is limited to Concentrated Solar Power plants operating with solar tower and parabolic trough technology. Parabolic trough is the most mature CSP technology and most of the research about solar thermal electricity generation focuses on it. However, solar tower deployment has been boosted in recent years due to its technical advantages (Chaanaoui et al., 2016). Hence, collecting information about this technology will add value to the current understanding of CSP technologies. Dish-Stirling systems are excluded from this research as they are the less mature technology (National Renewable Energy Laboratory, n.d.) and the information that can be found about the few existing projects is limited.

The research approach chosen is expected to provide valuable information useful to draw recommendations for policy makers when designing the energy transition. However, it is always important to understand the limitations of the model when interpreting the results. One of the biggest limitations when using IO tables is that all the activities within one sector are considered to be homogeneous (Caldés et al., 2009). In addition, it is a linear tool that assumes proportionality in the relations between the industries (Garrett-Peltier, 2017). Being aware of these characteristics will allow us to properly treat the results obtained while enjoying the main strength of this tool: its simplicity.

Regarding the experience curves, the one proposed here will be based in only one factor: cumulative installed capacity. Although the one-factor experience curve is the approach chosen in this study for the sake of simplicity, the results obtained are to be interpreted in a conservative way. As de la Tour et al. (2018) finds in his review about PV experience curves, learning rates derived from one-factor experience curves tend to be higher.

Finally, it is important to remark that using indicators is a useful tool to make comparison of the performance of different energy technologies. However, this approach can be considered relatively simplistic since the whole performance evaluation is reduced to their relation to the indicators defined. Yet, using this kind of indicators to assess environmental and socio-economic implications of an industry production have reached an extended consensus (Foran et al., 2005; Veiga et al., 2018; Wang et al., 2020).

2.1. Learning curve

Learning curves are used to predict how an industry performance evolves as it gains experience trough producing products (Yuan et al., 2018). This quantitative tool is commonly used in energy and environmental policy analysis to model endogenous technical change in long-term assessment of different technologies (Taylor et al., 2007).

The learning curve built here analyses the evolution of the costs associated with the installation and operation of CSP plants. It will be a one-factor learning curve where experience is the independent variable that explains cost changes over time. This approach brings many uncertainties due to the extrapolations made and the omitted-variable bias (Samadi, 2018; Yuan et al., 2018). Using multi-factor experience curves may look theoretically appealing. However, their construction is complex and data limitations are usually a drawback (Samadi, 2018). Regarding the continuity of the learning curve, this work considers a stable learning rate continuous through the different periods to describe the historical cost development of electricity generation from CSP plants. This learning rate will consider all the projects worldwide. This level of perspective implicitly assumes that the learning process takes level at industry level – in contrast to at firm level – being the learning spillovers between different actors of great significance. Obtaining several learning rates for the different parts of CSP plants (e.g. solar field, power block, storage) was discarded due to data availability.

The y-variable in the learning curve equation is represented by the investment costs per unit of electricity generated. Doing so, not only the technological improvements related to the construction and installation are captured but also the ones corresponding to the operation. The x-variable in this equation is the cumulative installed capacity, used as a proxy for experience gained as the technology is developed. Table 1 presents a summary of the characteristics of the learning curve here built.

Table 1. Characteristics of the experience curve built for electricity generation from CSP plants. Personal elaboration. Based on Samadi (2018).

Methodology		
Independent variable:	-	Only experience
Dependent variable	-	Investment costs
Experience curve continuity:	-	Continuous curve and stable learning rate
Learning system boundary		
Level of perspective:	-	Market perspective (no firm level)
Object of investigation:	-	Power plant project (no specific parts)
Definition of specific costs (dependent variable)		
Product definition:	-	Costs per unit of electricity generated
Geographical scope:	-	Costs from all relevant countries
Definition of experience (independent variable)		
Product definition:	-	Cumulative capacity
Geographical scope:	-	Global experience

The relation between costs and cumulative installed capacity is described by the learning curve equation (Samadi, 2018):

$$C = C_0 \cdot n^b \qquad [1]$$

Where C describes the investment costs per unit of electricity generated as a function of the cumulative installed capacity; C_0 is the cost of the first unit; n is the cumulative installed capacity worldwide; and b represents the experience index. Then, understanding the learning rate as the rate at which costs decrease for each doubling of cumulative capacity:

$$LR = 1 - 2^b \qquad [2]$$

The data for this study was collected from SolarPACES. This data was complemented with the information available on Lilliestam & Thonig (2019) and different reports and publications. Data collection took place between February and April 2020.

Following the method in Lilliestam et al. (2017), the results are based on all CSP plants with a capacity of 10 MW or more. In addition, CSP plants under construction are included but those projects “under development” or “announced” are discarded. Data for CSP plants can be found in Table 12 and Table 13 in Appendix A. Costs data are converted to US dollars using the average exchange rate (Forex, 2020) of the year when the plant started operating and then deflated to 2019 (EUROSTAT, 2020).

2.2. Environmentally Extended Input-Output Model

Input-Output (IO) modelling is an analytical tool that presents in a systematic way how the different sectors in the economy are interrelated. The framework presented by this tool is apparently simple: each column in the IO table presents the monetary inputs of each sector to either the other sectors defined in the economy or final demand (Caldés et al., 2009). Hence, the relation between the supply side and the total production output can be expressed as:

$$x_i = \sum_{j=1}^{n} x_{ij} + y_i \qquad [3]$$

Where x_i is total output of sector i; x_{ij} is input from sector i to sector j; and y_i represents the total final demand for sector i.

IO analyses are useful to estimate the impacts caused by changes in demand for the output of industries. They are frequently used to model the economy-wide impacts of investing in energy production (Garrett-Peltier, 2017). However, IO tables do not identify the renewable energy industries. This issue is solved following the approach proposed by Garret-Peltier (2017): since the activity of the renewable industries is captured implicitly in the IO framework, a vector is built identifying the components and their weights that make up the renewable energy industry. This vector will be called production recipe.

IO analysis brings the opportunity of evaluating the impacts on both the gross value added and the jobs development related to the deployment of CSP plants in different regions in the world. In addition, the carbon intensity of this technology can be studied using extended IO tables where also the total environmental emissions related to each sector are included. Linking the monetary flows related to the investment on CSP to the IO framework, it is possible to model both the direct and indirect socio-economic and environmental impacts generated on the rest of the economy. Hence, the model will estimate the job creation and GHG emissions generated in each sector of the economy as a consequence of every million euro spent on CSP installation and O&M.

Regarding the model, this analysis is based on the following Input-Output equation:

$$x = (I - A)^{-1} y \qquad [4]$$

Where x is the total output of a certain economy; I is the identity matrix; A is the technical coefficient matrix, which describes the monetary flow from each sector needed to produce one monetary unit of every sector; and y is the matrix of final demand. $(I - A)^{-1}$ is known as the Leontief matrix and describes the direct and indirect requirements per unit of final demand.

Let r be a so-called satellite block containing a generic account data – employment, gross value added or tons of air pollutants – related to each sector. Then:

$$b = r \cdot \hat{x}^{-1} \qquad [5]$$

describes the direct intensity vector. Combining eqs. 4 and 5, it is obtained the following expression to calculate the total impact along the supply chain caused by a change in final demand:

$$\Delta r = b' \cdot L \cdot \Delta y \qquad [6]$$

The model works with four different assumptions for the stimulus vector according to the region where the change in final demand is placed and the level of sector aggregation. They are presented in Table 2.

Table 2. Different assumptions for the stimulus vector according to location and level of aggregation.

	Origin of products	Number of sectors
Assumption 1	Only domestic	19
Assumption 2	Only domestic	200
Assumption 3	Domestic and foreign	19
Assumption 4	Domestic and foreign	200

Regarding where the change in final demand happens, the first alternative is a stimulus vector which only makes domestic purchases in the target country where CSP plants are installed. The starting point for the definition of the stimulus is a vector of purchases without regional detail (Δy^*). Then, the full multiregional vector (Δy) will be populated according to the following conditions (Eqs. 7-8):

$$\Delta y_i^r = \Delta y_i^* \qquad \text{If } r = t \qquad [7]$$

$$\Delta y_i^r = 0 \qquad \text{If } r \neq t \qquad [8]$$

Where the index i refers to the sectors (either 19 or 200 depending on the level of aggregation); r is an index referring to one of the 49 regions considered; and t is the index of the target region (the region where the project would be installed).

The second alternative considers a stimulus vector where demand is satisfied by domestic and foreign products. Then:

$$\Delta y_i^r = TS_i^r \cdot \Delta y_i^* \qquad [9]$$

Where TS is the trade share of region r in the purchases of product i of the target region. This trade share is calculated using as a proxy the ratio of purchases across all intermediate and final demand categories of product i by the target region that originate in region r (Eqs. 10-11).

$$TS_i^r = \frac{Q_i^r}{\sum_s Q_i^s} \qquad [10]$$

$$Q_i^r = \sum_j z_{i,j}^{r,t} + \sum_j y_{i,j}^{r,t} \qquad [11]$$

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

Regarding the number of sectors, the database used presents a system with 49 regions and 200 products. However, the production recipe built with the data collected presents 19 sectors. To address this issue, the first alternative is to re-aggregate the IO table. This re-aggregation is presented in Table 14 in Appendix A.

The other alternative is to disaggregate the production recipe. To do so, a rule of thumb is used since the data available was limited. For this purpose, the weight was set equal to 0 in the disaggregated vector in those sectors that were considered not relevant for CSP. Then, the weight of each sector was equally distributed to the corresponding sectors in the disaggregated vector. This disaggregated vector can be found in Table 15 in Appendix A. The results obtained from this last line of reasoning are useful to analyse how the level of aggregation affects the model, but they are not considered in further calculations.

The basis of the MRIO modelling used in this work is the EXIOBASE v3.4, a global, detailed Multi-Regional Environmentally Extended Supply-Use Table (MR-SUT) and Input-Output Table (MR-IOT) (EXIOBASE, 2020). This work relies in the most recent data available, covering the year 2011. Hence, all the monetary flows presented in the model are converted to €$_{2011}$ (EUROSTAT, 2020; Forex, 2020).

3. Results

In this chapter, the impacts of CSP plants are assessed. The subchapters are outlined as follows. Firstly, data collected for the different CSP plants and presented in Table 12-13 in Appendix A are processed to obtain the learning rate of this technology. Secondly, the production recipe of CSP plants is built based on the structure of investment of different existing plants. Thirdly, the Environmentally Extended Input-Output model provides an assessment of the environmental and socio-economic impacts associated with CSP plants. Finally, the previous results are projected up to 2050 according to the different energy scenarios. Then, this evolution is compared to other technologies.

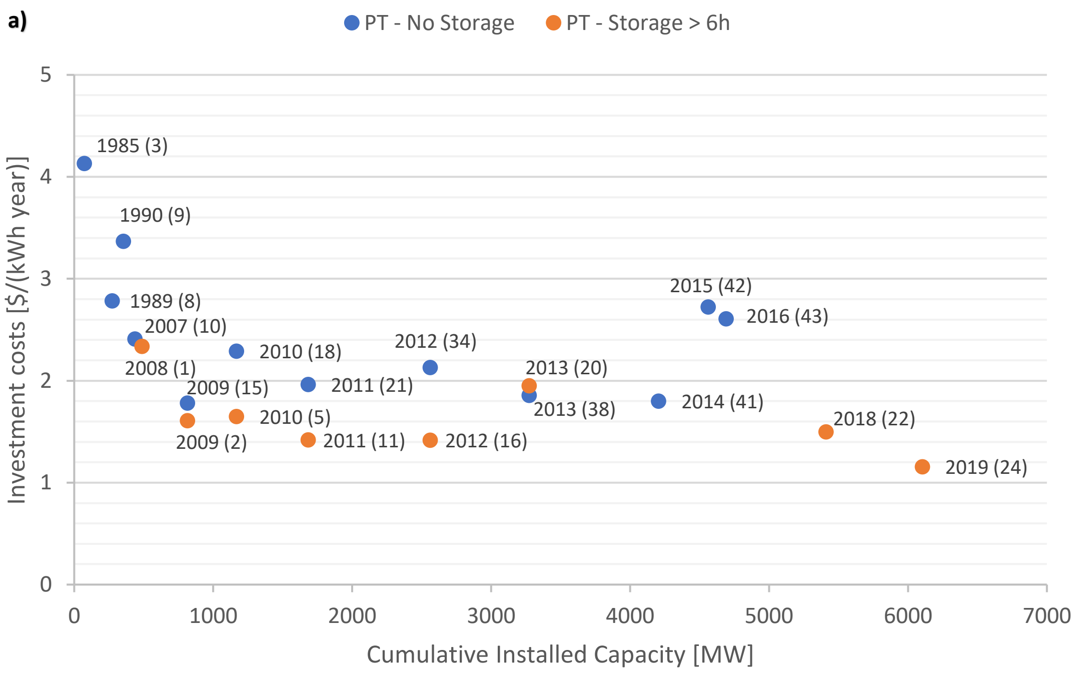
3.1. Historical evolution of CSP and learning rate

In this section, the learning rate (LR) of this technology is derived from the analysis of the observed investment costs development of CSP projects. This work focuses on parabolic trough (PT) and solar tower (ST) plants, which account for 90% of the total installed capacity worldwide. The configuration of CSP plants differs significantly depending on the technology used. Hence, it is analysed whether a common learning rate for the different CSP alternatives can be used or whether it is necessary to obtain separate learning rates for each technology. In addition, it is also studied how the thermal storage capacity influences the cost development.

This work describes the evolution of the average investment costs per expected yearly electricity generation to obtain the learning rate. The configurations differentiated are: PT with no storage capacity; PT with storage capacity; ST with little (<1h) or none storage capacity; and, ST with storage capacity. This is represented in Figure 2.

Firstly, this section evaluates this development for CSP plants with parabolic trough technology. It is concluded that those PT projects with and without thermal storage capacity follow the same trend. Hence, the same learning rate is applied to both. This is represented in Figure 2.a. Based on the findings by Lilliestam et al. (2017), four different phases are distinguished in this work: (1) The first phase (1985-1989) would include the implementation of the first projects in USA. It is characterized by significant cost reductions. (2) During the second phase (2007-2013) many new projects were implemented in Spain, boosted by the feed-in tariff (FIT) for CSP offered by the Spanish government (Lilliestam et al., 2017). This second phase is characterized by a smaller cost reduction than the previous phase. (3) During this third phase (2013-2018), several projects are implemented around the world. No cost reduction is identified during this period. (4) The final phase (2018-present) would include the development of new CSP projects, mainly in China, where cost reductions continue as the global cumulative installed capacity increases.

Then, it is analysed the development of the average investment costs per expected yearly electricity generation for CSP plants with solar tower technology. As there are only few plants conforming this series and they are placed in different locations and have different dimensions, it is impossible to identify any trend. This is shown in Figure 2.b.



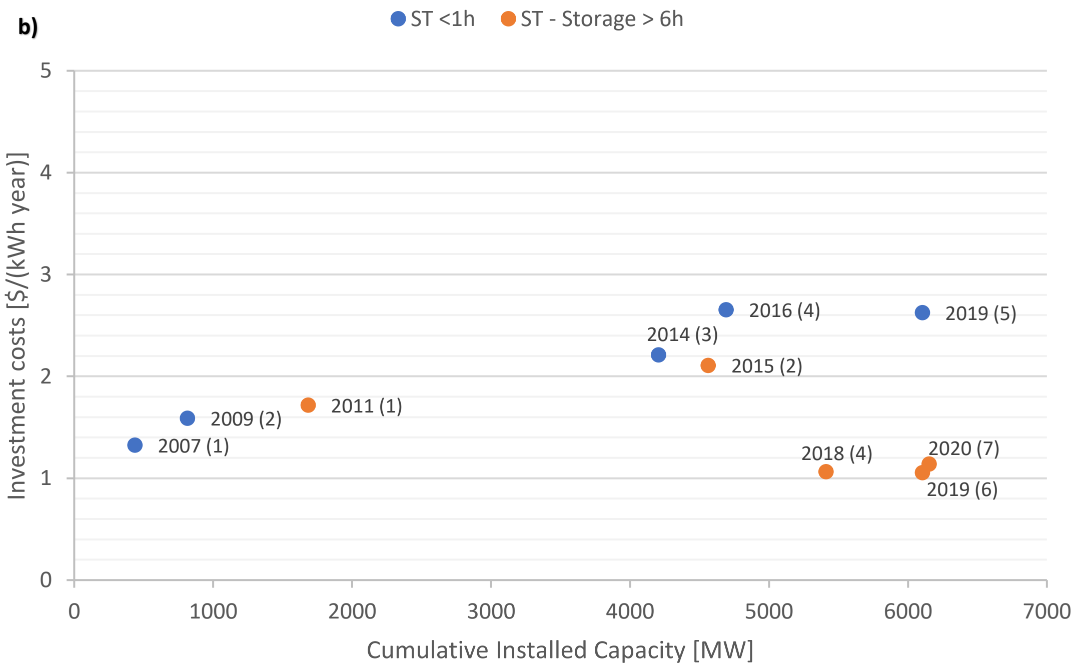


Figure 2. Investment costs development for (a) parabolic trough and (b) solar tower, given in 2019 US$. A distinction between plants by storage capacity is made. Data points represent yearly averages. The years on each data point indicate when the installed capacity was reached and the numbers in brackets indicate the number of stations of its kind existing by each year. Personal elaboration. Supplementary data associated with these figures can be found in Table 12 and Table 13 in Appendix A.

However, it is found a common trend for solar tower plants with thermal storage and parabolic trough projects. Hence, for this work, the same learning rate is considered for CSP projects using parabolic trough and solar tower technology, with or without thermal storage. This is shown in Figure 3.

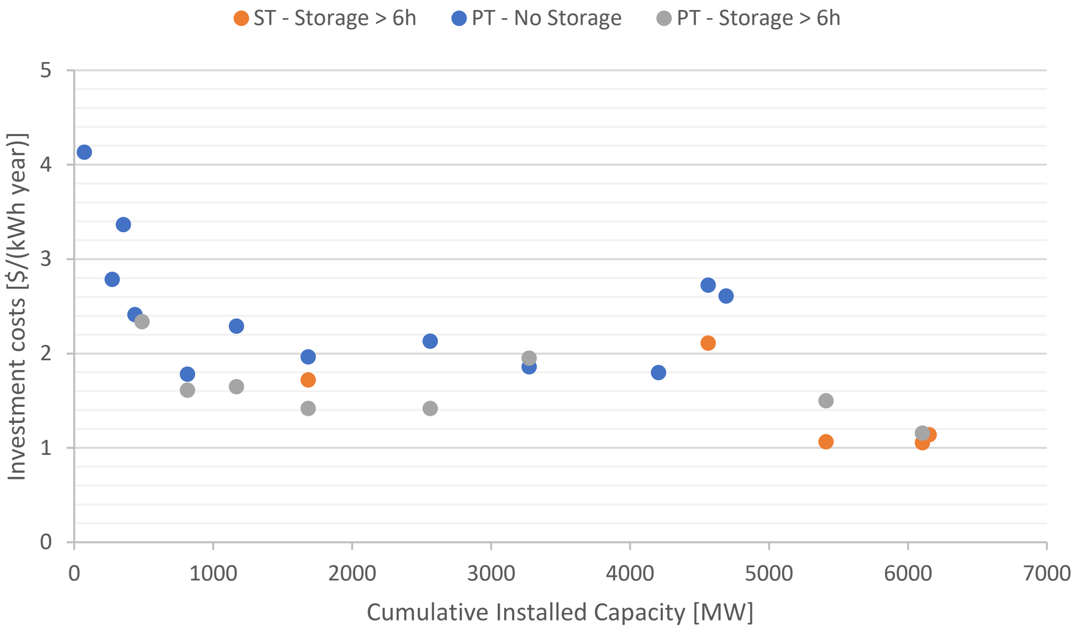


Figure 3. Investment costs development for CSP, given in 2019 US$. This table combines the values previously plotted in Figure 2.a and 2.b.

Finally, the learning curve shows the development of the global average CSP investment cost per yearly expected electricity generation from 1985 to 2020. It describes a learning rate of 16% (Equations 1 and 2 in the Methodology section) with a good fit (R^2 = 0.85). This means that the investment cost per unit of electricity produced annually is reduced a 16% per cumulative doubling of installed capacity. Figure 4 depicts the learning curve for CSP plants.

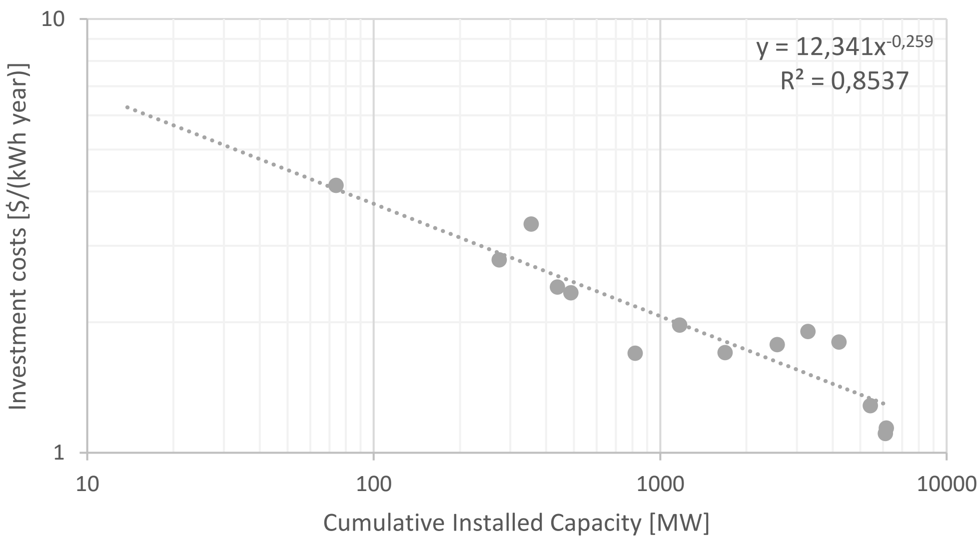


Figure 4. Costs development and fitted learning curve for CSP plants in log-log space, given in 2019 US$. Each point is the average of all stations entering into operation in that year. Personal elaboration. Supplementary data associated with this table can be found in Table 12 and Table 13 in Appendix A.

This study suggests a learning rate for CSP equal to 16%. This value shows that including the recent development of new CSP plants in the experience curve, the learning rate obtained is higher than previously assumed (Carpenter et al., 1999; Hernández-Moro & Martínez-Duart, 2013; Taylor et al., 2007). Hence, the potential for this technology could be considered more attractive than previously suggested.

In addition, considering the product definition of the dependent variable as the investment costs per unit of electricity generated instead of the investment cost per unit of installed capacity seems to capture not only the improvements in the manufacturing phase but also those in operation. The learning rate obtained here is applicable to the different CSP alternatives in a global scale. Table 3 presents a summary of the learning rates for CSP found in literature.

Table 3. Comparison between the learning rate found in this work and those found in the literature for concentrated solar thermal power (CSP) plants. Adapted from Samadi (2018).

Reference	Geographical domain	Experience	Costs or prices	Period	Learning rate (%)	R^2	Additional information
(Carpenter et al., 1999)	USA	Installed capacity	Investment costs per unit of installed capacity	1984-1990	12	n.s.	
(Taylor et al., 2007)	USA	Installed capacity	Investment costs per unit of installed capacity	1985-1991	3	0.12	
	USA	Electricity generation	O&M costs	1992-1998	35	0.93	
(Hernández-Moro & Martínez-Duart, 2013)	Global	Installed capacity	Investment costs per unit of installed capacity	1984-2010	11	n.s.	
(Pietzcker et al., 2014)	Global	Installed capacity	Investment costs per unit of installed capacity	2002-2013	10	n.s.	Additional independent variable: Plant configuration (size of the solar field and thermal storage)
(Platzer & Dinter, 2016)	Spain (parabolic trough)	Installed capacity	Investment costs per unit of installed capacity	2006-2011	16	n.s.	Additional independent variable: Plant configuration (size of the solar field and thermal storage)
(Lilliestam et al., 2017)	Global	Installed capacity	Investment costs per unit of installed capacity	1984-2018	18	n.s.	Discontinuous curve. Learning rate derived from different periods with separated learning rates
This work	Global	Installed capacity	Investment costs per unit of electricity generated	1984-2020	16	0.85	

3.2. Production recipe and supply chain structure

In this section, it is determined the distribution of the monetary investments on CSP plants to the different economic sectors. First, this work collects data for the structure of investment of different existing CSP projects. Then, this information is processed and analysed to obtain the CSP production recipe used here. This production recipe will be used in the following section to model the demand shock caused by the installation and operation of CSP projects.

The data analysed represent plants in different locations (mainly Spain and China) using both parabolic trough and solar tower technology. Since no significant changes in the investment structure were found regarding the location or the technology, the same production recipe is considered for CSP plants (parabolic trough and solar tower) in Europe and China. Additionally, it is assumed that the new plants built in the period 2020-2050 will have thermal storage capacity. This assumption is aligned with the current CSP trend and ensures the applicability of the data. In addition, the temporal distribution of the data allows us to analyse how the investment structure has changed over time. Since no significant changes are identified, for the purpose of this study, it will be assumed that the production recipe remains constant over time. Table 4 presents a summary of the data collected to build the CSP production recipe.

Table 4. Summary of the different CSP projects considered to build the CSP production recipe. Supplementary data associated with this table can be found in Table 16 in Appendix A.

Project	Technology	Country	Year	Storage [h]	Capacity [MW]	DNI [kWh/m2 year]	HTF	Reference
SEGS VI	PT	USA	1989	0	30	2725	Therminol	(Sargent & Lundy, 2003; W. Zhang, 2009)
Planta Solar 10	ST	Spain	2007	1	11	2076	Water	(Pitz-Paal et al., 2005)
Andasol-1 (AS-1)	PT	Spain	2008	7.5	50	2136	DowthermA	(Caldés et al., 2009)
Manchasol-1	PT	Spain	2011	7.5	50	2208	Diphenyl	(Corona et al., 2016)
Gemasolar	ST	Spain	2011	15	19.9	2072	Molten salt	(Caldés et al., 2009)
Delingha PT	PT	China	2018	9	50	1976	Thermal oil	(Asian Development Bank (ADB), 2013b, 2013a)
Shouhang Dunhuang Phase II	ST	China	2018	11	100	1654	Molten salt	(CSP Focus, 2018b; Zhifeng, 2019)
Hami	ST	China	2020	8	50	1789	Molten salt	(CSP Focus, 2018a)
Yumen	ST – Beam Down	China	Under construction	6	50	1800	Molten salt	(CSP Focus, 2019)

The data collected was mapped into the industrial categories defined for our IO table (Table 14 in Appendix A). This work takes a life cycle approach that considers the installation and the O&M to determine the impacts associated with CSP plants. Regarding the annual O&M costs, they are considered to be 3.17% of the total investment costs, based on the information presented in Table 16 in Appendix A. The dismantling of CSP plants is not studied due to lack of data regarding this phase. In addition, this phase is expected to have little influence in the results for this technology (Viebahn et al., 2011).

Table 5. Hypothesis for the distribution of the investment costs to the economic sectors included in the reduced IO table. Personal elaboration.

Sector code	Sector name	Value
8	Chemical	6.00%
9	Non-metallic mineral products	13.22%
10	Metal Products	16.23%
11	General and special machinery	25.98%
12	Electrical, electronic and measuring equipment	6.06%
15	Electricity	0.50%
16	Construction	16.64%
17	Services	13.85%
18	Transport	1.52%

Table 6. Hypothesis for the distribution of the O&M costs to the economic sectors included in the reduced IO table. Personal elaboration.

Sector code	Sector number	Value
8	Chemical	2.00%
9	Non-metallic mineral products	2.00%
12	Electrical, electronic and measuring equipment	2.00%
15	Electricity	26.00%
17	Services	68.00%

Finally, Table 5 and 6 describes the various sectors and weights composing the production recipe of CSP. Regarding the installation of CSP plants, amongst the nine sectors identified, the most relevant ones are “Non-metallic mineral products”, “Metal Products”, “General and special machinery”, “Construction” and “Services”. As observed in Table 5, the weight of each of these sectors lies between 13% and 26%. Table 6 describes the economic sectors satisfying this demand for the O&M. Here, five sectors are identified. The results indicate that most of the costs in this phase correspond to “Electricity and “Services” (26% and 68% of the O&M costs). As mentioned above, these production recipes will be considered to remain constant over the period 2020-2050 and will be applicable to parabolic trough and solar tower.

3.3. Concentrated solar power plants performance

In this section, the results given by the EEIO model are presented. Firstly, this work evaluates the impacts associated with the investments on CSP projects in China and Europe. Secondly, these impacts are further analysed assessing which sectors contribute the most. Finally, this section addresses the life cycle GHG and employment impacts of CSP plants in these two regions comparing them to other technologies.

First, the model evaluates the amount of CO_2eq emitted and the jobs created during the installation and O&M per M€ invested. These intensities are studied for different locations. Spain, Italy and Greece are considered the countries in Europe that fulfil the Direct Normal Irradiation (DNI) requirements for the proper operation of CSP plants (Estela et al., 2016) (See Figure 13 and 14 in Appendix B). Both the carbon intensity and the employment intensity for the three European countries are similar. Hence, the values for the European region will be considered the average of these three countries. In addition, it is also analysed the influence of the different assumptions for the vector of demand presented in the Methodology section. Regarding assumptions 2 and 4, which evaluated the influence of the level of aggregation in the results, they present values in the same range as assumptions 1 and 3. This provides consistency to the results obtained here and the level of aggregation in the IO framework used.

The results found that the carbon intensities for CSP plants are bigger in China than in Europe. Regarding the influence that the imports have in the result, increasing the imports needed for CSP (assumptions 3 and 4) in Europe causes a great increase in the carbon intensity. By contrast, increasing the imports in China (assumptions 3 and 4) brings a smaller carbon intensity. Figure 5 illustrates these results.

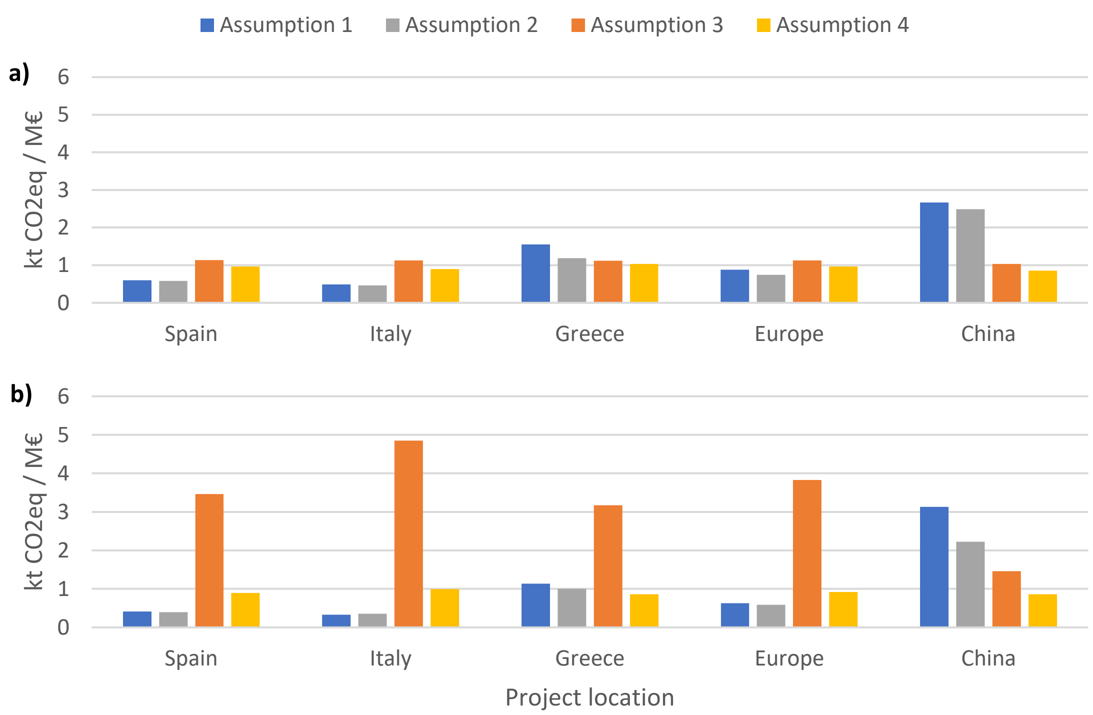


Figure 5. Total carbon impact per 2011 M€ invested on CSP plants. (a) Impact associated with the installation (b) Impact associated with the O&M. The different assumptions refer to those presented in Table 2 in the Methodology section. Personal elaboration. Supplementary data associated with this table can be found in Table 17 and Table 18 in Appendix A.

Regarding job creation, the model shows that the employment intensities for CSP plants are bigger in China than in Europe. Regarding the influence that the imports have in the result, increasing the imports needed for CSP (assumptions 3 and 4) in Europe causes a higher employment intensity. By contrast, increasing the imports in China brings a slightly smaller employment intensity. These results are shown in Figure 6.

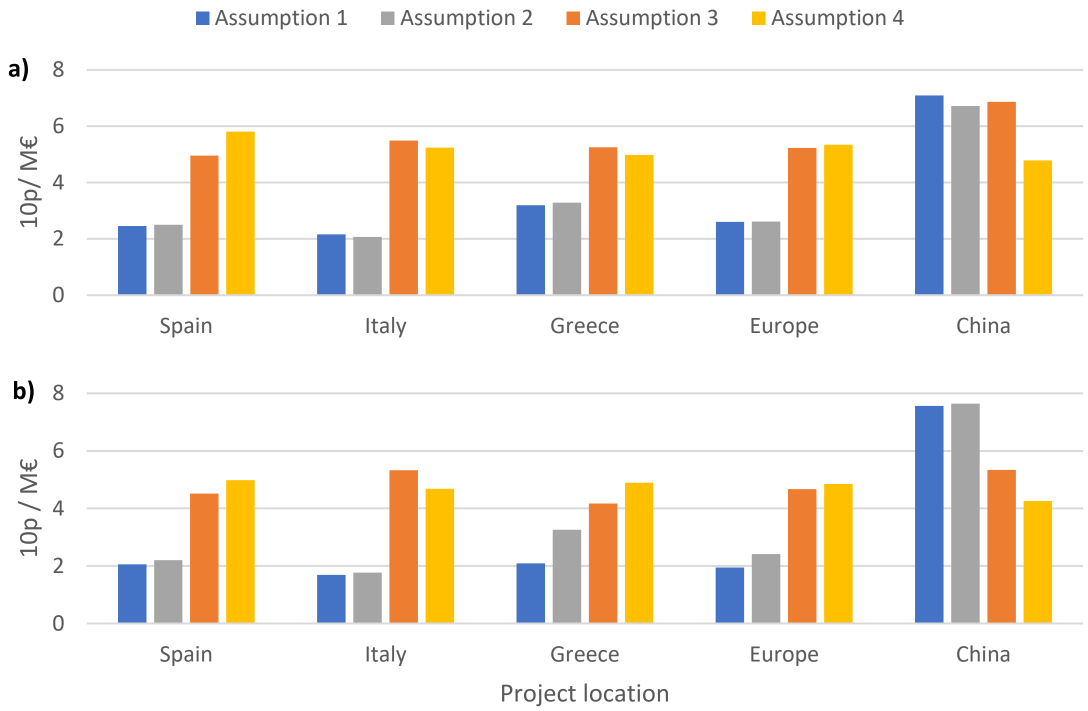


Figure 6. Total employment impact per 2011 M€ invested on CSP plants. (a) Impact associated with the installation (b) Impact associated with the O&M. The different assumptions refer to those presented in Table 2 in the Methodology section. Personal elaboration. Supplementary data associated with this table can be found in Table 19 and Table 20 in Appendix A.

It can be concluded that both the carbon intensity and the employment intensity for the installation and the O&M are higher in China than in Europe. The values that will be used in further calculations are the average of assumptions 1 and 3. Table 7 summarizes the results obtained in the model.

Table 7. Summary of the results obtained. Personal elaboration.

Impact	Unit	Europe	China
GHG - Installation	kt CO_2eq/M€	1.00	1.85
GHG – O&M	kt CO_2eq/M€	2.23	2.29
Employment – Installation	10p/M€	3.92	6.98
Employment – O&M	10p/M€	3.31	6.45

-

The results presented are further analysed to study how the different demand items contribute to the total impacts. In addition, a hotspot analysis identifying in which sectors impacts occur is presented in Table 25-28 in Appendix A.

Figure 7 represent the contribution of the demand from different sectors to the total carbon impact of CSP plants lifecycle. It shows the relevant role in the total carbon impact during the installation phase of the demand caused by non-metallic mineral products, metal products, construction and machinery. Regarding the O&M, Figure 8.b clearly illustrates the main role played by the electricity demanded. In addition, no significant difference is identified between the Chinese economic structure and the European one.

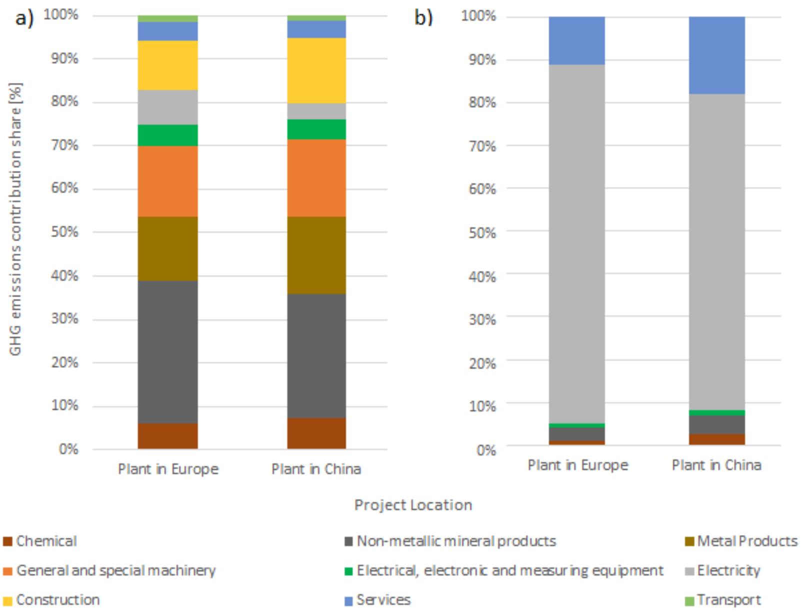


Figure 7. Contribution of the demand from different sectors to the total carbon impact of CSP plants lifecycle: (a) installation (b) O&M. Personal elaboration. Supplementary data associated with this table can be found in Table 21 and Table 22 in Appendix A.

Figure 8 shows the contribution of the demand from different sectors to the total employment impact of CSP plants lifecycle. It describes the relevant role in the total employment impact during the installation phase of the demand caused by non-metallic mineral products, metal products and construction. In addition, it can be highlighted how the contribution of the general and special machinery plays a greater role in the creation of jobs than in the emission of GHG. Regarding the O&M, Figure 8.b clearly illustrates the main role played by the services demanded. Finally, as in Figure 8, it was not possible to identify any significant difference between the Chinese economic structure and the European one.

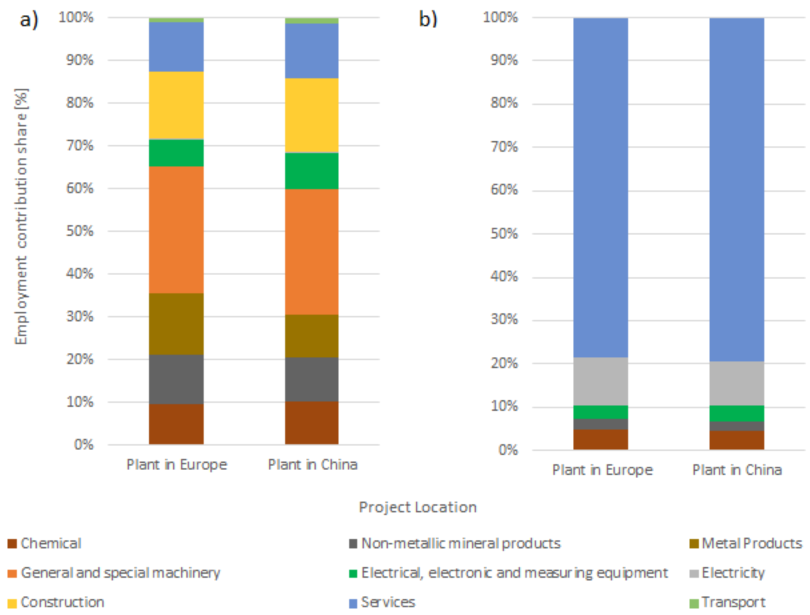


Figure 8. Contribution of the demand from different sectors to the total employment impact of CSP plants lifecycle: (a) installation (b) O&M. Personal elaboration. Supplementary data associated with this table can be found in Table 23 and Table 24 in Appendix A.

Finally, the previous results are converted to represent the impact per unit of electricity generated. This is done linking the intensities to the investment costs previously calculated and then using Equation 10. Most studies present their results using this unit. Hence, this conversion facilitates the comparison of CSP with other technologies. In addition, most LCA studies only assess the impacts per unit of electricity generated, not reporting separately the installation phase and O&M (Yuan et al., 2018).

$$Impact\ intensity = \frac{Installation\ impact[unit]}{Yearly\ Generation\ [kWh]}/Lifespan + \frac{Yearly\ O\&M\ Impact[unit]}{Yearly\ Generation\ [kWh]} \quad [10]$$

A lifespan of 25 years is assumed (Corona et al., 2016). The dismantling of CSP plants is not studied due to lack of data regarding this phase. In addition, this phase is expected to have little influence in the results for this technology (Viebahn et al., 2011)

Table 8. Life cycle GHG and employment impacts from CSP plants in Europe and China. Reference year is 2020. Personal elaboration.

Impact	Value	Unit	Europe	China
GHG	Average	gCO_2eq/kWh	99.76	129.65
	Range	gCO_2eq/kWh	26 - 184	54 - 181
Employment	Average	Jobs/GWh	2.28	4.23
	Range	Jobs/GWh	1.21 - 3.40	2.85 - 4.60

It is concluded that GHG emissions during the lifecycle of CSP projects amounts to 26-184 gCO_2eq/kWh for plants located in Europe and 54-181 gCO_2eq/kWh for those in China. Regarding the job creation, the results range between 1.21-3.40 job/GWh in Europe and 2.85-4.60 job/GWh. These ranges correspond to the different values derived from the four different assumptions considered. The results shown in Table 8 as Average correspond to the average of assumptions 1 and 3. These values are obtained considering CSP costs in 2020. A comparison of the CSP intensities to other technologies is provided in Table 29-32 in Appendix A. Here, it is found that the intensities for CSP are significantly greater regarding both emissions and job creation. It is possible to conclude that considering actual values, CSP presents positive values for job creation and has a good environmental performance in comparison to fossil technologies. However, CSP cannot be considered an environmentally beneficial alternative to produce electricity while mitigating climate change if compared to other low carbon technologies current performance.

3.4. Outlook for impacts of Concentrated Solar Power

In this section, it is analysed how the different energy scenarios presented in the methodology section will influence the impact of installation of CSP and its comparison with other energy technologies. Here, this work does not draw attention to the O&M. The rationale behind this choice is that, on the one hand, the data available for the installation work was more robust than the one for the O&M (Table 16 in Appendix A). In addition, the O&M costs ratio is similar across the several low carbon technologies studied (Table 33 in Appendix A). On the other hand, this facilitates the comparison of our results with the results obtained by Yuan et al. (2018) for other low carbon technologies, where a similar methodology is used. This choice does not affect the purpose of this section. The aim of this analysis is not to provide the most accurate prediction of the impacts associated with the different energy technologies, but to highlight the potential for improvement of CSP plants as they are in an early stage of deployment compared to other low carbon technologies.

The scenarios considered describe that by 2050 the cumulative installed capacity will increase by a 30% in Europe and by more than an 85% in China. According to the IEA – Current Scenario, the cumulative installed capacity of conventional power technologies such as natural gas and coal will keep growing, and so will do the carbon emissions. The IEA – New scenario also gives a secondary role to low carbon technologies. It predicts a great growth of natural gas power, and some expansion of wind and PV in Europe. Regarding coal, it remains stable in China while its share in Europe is gradually reduced. This allows to keep stable and to slightly reduce the carbon emissions (Figures 15-16 in Appendix B).

By contrast, the IEA – New Scenario and the NDRC – High RE scenario draw a future where not only the needed growth in installed capacity is satisfied with low carbon technologies, but the production previously dependant on coal is substituted by technologies with lower carbon impacts. It is in these two scenarios where it is observed a considerable boost in the deployment of CSP (Figure 9 and 10). Regarding the carbon impacts, achieving the targets proposed by these two scenarios would bring great reductions in the total GHG emitted (Figures 15-16 in Appendix B). Figures 17 and 18 in Appendix B show the projected growth in installed capacity of different energy technologies according to the scenarios studied.

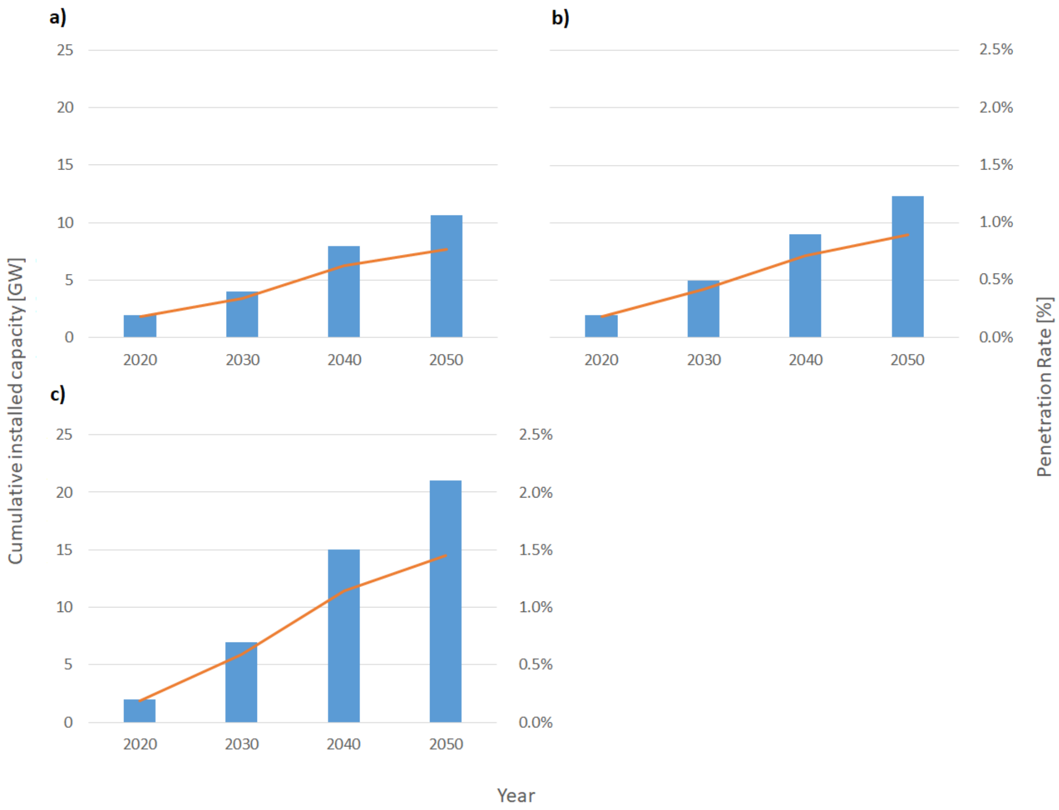


Figure 9. Different scenarios for growth in installed capacity of CSP in Europe. Stacked bars represent the cumulative installed capacity in Europe. Lines describe the CSP share in the regional total. (a) IEA - Current Scenario, (b) IEA - New, (c) IEA – 450. Personal elaboration based on the values from (International Energy Agency, 2016).

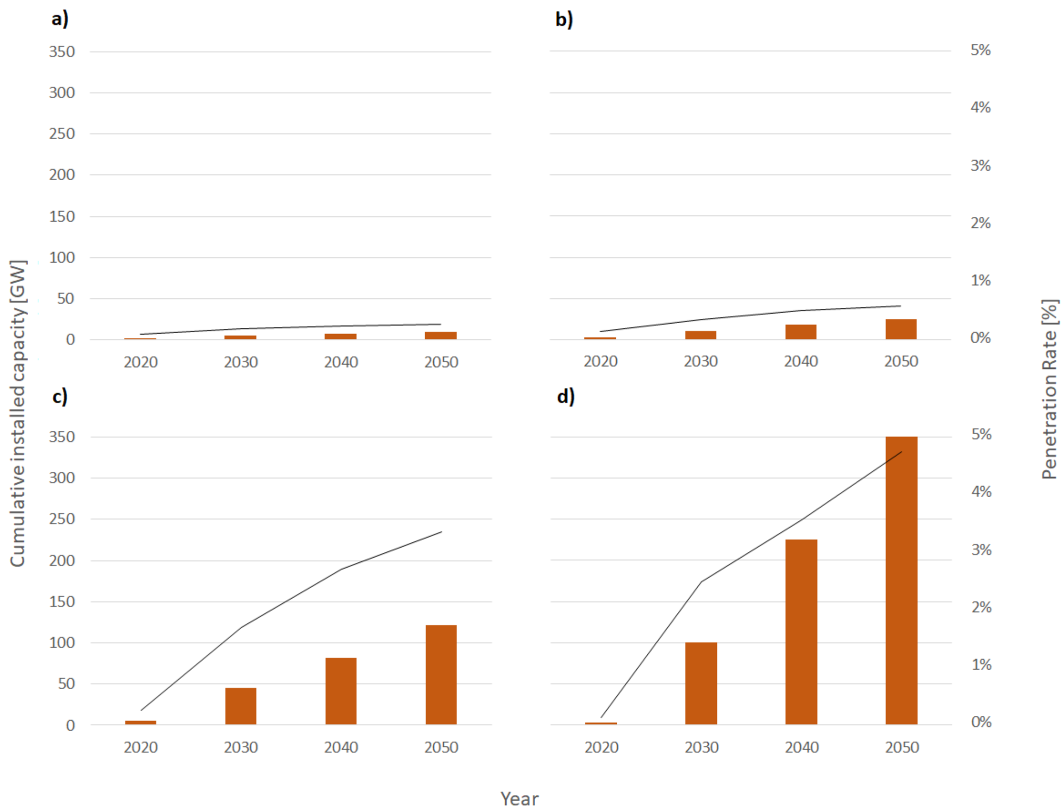


Figure 10. Different scenarios for growth in installed capacity of CSP in China. Stacked bars represent the cumulative installed capacity in China. Lines describe the CSP share in the regional total. (a) IEA - Current Scenario, (b) IEA - New, (c) IEA – 450, (d) NDRC – High RE. Personal elaboration based on the values from (International Energy Agency, 2016; National Development and Reform Commission, 2015).

Using the learning curve obtained in section 3.1, the impact of installation of CSP plants is evaluated under the different scenarios. It can be remarked the importance of the next decade in the evolution of this technology. The results indicate that the next ten years will be crucial for the deployment of this technology, and the learning curve that it experiences will determine whether it becomes competitive or not. Figure 11 shows the projected carbon intensities of investments on installation of CSP projects. These values are also compared with projected intensities for other technologies (Yuan et al., 2018). In the IEA-Current and IEA-New scenarios, CSP only reaches one doubling in cumulative capacity. As a consequence, costs reduction is not significant and CSP carbon intensity remains not competitive. IEA-450 and NDRC scenarios predicts that it will be required increased volumes of CSP electricity to satisfy the raising energy demand. The knowledge acquired causes significant investment cost reductions under these scenarios. This would also bring reduced carbon intensities of installation in Europe and China. These CSP intensities remain higher than those of other renewable technologies. However, the difference between them is significantly reduced. In addition, CSP intensities reach the range of nuclear energy, which is another low carbon technology able to provide dispatchable electricity.

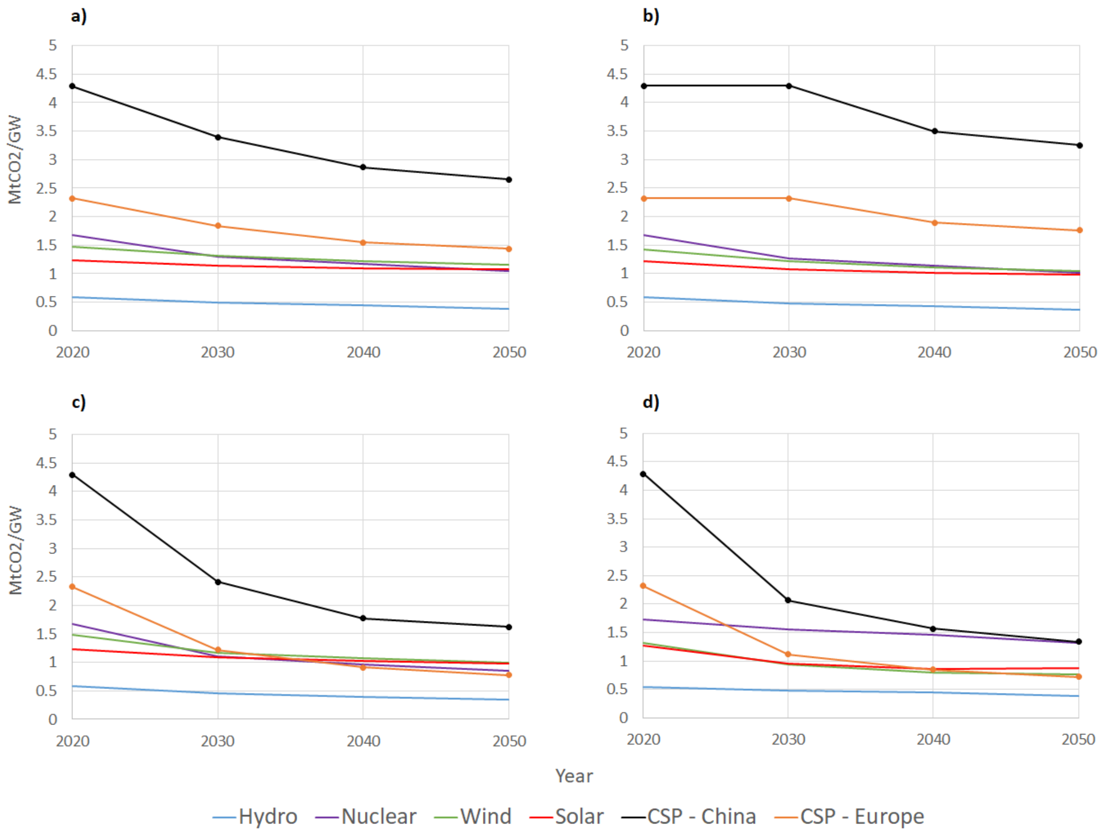


Figure 11. Evolution of the carbon intensity of different energy technologies based on global cumulative installed capacity under different scenarios. (a) IEA – Current scenario (b) IEA - New (c) IEA - 450 (d) NDRC – High RE Scenario. Personal elaboration. Results for CSP are based on the values obtained in this work. Results for other technologies are based on the values get from Yuan et al. (2018). Supplementary data can be found in Table 34 in Appendix A.

Similar findings to the GHG emissions are found regarding the job creation. The costs reduction in the next decade will significantly influence CSP employment intensity. It is important to highlight that the development of this technology brings a great opportunity for job creation. The growth in cumulative installed capacity would promote the creation of employment. This aspect could have a strong influence in political decision-making over the expansion of different energy alternatives (see Figures 20-23 in Appendix B). Figure 12 shows the projected employment intensity of investments on installation of CSP projects.

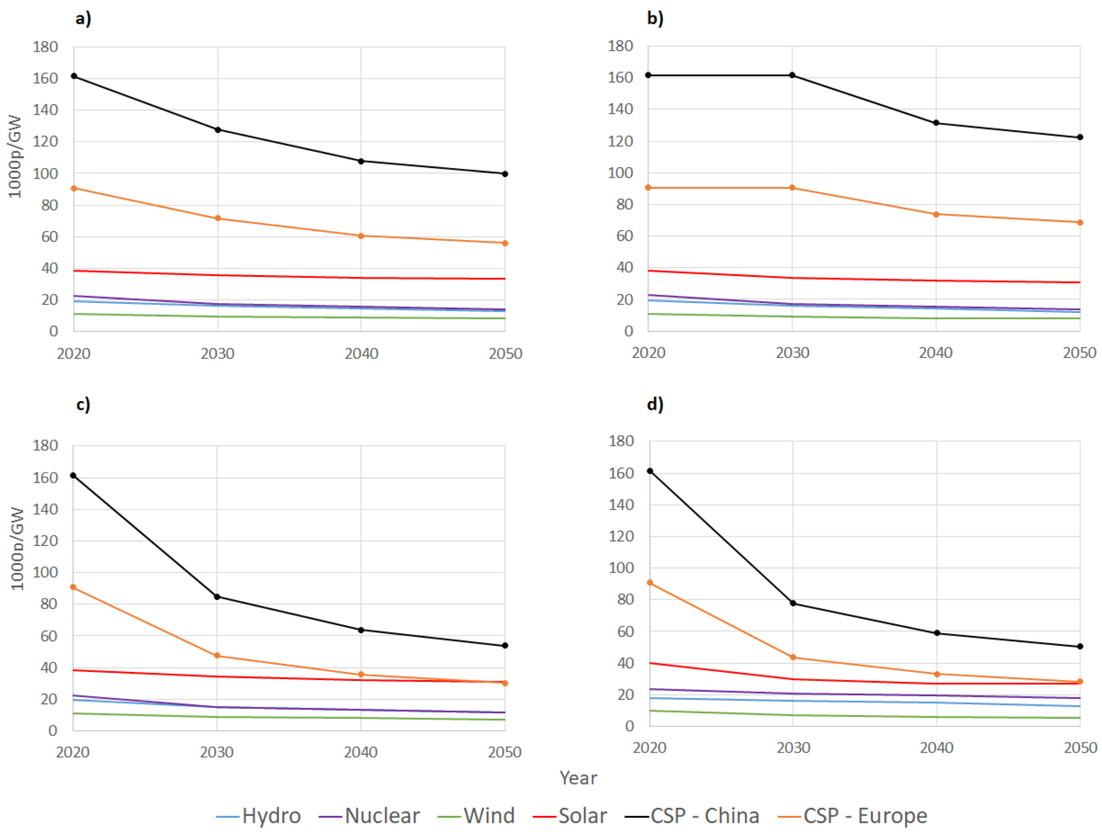


Figure 12. Evolution of the carbon intensity of different energy technologies based on global cumulative installed capacity under different scenarios. (a) IEA – Current scenario (b) IEA - New (c) IEA - 450 (d) NDRC – High RE Scenario. Personal elaboration. Results for CSP are based on the values obtained in this work. Results for other technologies are based on the values get from (Henriques et al., 2016; Wei et al., 2010; Yuan et al., 2018). Supplementary data can be found in Table 35 in Appendix A.

In this section, it is shown that current impacts associated with CSP plants are greater than those of other low carbon electricity technologies. CSP is in an early stage of its deployment and its installation requires high investments. This causes great impacts regarding both carbon emissions and jobs creation. However, the coming decades will be crucial for the competitiveness of CSP. This work shows that with a learning rate of 16%, the investment costs would evolve from 0.82 $€_{2011}$/kWh in 2020 to 0.21 $€_{2011}$/kWh in 2050 in those scenarios with a high penetration rate of CSP. In these scenarios, CSP carbon impact of installation can achieve values as low as the one for nuclear. In addition, the gap between this technology and wind and PV is greatly reduced. Regarding job creation, its intensity is also reduced. However, it remains the greatest for all the alternatives studied.

4. Discussion

Firstly, this section evaluates the results for the impacts of CSP and the learning rate. Then, this work introduces the main drivers and barriers influencing the deployment of this technology. Finally, this discussion closes with suggestions for further research that could address the limitations of the approach used.

In this thesis, the Environmentally Extended Input-Output (EEIO) model provides an assessment of the environmental and socio-economic impacts associated with CSP plants in Europe and China. The values obtained for GHG emissions and job creation are greater than for other low carbon technologies. This is caused by the high investment costs of CSP, a technology which is in the initial phase of its development. These findings suggest that current values do not allow CSP to compete with other renewable technologies regarding costs and emissions avoided. However, it can be remarked that CSP already shows a good environmental performance in comparison to fossil technologies (Viebahn et al., 2011)(see Table 29-32 in Appendix A). Although it is important to understand the limitations of the IO analysis when interpreting the results, the values obtained in this work are in the same range as other studies using IO analysis (Caldés et al., 2009; Corona et al., 2016; Henriques et al., 2016; Wei et al., 2010) and LCA (Corona et al., 2014; Klein & Rubin, 2013; Ko et al., 2018; Lechón et al., 2008; Viebahn et al., 2011; M. Zhang et al., 2012) (see Table 30 and Table 32 in Appendix A).

Regarding the experience curve, this work describes a learning rate for CSP of 16%. This suggests that the actual learning rate for this technology is higher than the values previously assumed (Carpenter et al., 1999; Hernández-Moro & Martínez-Duart, 2013; Pietzcker et al., 2014). This idea is aligned with recent findings in the literature (Lilliestam et al., 2017). Hence, the investment costs are significantly reduced causing low carbon intensities while significantly contributing to job creation in the scenarios with high penetration rate of CSP. This work only considers the endogenous technical change caused by the experience gained with increased cumulative capacity. As new low carbon technologies are deployed, the emissions of the electricity system will be reduced. Hence, causing a feedback loop effect on the carbon intensity of CSP. This effect can be expected to have a great influence, as the electricity sector was identified by the hotspot analysis (Tables 25-26 in Appendix A) as one of the main contributors in the installation and O&M. In general, the findings in this work show significant positive environmental and socio-economic impacts associated with the CSP deployment. This optimistic consideration of CSP is shared in recent articles about the future of CSP, suggesting potential for a large-scale and long-term deployment of this technology (del Río et al., 2018; del Río & Kiefer, 2018; Estela et al., 2016; Köberle et al., 2015; Labordena & Lilliestam, 2015; Lilliestam et al., 2018; Viebahn et al., 2011)

The main driver influencing the deployment of CSP in several scenarios is its potential for climate protection and its dispatchability. This technology presents the possibility of being integrated with thermal storage. The energy can be extracted from the storage system when there is no sun radiation enough to keep the plant operating, making it possible to meet both peak and baseload demand (Estela et al., 2016). Therefore, considering the growing trend to installed intermittent renewable energy sources, the value of CSP raises as it offers the possibility of adding stability to the grid. Regarding costs, CSP is still in an early stage of its development, having large cost reduction potential left (Lilliestam et al., 2018). This work suggests that this learning rate could be even greater than previously assumed. Furthermore, this technology is suitable for novel applications such as desalination, process heat and hybridisation with heat from other sources (e.g. biomass or fossil fuels)(Estela et al., 2016). According to innovation theory, these side applications may offer the opportunity to improve its performance, enhancing its deployment (del Río et al., 2018).

However, despite this complementarity with other renewable sources, direct competition with PV power is usually considered a barrier delaying the deployment of CSP (del Río et al., 2018). Nevertheless, the value of CSP will increase as the share of PV grows due to its contribution to grid balancing. Another barrier is the high investment costs and the uncertain cost reductions. CSP needs to be boosted in order to reduce the costs and the carbon intensity. Then, its evolution needs to match the expected cost reductions. However, some authors point that CSP costs reduction was lower than initially expected in past periods of its deployment (del Río et al., 2018; Lilliestam et al., 2017). If CSP deployment in the coming decades does not gain momentum, reducing costs at the expected pace, this industry may collapse and a potential technology able to contribute to the energy transition would be lost (Lilliestam et al., 2018).

Regarding the approach taken in this work, high employment intensity of CSP has been considered a positive aspect that can influence the political decision-makers in favour of this technology. However, as this is related to higher investment costs, greater electricity costs may have negative net effects in the economy. A net calculation of the effect of CSP in the two regions covering the period 2020-2050 may provide a better insight in the socio-economic consequences of CSP deployment. So far, the net calculations in Corona et al. (2016) for CSP in Spain covering the year 2011 were regarded as positive. Finally, it is important to remark that this work focuses on GHG emissions, overlooking other relevant environmental impacts associated with this technology such as land change, water demand and impact on landscape (del Río et al., 2018).

5. Conclusion

This study uses the concept of learning curve and an environmentally extended input-output (EEIO) model to answer the main research question:

What are the expected and potential environmental and socio-economic impacts of Concentrated Solar Power (CSP) in China and Europe 2020-2050?

To structure the report and answer the main research question, the following sub-questions were defined:

1. What is the historical and expected evolution of CSP penetration rate and performance?
2. What is the production recipe and supply chain structure of the existing CSP projects?
3. What is the predicted environmental and socio-economic impact of CSP plants?
4. How do these impacts compare to other technologies?
5. What are the main drivers and barriers influencing the potential deployment of this technology?

To answer the first sub-question, the information about the existing projects worldwide was processed and analysed. This study suggests a learning rate for CSP higher than previously assumed, equal to 16%. Hence, the potential for this technology could be considered more attractive than previously suggested. This work presents a one-factor learning curve where experience is the independent variable that explains cost changes over time. For this purpose, cumulative installed capacity is taken as a proxy for the experience gained. The y-variable in the learning curve equation is represented by the investment costs per unit of electricity generated. This decision is made as an attempt to capture not only the improvements in the manufacturing phase but also those in the operation phase.

The second sub-question is answered collecting information about the structure of investment of different projects. Table 5 and Table 6 describe the production recipe of installation and O&M of CSP plants. This data was collected from scientific publications and different reports and publications, and it is representative for plants in different locations (mainly Europe and China) using both parabolic trough and solar tower technology. Since no significant changes were identified regarding the time of installation, the location or the technology used, the production recipe is considered fixed.

The third sub-question is answered using the results obtained in the EEIO analysis. The carbon intensity of this energy technology is found to be 99.76 gCO_2eq/kWh and 129.65 gCO_2eq/kWh for plants located in Europe and China. Regarding job intensity, gross effects of CSP are found to be lower in Europe than in China as well (2.28 and 4.23 jobs/GWh). For the scenarios with a great CSP penetration rate (e.g. NDRC), costs are reduced from the actual value of 0.82 $€_{2011}$/kWh in 2020 to 0.21 $/kWh in 2050. The model used links the monetary flows related to the investment on CSP to the carbon and employment intensities through the IO framework. Hence, GHG emissions and job creation during the lifecycle of CSP plants will be reduced as well. For these high CSP penetration rate scenarios (e.g. NDRC), by 2050, carbon intensity for this technology will be 31.10 gCO_2eq/kWh in Europe and 40.42 gCO_2eq/kWh in China; and employment intensity will be 0.71 jobs/GWh in Europe and 1.32 jobs/GWh in China.

To answer the fourth sub-question, we yield a dynamic comparison between the results for CSP from the model built in this thesis and the results for other energy technologies obtained from the literature. It is found that CSP intensities are higher than the intensities of other low carbon technologies (Henriques et al., 2016; Wei et al., 2010; Yuan et al., 2018). However, it can be remarked that CSP already shows a good environmental performance in comparison to fossil technologies (Viebahn et al., 2011). Regarding the projections under the different scenarios, CSP has large cost reduction potential left as it is still in an early stage of its development. CSP carbon impact of installation can achieve values as low as the one for nuclear in those scenarios with a high penetration rate of CSP. In addition, the gap between this technology and wind and PV may be greatly reduced as well. Regarding job creation, its value would also be reduced. However, it remains the greater for all the alternatives studied.

Finally, the last sub-question is answered in the discussion section. The main driver influencing the deployment of CSP plants in several scenarios is its potential for climate protection and storage system. As PV and wind energy become more important, CSP plants with thermal storage are presented as a potential renewable solution to contribute to grid balancing. In addition, as the results in this work suggest, this technology is in an early stage and it has large cost reduction potential left. However, direct competition with PV and high costs are usually pointed as barriers delaying its deployment. If CSP deployment in the coming decades does not gain momentum, reducing costs at the expected pace, this industry may collapse and a potential technology able to contribute to the energy transition would be lost.

The results obtained in this work support the strong and long-term deployment of CSP. As the results show, CSP plants could have a positive impact regarding emissions reduction and job creation in the energy transition. They already present lower carbon emissions than fossil fuels and they have the potential of reducing the gap with other low carbon technologies. However, it will be the coming energy policies and whether this technology matches the expected evolution what will define the role of CSP in the future energy market.

This work suggests that the learning rate of CSP could be higher than previously assumed. This is done considering the recent developments in this technology and stressing the importance of the operation phase when building the experience curve. In addition, this thesis provides an extensive data collection for the structure of investments on CSP plants. This information can be useful for future studies analysing this technology. Regarding the geographical factors, China-specific values are considered. This can be considered valuable as the literature focuses in Europe and USA, the regions where the initial development of CSP took place. However, as China is expected to play a major role in the next phase of CSP development, covering this country could give more insights regarding the potential of CSP.

6. Bibliography

Aden, N., Marty, A., & Muller, M. (2010). *Comparative Life-cycle Assessment of Non-fossil Electricity Generation Technologies: China 2030 Scenario Analysis*.

Anderson, D. (2007). *Electricity Generation Costs and Investment Decisions: a review*. https://ukerc.rl.ac.uk/UCAT/PUBLICATIONS/Electricity_Generation_Costs_and_Investment_Decisions-A_Review.pdf

Asian Development Bank (ADB). (2013a). *Proposed Loan People's Republic of China: Qinghai Delingha Concentrated Solar Thermal Power Project - Initial Environmental Examination*. http://adb.org/sites/default/files/projdocs/2013/46058-002-rrp.pdf

Asian Development Bank (ADB). (2013b). *Proposed Loan People's Republic of China: Qinghai Delingha Concentrated Solar Thermal Power Project - Project Administration Manual*. http://adb.org/sites/default/files/projdocs/2013/46058-002-rrp.pdf

Bensebaa, F. (2011). Solar based large scale power plants: What is the best option? *Progress in Photovoltaics: Research and Applications*, *19*(2), 240–246. https://doi.org/10.1002/pip.998

Blanco, I., & Kjaer, C. (2009). Wind At Work. Wind energy and job creation in the EU. *European Wind Energy Association*. http://www.ewea.org/fileadmin/files/library/publications/reports/Wind_at_work.pdf

Bonou, A., Laurent, A., & Olsen, S. I. (2016). Life cycle assessment of onshore and offshore wind energy-from theory to application. *Applied Energy*, *180*, 327–337. https://doi.org/10.1016/j.apenergy.2016.07.058

Caldés, N., Varela, M., Santamaría, M., & Sáez, R. (2009). Economic impact of solar thermal electricity deployment in Spain. *Energy Policy*, *37*(5), 1628–1636. https://doi.org/10.1016/j.enpol.2008.12.022

Carpenter, S., Kemp, S., Robillard, P., & Whittaker, S. (1999). *Cost reduction study for solar thermal power plants*.

Chaanaoui, M., Vaudreuil, S., & Bounahmidi, T. (2016). Benchmark of Concentrating Solar Power Plants: Historical, Current and Future Technical and Economic Development. *Procedia Computer Science*, *83*, 782–789. https://doi.org/10.1016/j.procs.2016.04.167

Chang, Y., Huang, R., Ries, R. J., & Masanet, E. (2015). Life-cycle comparison of greenhouse gas emissions and water consumption for coal and shale gas fired power generation in China. *Energy*, *86*, 335–343. https://doi.org/10.1016/j.energy.2015.04.034

Chen, W., Hong, J., Yuan, X., & Liu, J. (2016). Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: A case study in China. *Journal of Cleaner Production*, *112*, 1025–1032. https://doi.org/10.1016/j.jclepro.2015.08.024

Corona, B., Rúa, C. de la, & San Miguel, G. (2016). Socio-economic and environmental effects of concentrated solar power in Spain: A multiregional input output analysis. *Solar Energy Materials and Solar Cells*, *156*, 112–121. https://doi.org/10.1016/j.solmat.2016.03.014

Corona, B., San Miguel, G., & Cerrajero, E. (2014). Life cycle assessment of concentrated solar power (CSP) and the influence of hybridising with natural gas. *International Journal of Life Cycle Assessment*, *19*(6), 1264–1275. https://doi.org/10.1007/s11367-014-0728-z

CSP Focus. (2018a). *CPECC Hami 50MW Tower CSP Project*.

http://www.cspfocus.cn/en/report/detail_74.htm

CSP Focus. (2018b). *Shouhang Dunhuang 100MW Molten Salt Tower CSP Plant*. http://www.cspfocus.cn/en/report/detail_43.htm

CSP Focus. (2019). *Yumen Xinneng 50MW Molten Salt Tower CSP Project*. http://www.cspfocus.cn/en/report/detail_39.htm

De Feo, G., Forni, M., Petito, F., & Renno, C. (2016). Life cycle assessment and economic analysis of a low concentrating photovoltaic system. *Environmental Technology (United Kingdom)*, *37*(19), 2473–2482. https://doi.org/10.1080/09593330.2016.1152308

De Wild-Scholten, M. J. (2013). Energy payback time and carbon footprint of commercial photovoltaic systems. *Solar Energy Materials and Solar Cells*, *119*, 296–305. https://doi.org/10.1016/j.solmat.2013.08.037

del Río, P., & Kiefer, C. P. (2018). Analysis of the Drivers and Barriers to the Market Uptake of CSP in the EU. *Deliverable 4.3, MUSTEC Project*, *764626*.

del Río, P., Peñasco, C., & Mir-Artigues, P. (2018). An overview of drivers and barriers to concentrated solar power in the European Union. *Renewable and Sustainable Energy Reviews*, *81*, 1019–1029. https://doi.org/10.1016/j.rser.2017.06.038

Dones, R., Bauer, C., Bolliger, R., Burger, B., Heck, T., Röder, A., Institut, P. S., Emmenegger, M. F., Frischknecht, R., Jungbluth, N., & Tuchschmid, M. (2007). Life Cycle Inventories of Energy Systems : Results for Current Systems in Switzerland and other UCTE Countries. Ecoinvent report No. 5. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories. *Ecoinvent Report*, *5*.

EPIA, & Greenpeace. (2008). *Solar Electricity for over One Billion People and Two Million Jobs by 2020*. 1–76. https://www.globalccsinstitute.com/archive/hub/publications/142118/solar-generation-v-2008-solar-electricitschola-one-billion-people-two-million-jobs-2020.pdf

Estela, Greenpeace, & SolarPACES. (2016). *Solar Thermal Electricity - Global Outlook 2016*. 114. https://www.inship.eu/docs/General 10 ESTELA SolarPACES Solar Thermal Electricity Global Outlook 2016.pdf

European Small Hydropower Association. (n.d.). *State of the art of small hydropower in EU - 25. Advantages of Small Hydropower*. https://www.bt-projects.com/wp-content/uploads/documents-public/Rivers/ESHA-2010-State-of-the-art-of-Small-Hydropower-in-EU-25.pdf

EUROSTAT. (2020). *GDP Deflator*. https://ec.europa.eu/eurostat/tgm/table.do?tab=table&plugin=1&language=en&pcode=teina110

EXIOBASE. (2020). *About EXIOBASE*. https://www.exiobase.eu/index.php/about-exiobase

Feng, K., Hubacek, K., Siu, Y. L., & Li, X. (2014). The energy and water nexus in Chinese electricity production: A hybrid life cycle analysis. *Renewable and Sustainable Energy Reviews*, *39*, 342–355. https://doi.org/10.1016/j.rser.2014.07.080

Foran, B., Lenzen, M., Dey, C., & Bilek, M. (2005). Integrating sustainable chain management with triple bottom line accounting. *Ecological Economics*, *52*(2), 143–157. https://doi.org/10.1016/j.ecolecon.2004.06.024

Forex, U. (2020). *Yearly Average Rates*. https://www.ofx.com/en-us/forex-news/historical-exchange-rates/

Fu, Y., Liu, X., & Yuan, Z. (2015). Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China. *Journal of Cleaner Production*, *86*, 180–190. https://doi.org/10.1016/j.jclepro.2014.07.057

Garrett-Peltier, H. (2017). Green versus brown: Comparing the employment impacts of energy efficiency, renewable energy, and fossil fuels using an input-output model. *Economic Modelling*, *61*, 439–447. https://doi.org/10.1016/j.econmod.2016.11.012

Guezuraga, B., Zauner, R., & Pölz, W. (2012). Life cycle assessment of two different 2 MW class wind turbines. *Renewable Energy*, *37*(1), 37–44. https://doi.org/10.1016/j.renene.2011.05.008

Handayani, K., Krozer, Y., & Filatova, T. (2017). Trade-offs between electrification and climate change mitigation: An analysis of the Java-Bali power system in Indonesia. *Applied Energy*, *208*, 1020–1037. https://doi.org/10.1016/j.apenergy.2017.09.048

Heavner, B., Churchill, S., & Trust, C. C. (2002). Renewables work: job growth from renewable energy development in California. *CALPIRG Charitable Trust*. https://www.policyarchive.org/handle/10207/5556

Henriques, C. O., Coelho, D. H., & Cassidy, N. L. (2016). Employment impact assessment of renewable energy targets for electricity generation by 2020—An IO LCA approach. *Sustainable Cities and Society*, *26*, 519–530. https://doi.org/10.1016/j.scs.2016.05.013

Hernández-Moro, J., & Martínez-Duart, J. M. (2013). Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution. *Renewable and Sustainable Energy Reviews*, *20*, 119–132. https://doi.org/10.1016/j.rser.2012.11.082

Hou, G., Sun, H., Jiang, Z., Pan, Z., Wang, Y., Zhang, X., Zhao, Y., & Yao, Q. (2016). Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. *Applied Energy*, *164*, 882–890. https://doi.org/10.1016/j.apenergy.2015.11.023

International Energy Agency. (2016). *World Energy Outlook 2016*. https://webstore.iea.org/download/direct/202

International Energy Agency. (2019). *Solar*. https://www.iea.org/fuels-and-technologies/solar

Klein, S. J. W., & Rubin, E. S. (2013). Life cycle assessment of greenhouse gas emissions, water and land use for concentrated solar power plants with different energy backup systems. *Energy Policy*, *63*, 935–950. https://doi.org/10.1016/j.enpol.2013.08.057

Ko, N., Lorenz, M., Horn, R., Krieg, H., & Baumann, M. (2018). Sustainability Assessment of Concentrated Solar Power (CSP) Tower Plants - Integrating LCA, LCC and LCWE in One Framework. *Procedia CIRP*, *69*, 395–400. https://doi.org/10.1016/j.procir.2017.11.049

Köberle, A. C., Gernaat, D. E. H. J., & van Vuuren, D. P. (2015). Assessing current and future techno-economic potential of concentrated solar power and photovoltaic electricity generation. *Energy*, *89*, 739–756. https://doi.org/10.1016/j.energy.2015.05.145

Koornneef, J., van Keulen, T., Faaij, A., & Turkenburg, W. (2008). Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2. *International Journal of Greenhouse Gas Control*, *2*(4), 448–467. https://doi.org/10.1016/j.ijggc.2008.06.008

Koroneos, C. J., Piperidis, S. A., Tatatzikidis, C. A., & Rovas, D. C. (2008). Life Cycle Assessment of a Solar Thermal Concentrating System. *WSEAS Conferences in Spain*. https://pdfs.semanticscholar.org/af9d/31f5147b5abb43c5c417340ad8690d2645f1.pdf

Labordena, M., & Lilliestam, J. (2015). Cost and Transmission Requirements for Reliable Solar Electricity from Deserts in China and the United States. *Energy Procedia*, *76*, 77–86. https://doi.org/10.1016/j.egypro.2015.07.850

Lamnatou, C., & Chemisana, D. (2017). Concentrating solar systems: Life Cycle Assessment (LCA) and environmental issues. *Renewable and Sustainable Energy Reviews*, *78*, 916–932. https://doi.org/10.1016/j.rser.2017.04.065

Lechón, Y., De La Rúa, C., & Sáez, R. (2008). Life cycle environmental impacts of electricity production by solarthermal power plants in Spain. *Journal of Solar Energy Engineering, Transactions of the ASME*, *130*(2), 0210121–0210127. https://doi.org/10.1115/1.2888754

Lecointe, C., Lecarpentier, D., Maupu, V., Le Boulch, D., Richard, R., Garzenne, C., & Bachmann, T. M. (2007). *Final report on technical data, costs and life cycle inventories of nuclear power plants*. 1–62. http://www.needs-project.org/RS1a/RS1a D14.2 Final report on nuclear.pdf

Li, Z., Du, H., Xiao, Y., & Guo, J. (2017). Carbon footprints of two large hydro-projects in China: Life-cycle assessment according to ISO/TS 14067. *Renewable Energy*, *114*, 534–546. https://doi.org/10.1016/j.renene.2017.07.073

Liang, X., Wang, Z., Zhou, Z., Huang, Z., Zhou, J., & Cen, K. (2013). Up-to-date life cycle assessment and comparison study of clean coal power generation technologies in China. *Journal of Cleaner Production*, *39*, 24–31. https://doi.org/10.1016/j.jclepro.2012.08.003

Lilliestam, J., Barradi, T., Caldés, N., Gomez, M., Hanger, S., Kern, J., Komendantova, N., Mehos, M., Hong, W. M., Wang, Z., & Patt, A. (2018). Policies to keep and expand the option of concentrating solar power for dispatchable renewable electricity. *Energy Policy*, *116*, 193–197. https://doi.org/10.1016/j.enpol.2018.02.014

Lilliestam, J., Labordena, M., Patt, A., & Pfenninger, S. (2017). Empirically observed learning rates for concentrating solar power and their responses to regime change. *Nature Energy*, *2*(7). https://doi.org/10.1038/nenergy.2017.94

Lilliestam, J., & Thonig, R. (2019). *CSP.guru*. https://doi.org/10.5281/zenodo.3466625

Louwen, A., van Sark, W. G. J. H. M., Schropp, R. E. I., Turkenburg, W. C., & Faaij, A. P. C. (2015). Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs. *Progress in Photovoltaics: Research and Applications*, *23*(10), 1406–1428. https://doi.org/10.1002/pip

Lu, H., Guo, L., & Zhang, Y. (2019). Oil and gas companies' low-carbon emission transition to integrated energy companies. *Science of the Total Environment*, *686*, 1202–1209. https://doi.org/10.1016/j.scitotenv.2019.06.014

Lu, L., & Yang, H. X. (2010). Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong. *Applied Energy*, *87*(12), 3625–3631. https://doi.org/10.1016/j.apenergy.2010.06.011

Martínez, E., Sanz, F., Pellegrini, S., Jiménez, E., & Blanco, J. (2009). Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *International Journal of Life Cycle Assessment*, *14*(1), 52–63. https://doi.org/10.1007/s11367-008-0033-9

National Development and Reform Commission. (2015). *China 2050 High Renewable Energy*

Penetration Scenario and Roadmap study. http://www.efchina.org/Attachments/Report/report-20150420/China-2050-High-Renewable-Energy-Penetration-Scenario-and-Roadmap-Study-Executive-Summary.pdf

National Renewable Energy Laboratory. (n.d.). *Concentrating Solar Power Projects*. https://solarpaces.nrel.gov/by-country

Neves, A., Blondel, L., Brand, K., Hendel Blackford, S., Calvete, S. R., Iancu, A., Melica, G., Koffi, B., Zancanella, P., & Kona, A. (2016). *The Covenant of Mayors for Climate and Energy Reporting Guidelines*. *0*, 1–69. https://doi.org/10.2790/586693

Odeh, N. A., & Cockerill, T. T. (2008). Life cycle analysis of UK coal fired power plants. *Energy Conversion and Management*, *49*(2), 212–220. https://doi.org/10.1016/j.enconman.2007.06.014

Pietzcker, R. C., Stetter, D., Manger, S., & Luderer, G. (2014). Using the sun to decarbonize the power sector: The economic potential of photovoltaics and concentrating solar power. *Applied Energy*, *135*, 704–720. https://doi.org/10.1016/j.apenergy.2014.08.011

Pitz-Paal, R., Dersch, J., & Milow, B. (2005). European concentrated solar thermal road-mapping – roadmap document. *Concrete*, 142. https://doi.org/10.1049/ess:20030508

Platzer, W. J., & Dinter, F. (2016). A learning curve for solar thermal power. *AIP Conference Proceedings*, *1734*. https://doi.org/10.1063/1.4949254

Ram, M., Aghahosseini, A., & Breyer, C. (2020). Job creation during the global energy transition towards 100% renewable power system by 2050. *Technological Forecasting and Social Change*, *151*, 119682. https://doi.org/10.1016/j.techfore.2019.06.008

Samadi, S. (2018). The experience curve theory and its application in the field of electricity generation technologies – A literature review. *Renewable and Sustainable Energy Reviews*, *82*, 2346–2364. https://doi.org/10.1016/j.rser.2017.08.077

Sargent & Lundy. (2003). *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts. , Sargent and Lundy Consulting Group Chicago, Illinois. NREL/SR-550-34440*.

Simons, G., & Peterson, T. (2001). California renewable technology market and benefits assessment. *Electric Power Research Institute (EPRI) and California Energy Commission (CEC)*. https://www.epri.com/research

Singh, V., & Fehrs, J. E. (2001). The work that goes into renewable energy. *Renewable Energy Policy Project*, *13*, 27. https://www.globalurban.org/The_Work_that_Goes_into_Renewable_Energy.pdf

SolarGIS. (2020). *Bankable solar data for better decisions*. https://solargis.com/

Taylor, M., Nemet, G., Colvin, M., Begley, L., Wadia, C., & Dillavou, T. (2007). Government actions and innovation in clean energy technologies : the cases of photovoltaic cells, solar thermal electric power, and solar water heating : PIER project report. *California Climate Change Center Report Series*. https://seeds.lbl.gov/wp-content/uploads/sites/29/2018/02/CEC-500-2007-012.pdf

Turconi, R., Boldrin, A., & Astrup, T. (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renewable and Sustainable Energy Reviews*, *28*, 555–565. https://doi.org/10.1016/j.rser.2013.08.013

Vattenfall. (2010). *Environemtal Product Declaration Ringhals Nuclear Power Plant*.

Veiga, J. P. S., Malik, A., Lenzen, M., Ferreira Filho, J. B. de S., & Romanelli, T. L. (2018). Triple-bottom-line assessment of São Paulo state's sugarcane production based on a Brazilian multi-regional input-output matrix. *Renewable and Sustainable Energy Reviews*, *82*, 666–680. https://doi.org/10.1016/j.rser.2017.09.075

Viebahn, P., Lechon, Y., & Trieb, F. (2011). The potential role of concentrated solar power (CSP) in Africa and Europe-A dynamic assessment of technology development, cost development and life cycle inventories until 2050. *Energy Policy*, *39*(8), 4420–4430. https://doi.org/10.1016/j.enpol.2010.09.026

Viebahn, P., Nitsch, J., Fischedick, M., Esken, A., Schüwer, D., Supersberger, N., Zuberbühler, U., & Edenhofer, O. (2007). Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany. *International Journal of Greenhouse Gas Control*, *1*(1), 121–133. https://doi.org/10.1016/S1750-5836(07)00024-2

Wang, C., Malik, A., Wang, Y., Chang, Y., Lenzen, M., Zhou, D., Pang, M., & Huang, Q. (2020). The social, economic, and environmental implications of biomass ethanol production in China: A multi-regional input-output-based hybrid LCA model. *Journal of Cleaner Production*, *249*, 119326. https://doi.org/10.1016/j.jclepro.2019.119326

Wei, M., Patadia, S., & Kammen, D. M. (2010). Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, *38*(2), 919–931. https://doi.org/10.1016/j.enpol.2009.10.044

Wiedmann, T. O., Suh, S., Feng, K., Lenzen, M., Acquaye, A., Scott, K., & Barrett, J. R. (2011). Application of hybrid life cycle approaches to emerging energy technologies - The case of wind power in the UK. *Environmental Science and Technology*, *45*(13), 5900–5907. https://doi.org/10.1021/es2007287

Yao, Y., Chang, Y., & Masanet, E. (2014). A hybrid life-cycle inventory for multi-crystalline silicon PV module manufacturing in China. *Environmental Research Letters*, *9*(11). https://doi.org/10.1088/1748-9326/9/11/114001

Yuan, R., Behrens, P., Tukker, A., & Rodrigues, J. F. D. (2018). Carbon overhead: The impact of the expansion in low-carbon electricity in China 2015–2040. *Energy Policy*, *119*, 97–104. https://doi.org/10.1016/j.enpol.2018.04.027

Zhang, M., Wang, Z., Xu, C., & Jiang, H. (2012). Embodied energy and emergy analyses of a concentrating solar power (CSP) system. *Energy Policy*, *42*, 232–238. https://doi.org/10.1016/j.enpol.2011.11.080

Zhang, Q., Karney, B., MacLean, H. L., & Feng, J. (2007). Life-cycle inventory of energy use and greenhouse gas emissions for two hydropower projects in China. *Journal of Infrastructure Systems*, *13*(4), 271–279. https://doi.org/10.1061/(ASCE)1076-0342(2007)13:4(271)

Zhang, W. (2009). *Concentrating Solar Power - State of the Art, Cost Analysis and Pre-Feasibility Study for the Implementation in China*. http://www.efchina.org/Attachments/Report/reports-efchina-20101222-2-en/Concentrating Solar Power - State of the Art, Cost Analysis and Pre-Feasibility Study for the Implementation in China.pdf

Zhifeng, W. (2019). *CSP Technology and Industry Development in China*. https://www.energy.gov/sites/prod/files/2019/04/f61/CSP Summit 2019 Panel 3 – CAS Wang.pdf

Appendix A. Tables

Table 9. Scenarios China.

Scenario	Year	Other	PV	Wind	Hydro	Nuclear	Oil	NG	Coal	CSP	Total Capacity [GW]	CSP (%)
IEA - Current Policies	2020	16	100	200	365	55	9	98	1069	2	1914	0.10%
	2030	26	167	312	430	106	9	165	1309	5	2529	0.20%
	2040	38	230	406	483	136	6	210	1472	7	2988	0.23%
	2050	49	296	512	544	180	5	270	1686	10	3551	0.27%
IEA - 450	2020	16	160	250	365	55	9	95	1015	5	1970	0.25%
	2030	37	411	533	459	158	9	149	861	45	2662	1.69%
	2040	61	624	713	514	223	5	197	607	82	3026	2.71%
	2050	83	862	962	595	313	4	249	420	121	3609	3.35%
IEA - New	2020	156	140	230	365	55	9	99	1040	3	2097	0.14%
	2030	346	317	406	447	112	9	158	1123	10	2928	0.34%
	2040	529	482	537	500	155	5	198	1137	18	3561	0.51%
	2050	717	655	698	572	207	4	251	1197	25	4326	0.59%
NDRC	2020	111	156	317	314	51	1	110	1083	1	2144	0.03%
	2030	169	949	1104	441	66	1	130	1052	100	4012	2.49%
	2040	317	1981	2092	472	78	1	173	972	225	6312	3.56%
	2050	527	2346	2397	554	100	1	220	887	350	7381	4.74%

Table 10. Scenarios Europe.

Scenario	Year	Other	PV	Wind	Hydro	Nuclear	Oil	NG	Coal	CSP	Total Capacity [GW]	CSP (%)
IEA - Current Policies	2020	46	114	183	157	121	39	229	172	2	1063	0.19%
	2030	53	134	241	165	97	19	329	129	4	1171	0.34%
	2040	62	146	282	170	89	12	411	95	8	1275	0.63%
	2050	70	163	334	177	70	0	505	55	11	1385	0.77%
IEA - 450	2020	47	120	187	157	125	38	219	164	2	1059	0.19%
	2030	59	161	292	169	123	18	255	98	7	1182	0.59%
	2040	83	195	381	176	125	11	272	55	15	1313	1.14%
	2050	99	234	481	186	124	0	302	0	21	1447	1.45%
IEA - New	2020	47	118	186	157	121	39	226	169	2	1065	0.19%
	2030	56	150	271	166	103	19	292	114	5	1176	0.43%
	2040	71	166	326	171	102	12	338	70	9	1265	0.71%
	2050	82	193	401	179	90	0	397	19	12	1372	0.90%

Table 11. Scenarios Global.

Scenario	Year	Other	PV	Wind	Hydro	Nuclear	Oil	NG	Coal	CSP	Total Capacity [GW]	CSP (%)
IEA - Current Policies	2020	18	424	621	1338	437	375	1875	2201	6	7294	0.08%
	2030	31	708	940	1571	488	300	2443	2617	24	9122	0.26%
	2040	56	991	1214	1770	529	264	3035	3030	50	10939	0.46%
	2050	73	1275	1518	1992	577	202	3612	3445	71	12763	0.55%
IEA - 450	2020	19	517	710	1348	449	367	1789	2094	6	7299	0.08%
	2030	52	1278	1572	1718	642	261	2010	1687	101	9321	1.08%
	2040	116	2108	2312	2057	820	211	2251	1194	337	11406	2.95%
	2050	159	2892	3133	2417	1008	124	2479	758	479	13449	3.56%
IEA - New	2020	18	481	670	1345	438	373	1844	2159	10	7338	0.14%
	2030	37	949	1119	1622	520	292	2262	2318	34	9153	0.37%
	2040	76	1405	1505	1848	606	254	2703	2437	76	10910	0.70%
	2050	102	1869	1933	2108	689	187	3129	2583	106	12706	0.83%
NDRC	2020	19	517	710	1348	449	367	1789	2094	6	7299	0.08%
	2030	52	1278	1572	1718	642	261	2010	1687	186	9406	1.98%
	2040	116	2108	2312	2057	820	211	2251	1194	550	11619	4.73%
	2050	159	2892	3133	2417	1008	124	2479	758	1010	13980	7.22%

Table 12. Data for the existing Parabolic Trough CSP plants.

Power_Station	Country	Year Opearational	Status	Capacity	Total Investment	Unit of Total Investment	Storage [h]	Expected generation [MWh/year]
Solar Electric Generating Station I (SEGS I)	USA	1984	Currently non-operational	13.8	62	M USD	3	16500
Solar Electric Generating Station II (SEGS II)	USA	1985	Currently non-operational	30	135	M USD	0	32500
Solar Electric Generating Station III (SEGS III)	USA	1985	Currently non-operational	30	102	M USD	0	68555
Solar Electric Generating Station IV (SEGS IV)	USA	1989	Operational	30	102	M USD	0	68278
Solar Electric Generating Station V (SEGS V)	USA	1989	Operational	30	102	M USD	0	72879
Solar Electric Generating Station VI (SEGS VI)	USA	1989	Operational	30	102	M USD	0	67758
Solar Electric Generating Station VII (SEGS VII)	USA	1989	Operational	30	102	M USD	0	65048
Solar Electric Generating Station VIII (SEGS VIII)	USA	1989	Operational	80	230	M USD	0	137990
Solar Electric Generating Station IX (SEGS IX)	USA	1990	Operational	80	230	M USD	0	125036
Saguaro Power Plant	USA	2006	Currently non-operational	1			0	
Nevada Solar One (NSO)	USA	2007	Operational	72	266	M USD	0	134000
Andasol-1 (AS-1)	Spain	2008	Operational	50	310	M USD	7.5	158000
Andasol-2 (AS-2)	Spain	2009	Operational	50	300	M€	7.5	158000
Holaniku at Keahole Point	USA	2009	Currently non-operational	2			2	
La Risca (Alvarado I)	Spain	2009	Operational	50	230	M€	0	105000
Ibersol Ciudad Real (Puertollano)	Spain	2009	Operational	50	200	M€	0	
Solnova 1	Spain	2009	Operational	50	250	M€	0	113520
Solnova 3	Spain	2009	Operational	50	250	M€	0	113520
Solnova 4	Spain	2009	Operational	50	210	M€	0	113520
Archimede	Italy	2010	Operational	5			8	
Colorado Integrated Solar Project (Cameo)	USA	2010	Currently non-operational	2			0	
Extresol-1 (EX-1)	Spain	2010	Operational	50	300	M €	7.5	158000
Extresol-2 (EX-2)	Spain	2010	Operational	50	300	M €	7.5	158000
ISCC Ain Beni Mathar	Morocco	2010	Operational	20			0	
La Florida	Spain	2010	Operational	50	319	M €	7.5	175000
Majadas I	Spain	2010	Operational	50	237	M €	0	104500
Martin Next Generation Solar Energy Center (MNGSEC)	USA	2010	Operational	75	476	M USD	0	155000
Palma del Río II	Spain	2010	Operational	50	247	M €	0	115500
Andasol-3 (AS-3)	Spain	2011	Operational	50	315	M €	7.5	175000
Arcosol 50 (Valle 1)	Spain	2011	Operational	50	270	M €	7.5	175000
Helioenergy 1	Spain	2011	Operational	50	240	M €	0	95000
ISCC Hassi R'mel (ISCC Hassi R'mel)	Algeria	2011	Operational	20			0	
ISCC Kuraymat (ISCC Kuraymat)	Egypt	2011	Operational	20			0	
La Dehesa	Spain	2011	Operational	50	309	M €	7.5	175000
Lebrija 1 (LE-1)	Spain	2011	Operational	50	303	M €	0	120000
Manchasol-1 (MS-1)	Spain	2011	Operational	50	300	M €	7.5	158000
Manchasol-2 (MS-2)	Spain	2011	Operational	50	300	M €	7.5	159000
Palma del Río I	Spain	2011	Operational	50	247	M €	0	114500
Termesol 50 (Valle 2)	Spain	2011	Operational	50	270	M €	7.5	175000
Aste 1A	Spain	2012	Operational	50	238	M €	8	170000
Aste 1B	Spain	2012	Operational	50	225	M €	8	170000
Astexol II	Spain	2012	Operational	50	225	M €	8	170000
Borges Termosolar	Spain	2012	Operational	22.5	153	M €	0	44100
Extresol-3 (EX-3)	Spain	2012	Operational	50	390	M €	7.5	158000
Guzmán	Spain	2012	Operational	50	272	M €	0	104000
Helioenergy 2	Spain	2012	Operational	50	240	M €	0	95000
Helios I (Helios I)	Spain	2012	Operational	50	215	M €	0	97000
Helios II (Helios II)	Spain	2012	Operational	50	215	M €	0	97000
La Africana	Spain	2012	Operational	50	387	M €	7.5	170000
Morón	Spain	2012	Operational	50	295	M €	0	100000
National Solar Thermal Power Facility	India	2012	Operational	1			0	
Olivenza 1	Spain	2012	Operational	50	284	M €	0	100000
Orellana	Spain	2012	Operational	50	240	M €	0	118000
Solaben 1	Spain	2012	Operational	50	240	M €	0	100000
Solaben 2	Spain	2012	Operational	50	229	M €	0	100000
Solaben 3	Spain	2012	Operational	50	229	M €	0	100000
Solacor 1	Spain	2012	Operational	50	229	M €	0	100000
Solacor 2	Spain	2012	Operational	50	229	M €	0	100000

Thai Solar Energy 1 (TSE1)	Thailand	2012	Operational	5			0	
Arenales	Spain	2013	Operational	50	314	M €	7	166000
ASE Demo Plant	Italy	2013	Operational	0.35			0	
Casablanca	Spain	2013	Operational	50	345	M €	7.5	160000
Enerstar (Villena)	Spain	2013	Operational	50	225	M €	0	100000
Godawari Solar Project	India	2013	Operational	50	7900	M INR	0	118000
Shams 1 (Shams 1)	UAE	2013	Operational	100	600	M USD	0	210000
Solaben 6	Spain	2013	Operational	50	240	M €	0	100000
Solana Generating Station (Solana)	USA	2013	Operational	250	2000	M USD	6	944000
Termosol 1	Spain	2013	Operational	50	410	M €	9	180000
Termosol 2	Spain	2013	Operational	50	410	M €	9	180000
Airlight Energy Ait-Baha Pilot Plant	Morocco	2014	Operational	3			5	
City of Medicine Hat ISCC Project	Canada	2014	Operational	1.1			0	
Genesis Solar Energy Project	USA	2014	Operational	250	1216	M €	0	580000
Megha Solar Plant	India	2014	Operational	50	8480	M INR	0	110000
Mojave Solar Project	USA	2014	Operational	250	1600	M USD	0	600000
KaXu Solar One	South Africa	2015	Operational	100	860	M USD	2.5	330000
NOOR I	Morocco	2015	Operational	146	1042	M€	0	370000
Stillwater GeoSolar Hybrid Plant	USA	2015	Operational	2			0	
Aalborg CSP-Brønderslev CSP with ORC project	Denmark	2016	Operational	16.6			0	
Bokpoort	South Africa	2016	Operational	50	565	M USD	9.3	230000
Delingha 50MW Thermal Oil Parabolic Trough project	China	2018	Operational	50	1938	M RMB	9	199000
Ilanga I	South Africa	2018	Operational	100	690	M USD	5	320000
NOOR II	Morocco	2018	Operational	185	1100	M USD	7	600000
Xina Solar One	South Africa	2018	Operational	100	880	M USD	5	
Ashalim (Negev)	Israel	2019	Operational	121	1000	M USD	4.5	415000
Kathu Solar Park	South Africa	2019	Operational	100	12000	M ZAR	4.5	500000
Shagaya CSP Project	Kuwait	2019	Operational	50	116	M KWD	9	180000
Urat Royal Tech 100MW Thermal Oil Parabolic Trough project	China	2019	Operational	100	2800	M RMB	10	350000
DEWA CSP Trough Project	Dubai	2021	Under construction	600	14200	AED	15	3460200
Rayspower Yumen 50MW Thermal Oil Trough project	China		Under construction	50	1500	M RMB	7	
Yumen 50MW Thermal Oil Trough CSP project	China		Under development	50	1345	M RMB	7	169300

Table 13. Data for the existing central receiver CSP plants.

Power_Station	Country	Year Opearational	Status	Capacity	Total Investment	Unit of Total Investment	Storage [h]	Expected Generation [MWh]
Planta Solar 10	Spain	2007	Operational	11	35	M €	1	23400
Jülich Solar Tower	Germany	2008	Operational	1.5				
Sierra SunTower	United States	2009	Currently non-operational	5				
Planta Solar 20	Spain	2009	Operational	20	90	M €	1	48000
Lake Cargelligo	Australia	2011	Currently non-operational	3				
ACME Solar Tower	India	2011	Operational	2.5				
Gemasolar Thermosolar Plant	Spain	2011	Operational	19.9	230	M €	15	110000
Greenway CSP Mersin Tower Plant	Turkey	2012	Operational	1				
Dahan Power Plant	China	2012	Operational	1				
SUPCON Delingha 10 MW Tower	China	2013	Operational	10	150	M RMB	2.5	24000
Ivanpah Solar Electric Generating System	United States	2014	Operational	377	2200	M USD	0	1079000
Crescent Dunes Solar Energy Project	United States	2015	Operational	110	983	M USD	10	500000
Khi Solar One	South Africa	2016	Operational	50	450	M USD	2	180000
Shouhang Dunhuang 10 MW Phase I	China	2016	Operational	10	420	M USD	15	
Sundrop CSP Project	Australia	2016	Operational	1.5				
Jemalong Solar Thermal Station	Australia	2017	Operational	1				
SUPCON Delingha 50 MW Tower	China	2018	Operational	50	1050	M RMB	6	136000
Shouhang Dunhuang 100 MW Phase II	China	2018	Operational	100	3040	M RMB	11	483000
NOOR III	Morocco	2018	Operational	134	862	M USD	7	500000
Qinghai Gonghe 50 MW CSP Plant	China	2019	Operational	50	1222	M RMB	6	157000
Luneng Haixi 50MW Molten Salt Tower	China	2019	Operational	50	1100	M RMB	12	160000
Yumen 100MW Molten Salt Tower CSP project	China	2019	Currently non-operational	100				
Ashalim Plot B	Israel	2019	Operational	121	840	M USD	0	320000
Hami 50 MW CSP Project	China	2020	Operational	50	1580	M RMB	8	198400
Huanghe Qinghai Delingha 135 MW DSG Tower CSP Project	China		Under construction	135			3.7	
Yumen 50MW Molten Salt Tower CSP project	China		Under construction	50	1780	M RMB	6	226000
Golden Tower 100MW Molten Salt project	China		Under construction	100				
Golmud	China		Under construction	200	5380	M RMB	15	1120000
Atacama-1	Chile		Under construction	110	1400	M USD	17.5	
DEWA CSP Tower Project	UAE		Under construction	100	14200	M USD	15	
Redstone Solar Thermal Power Plant	South Africa		Under construction	100	789	M USD	12	480000

Table 14. Sectors classification for the IO analysis of CSP plants.

New sector code	Sector name	EXIOBASE code
1	Agriculture	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19
2	Mining	20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42
3	Food and tobacco	43, 44, 45, 46, 47, 48, 49, 50, 51, 52
4	Textile	55, 56, 57
5	Furniture and timber	58, 59, 125
6	Paper products	60, 61, 62, 63
7	Petroleum	64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85
8	Chemicals	86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96
9	Non-metallic mineral products	97, 98, 99, 100, 101, 102, 103
10	Metal products	104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117
11	General and special Machinery	118, 119
12	Electronic, electronical and measuring devices	120, 121, 122
13	Transport equipment	123, 124
14	Other manufacturing	126, 127
15	Electricity	128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149
16	Construction	150, 151
17	Services	152, 153, 154, 155, 156, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175,196, 197, 198, 199, 200
18	Transport	157, 158, 159, 160, 161, 162
19	Waste treatment	176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195

Table 15. CSP production recipe. Disaggregated.

Sector name	Value [%]
Plastics, basic	0.015000
Chemicals nec	0.015000
Additives/Blending Components	0.015000
Rubber and plastic products (25)	0.015000
Glass and glass products	0.026438
Secondary glass for treatment, Re-processing of secondary glass into new glass	0.026438
Ceramic goods	0.000000
Bricks, tiles and construction products, in baked clay	0.026438
Cement, lime and plaster	0.026438
Other non-metallic mineral products	0.026438
Basic iron and steel and of ferro-alloys and first products thereof	0.013522
Secondary steel for treatment, Re-processing of secondary steel into new steel	0.013522
Aluminium and aluminium products	0.013522
Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium	0.013522
Lead, zinc and tin and products thereof	0.013522
Secondary lead for treatment, Re-processing of secondary lead into new lead	0.013522
Copper products	0.013522
Secondary copper for treatment, Re-processing of secondary copper into new copper	0.013522
Other non-ferrous metal products	0.013522
Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	0.013522
Foundry work services	0.013522
Fabricated metal products, except machinery and equipment (28)	0.013522
Machinery and equipment n.e.c. (29)	0.259840
Electrical machinery and apparatus n.e.c. (31)	0.020188
Radio, television and communication equipment and apparatus (32)	0.020188
Medical, precision and optical instruments, watches and clocks (33)	0.020188
Electricity by coal	0.000227
Electricity by gas	0.000227
Electricity by nuclear	0.000227
Electricity by hydro	0.000227
Electricity by wind	0.000227
Electricity by petroleum and other oil derivatives	0.000227
Electricity by biomass and waste	0.000227
Electricity by solar photovoltaic	0.000227
Electricity by solar thermal	0.000227
Electricity by tide, wave, ocean	0.000227
Electricity by Geothermal	0.000227
Electricity nec	0.000227
Transmission services of electricity	0.000227
Distribution and trade services of electricity	0.000227
Coke oven gas	0.000227
Blast Furnace Gas	0.000227
Oxygen Steel Furnace Gas	0.000227
Gas Works Gas	0.000227
Biogas	0.000227
Distribution services of gaseous fuels through mains	0.000227
Steam and hot water supply services	0.000227
Collected and purified water, distribution services of water (41)	0.000227
Construction work (45)	0.166448
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	0.009894
Retail trade services of motor fuel	0.009894
Wholesale trade and commission trade services, except of motor vehicles and motorcycles (51)	0.009894
Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)	0.009894
Railway transportation services	0.002529
Other land transportation services	0.002529
Transportation services via pipelines	0.002529
Sea and coastal water transportation services	0.002529
Inland water transportation services	0.002529
Air transport services (62)	0.002529
Post and telecommunication services (64)	0.009894
Financial intermediation services, except insurance and pension funding services (65)	0.009894
Insurance and pension funding services, except compulsory social security services (66)	0.009894
Services auxiliary to financial intermediation (67)	0.009894
Real estate services (70)	0.009894
Renting services of machinery and equipment without operator and of personal and household goods (71)	0.009894
Computer and related services (72)	0.009894
Research and development services (73)	0.009894
Other business services (74)	0.009894
Public administration and defence services; compulsory social security services (75)	0.009894

Table 16. Breakdown of investment and O&M costs associated with the different CSP plants.

Project Phase	Sector Code	Sector Name	SEGS VI	Andasol-1	Manchasol-1	Delingha PT	PS-10	Gemasolar	Shouhang Dunhuang	Hami 50 MW	Yumen 50MW
Installation	Total investment [€ 2019]		1.87E+08	3.69E+08	2.47E+08	2.99E+08	3.10E+07	1.89E+08	4.67E+08	2.26E+08	2.55E+08
	1	Agriculture		0.06%				0.13%			
	2	Mining			7.97%						
	8	Chemical	0.88%	5.10%	3.90%	6.47%		2.31%			
	9	Non-metallic mineral products	8.79%	8.92%	7.18%	7.91%	13.76%	15.32%	23.64%	9.30%	15.15%
	19	Metal Products	11.24%	22.69%	11.97%	21.82%	18.06%	18.35%	16.42%	9.36%	16.13%
	12	Electrical, electronic and measuring equipment	1.74%	6.39%	5.31%	7.91%	8.95%	6.12%	9.73%	3.16%	5.20%
	11	General and special machinery	64.77%	19.50%	20.30%	18.72%	29.55%	31.59%	29.38%	31.10%	27.71%
	15	Electricity		0.05%			0.20%	0.11%	0.04%	2.00%	1.41%
	16	Construction	8.47%	22.16%	19.42%	12.10%	11.11%	17.55%	13.77%	20.73%	22.59%
	18	Transport	0.38%	5.22%	2.59%	3.50%	0.56%	0.53%	0.22%	0.08%	0.57%
	17	Services	3.73%	9.90%	21.37%	21.56%	17.80%	8.00%	6.80%	24.27%	11.24%
O&M	Annual O&M [% of total investment]		1.30%	4.86%	6.34%	-	3.17%	5.16%	-	-	-
	15	Electricity		24.99%	40.13%		4.94%	26.06%			
	8	Chemical		2.45%	0.00%		0.00%	2.38%			
	9	Non-metallic mineral products	2.45%				2.38%				
	12	Electrical, electronic and measuring equipment	2.45%				2.38%				
	17	Services		67.66%	59.87%		95.06%	66.81%			

Table 17. Carbon impact of installation.

Region	Assumption	Carbon Impact [kt CO_2eq/M€]
Spain	1	0.60
	2	0.58
	3	1.14
	4	0.97
Italy	1	0.49
	2	0.46
	3	1.13
	4	0.90
Greece	1	1.55
	2	1.19
	3	1.12
	4	1.03
Europe	1	0.88
	2	0.74
	3	1.13
	4	0.97
China	1	2.67
	2	2.49
	3	1.04
	4	0.86
Europe	Average	1.00
China	Average	1.85

Table 18. Carbon impact of O&M.

Region	Assumption	Carbon Impact [kt CO_2eq/M€]
Spain	1	0.41
	2	0.39
	3	3.46
	4	0.89
Italy	1	0.33
	2	0.36
	3	4.85
	4	0.99
Greece	1	1.13
	2	1.00
	3	3.17
	4	0.86
Europe	1	0.62
	2	0.58
	3	3.83
	4	0.92
China	1	3.13
	2	1.46
	3	2.23
	4	0.86
Europe	Average	2.23
China	Average	2.29

Table 19. Employment impact of installation.

Region	Assumption	Employment Impact [10p/M€]
Spain	1	2.46
	2	2.51
	3	4.96
	4	5.81
Italy	1	2.17
	2	2.07
	3	5.49
	4	5.24
Greece	1	3.19
	2	3.28
	3	5.25
	4	4.98
Europe	1	2.61
	2	2.62
	3	5.23
	4	5.34
China	1	7.10
	2	6.72
	3	6.87
	4	4.78
Europe	Average	3.92
China	Average	6.98

Table 20. Employment impact of O&M.

Region	Assumption	Employment Impact [10p/M€]
Spain	1	2.06
	2	2.20
	3	4.52
	4	4.98
Italy	1	1.69
	2	1.77
	3	5.33
	4	4.68
Greece	1	2.09
	2	3.26
	3	4.17
	4	4.89
Europe	1	1.95
	2	2.41
	3	4.67
	4	4.85
China	1	7.57
	2	7.64
	3	5.33
	4	4.26
Europe	Average	3.31
China	Average	6.45

Table 21. Contribution of the demand from different sectors to the total carbon impact of installation CSP plants.

Sector	Plant in Spain	Plant in Italy	Plant in Greece	Plant in Europe	Plant in China
Agriculture	0.00%	0.00%	0.00%	0.00%	0.00%
Mining	0.00%	0.00%	0.00%	0.00%	0.00%
Food and Tobacco	0.00%	0.00%	0.00%	0.00%	0.00%
Textile	0.00%	0.00%	0.00%	0.00%	0.00%
Furniture and timber	0.00%	0.00%	0.00%	0.00%	0.00%
Paper Products	0.00%	0.00%	0.00%	0.00%	0.00%
Petroleum	0.00%	0.00%	0.00%	0.00%	0.00%
Chemical	7.51%	6.38%	4.61%	6.16%	7.25%
Non-metallic mineral products	31.17%	25.34%	41.67%	32.73%	28.70%
Metal Products	15.67%	15.55%	12.70%	14.64%	17.81%
General and special machinery	17.10%	17.83%	14.64%	16.52%	17.85%
Electrical, electronic and measuring equipment	3.70%	4.81%	5.68%	4.73%	4.50%
Transport equipment	0.00%	0.00%	0.00%	0.00%	0.00%
Other manufacturing	0.00%	0.00%	0.00%	0.00%	0.00%
Electricity	7.55%	11.41%	5.01%	7.99%	3.64%
Construction	11.80%	13.07%	9.25%	11.37%	15.04%
Services	4.10%	4.37%	4.18%	4.22%	3.88%
Transport	1.39%	1.25%	2.26%	1.63%	1.33%
Waste management disposal	0.00%	0.00%	0.00%	0.00%	0.00%

Table 22. Contribution of the demand from different sectors to the total carbon impact of operating CSP plants.

Sector	Plant in Spain	Plant in Italy	Plant in Greece	Plant in Europe	Plant in China
Agriculture	0.00%	0.00%	0.00%	0.00%	0.00%
Mining	0.00%	0.00%	0.00%	0.00%	0.00%
Food and Tobacco	0.00%	0.00%	0.00%	0.00%	0.00%
Textile	0.00%	0.00%	0.00%	0.00%	0.00%
Furniture and timber	0.00%	0.00%	0.00%	0.00%	0.00%
Paper Products	0.00%	0.00%	0.00%	0.00%	0.00%
Petroleum	0.00%	0.00%	0.00%	0.00%	0.00%
Chemical	1.40%	0.83%	1.19%	1.14%	2.44%
Non-metallic mineral products	2.64%	1.50%	4.88%	3.01%	4.39%
Metal Products	0.00%	0.00%	0.00%	0.00%	0.00%
General and special machinery	0.00%	0.00%	0.00%	0.00%	0.00%
Electrical, electronic and measuring equipment	0.69%	0.62%	1.45%	0.92%	1.50%
Transport equipment	0.00%	0.00%	0.00%	0.00%	0.00%
Other manufacturing	0.00%	0.00%	0.00%	0.00%	0.00%
Electricity	84.66%	89.16%	77.52%	83.78%	73.55%
Construction	0.00%	0.00%	0.00%	0.00%	0.00%
Services	10.61%	7.90%	14.96%	11.16%	18.11%
Transport	0.00%	0.00%	0.00%	0.00%	0.00%
Waste management disposal	0.00%	0.00%	0.00%	0.00%	0.00%

Table 23. Contribution of the demand from different sectors to the total employment impact of installation CSP plants.

Sector	Plant in Spain	Plant in Italy	Plant in Greece	Plant in Europe	Plant in China
Agriculture	0.00%	0.00%	0.00%	0.00%	0.00%
Mining	0.00%	0.00%	0.00%	0.00%	0.00%
Food and Tobacco	0.00%	0.00%	0.00%	0.00%	0.00%
Textile	0.00%	0.00%	0.00%	0.00%	0.00%
Furniture and timber	0.00%	0.00%	0.00%	0.00%	0.00%
Paper Products	0.00%	0.00%	0.00%	0.00%	0.00%
Petroleum	0.00%	0.00%	0.00%	0.00%	0.00%
Chemical	9.96%	10.21%	9.11%	9.76%	10.32%
Non-metallic mineral products	10.94%	10.00%	13.03%	11.32%	10.10%
Metal Products	13.67%	14.93%	15.12%	14.57%	10.21%
General and special machinery	29.65%	29.76%	29.31%	29.57%	29.35%
Electrical, electronic and measuring equipment	6.51%	6.26%	6.17%	6.31%	8.27%
Transport equipment	0.00%	0.00%	0.00%	0.00%	0.00%
Other manufacturing	0.00%	0.00%	0.00%	0.00%	0.00%
Electricity	0.39%	0.47%	0.27%	0.38%	0.38%
Construction	15.54%	14.99%	15.65%	15.39%	17.34%
Services	12.10%	12.34%	10.15%	11.53%	12.69%
Transport	1.24%	1.04%	1.19%	1.16%	1.34%
Waste management disposal	0.00%	0.00%	0.00%	0.00%	0.00%

Table 24. Contribution of the demand from different sectors to the total employment impact of operating CSP plants.

Sector	Plant in Spain	Plant in Italy	Plant in Greece	Plant in Europe	Plant in China
Agriculture	0.00%	0.00%	0.00%	0.00%	0.00%
Mining	0.00%	0.00%	0.00%	0.00%	0.00%
Food and Tobacco	0.00%	0.00%	0.00%	0.00%	0.00%
Textile	0.00%	0.00%	0.00%	0.00%	0.00%
Furniture and timber	0.00%	0.00%	0.00%	0.00%	0.00%
Paper Products	0.00%	0.00%	0.00%	0.00%	0.00%
Petroleum	0.00%	0.00%	0.00%	0.00%	0.00%
Chemical	4.68%	4.64%	5.12%	4.81%	4.65%
Non-metallic mineral products	2.33%	2.06%	3.32%	2.57%	2.07%
Metal Products	0.00%	0.00%	0.00%	0.00%	0.00%
General and special machinery	0.00%	0.00%	0.00%	0.00%	0.00%
Electrical, electronic and measuring equipment	3.03%	2.82%	3.44%	3.10%	3.70%
Transport equipment	0.00%	0.00%	0.00%	0.00%	0.00%
Other manufacturing	0.00%	0.00%	0.00%	0.00%	0.00%
Electricity	11.12%	12.75%	9.02%	10.96%	10.28%
Construction	0.00%	0.00%	0.00%	0.00%	0.00%
Services	78.83%	77.72%	79.10%	78.55%	79.30%
Transport	0.00%	0.00%	0.00%	0.00%	0.00%
Waste management disposal	0.00%	0.00%	0.00%	0.00%	0.00%

Table 25. Hotspot analysis of the carbon impact of installation of CSP plants.

Sector	Plant in Spain	Plant in Italy	Plant in Greece	Plant in Europe	Plant in China
Agriculture	2.33%	2.58%	1.62%	2.18%	2.83%
Mining	13.51%	12.41%	8.21%	11.38%	12.51%
Food and Tobacco	0.13%	0.13%	0.09%	0.11%	0.12%
Textile	0.04%	0.04%	0.02%	0.03%	0.06%
Furniture and timber	0.28%	0.26%	1.11%	0.55%	0.26%
Paper Products	0.21%	0.20%	0.11%	0.17%	0.24%
Petroleum	1.94%	2.10%	1.60%	1.88%	1.34%
Chemical	4.82%	4.60%	2.97%	4.13%	5.21%
Non-metallic mineral products	28.37%	23.32%	40.81%	30.83%	25.62%
Metal Products	10.49%	12.01%	7.78%	10.09%	13.39%
General and special machinery	1.51%	1.30%	1.30%	1.37%	0.86%
Electrical, electronic and measuring equipment	1.32%	2.63%	3.72%	2.56%	0.75%
Transport equipment	0.07%	0.06%	0.04%	0.06%	0.05%
Other manufacturing	0.27%	0.21%	0.12%	0.20%	0.07%
Electricity	23.35%	25.19%	17.20%	21.92%	29.68%
Construction	2.39%	3.36%	1.11%	2.29%	1.46%
Services	3.28%	3.88%	5.66%	4.27%	1.80%
Transport	4.96%	4.92%	5.93%	5.27%	3.44%
Waste management disposal	0.72%	0.81%	0.61%	0.71%	0.29%

Table 26. Hotspot analysis of the carbon impact of the O&M phase of CSP plants.

Sector	Plant in Spain	Plant in Italy	Plant in Greece	Plant in Europe	Plant in China
Agriculture	1.05%	0.75%	0.91%	0.90%	2.58%
Mining	2.02%	1.50%	2.11%	1.88%	4.02%
Food and Tobacco	0.08%	0.05%	0.07%	0.07%	0.13%
Textile	0.02%	0.01%	0.01%	0.01%	0.05%
Furniture and timber	0.07%	0.04%	0.11%	0.07%	0.09%
Paper Products	0.09%	0.06%	0.07%	0.07%	0.22%
Petroleum	0.58%	0.40%	0.54%	0.51%	0.69%
Chemical	1.08%	0.72%	0.83%	0.88%	2.37%
Non-metallic mineral products	2.40%	1.43%	4.64%	2.82%	3.88%
Metal Products	0.45%	0.37%	0.43%	0.42%	1.36%
General and special machinery	0.02%	0.02%	0.02%	0.02%	0.05%
Electrical, electronic and measuring equipment	0.23%	0.36%	0.95%	0.51%	0.24%
Transport equipment	0.02%	0.01%	0.02%	0.02%	0.03%
Other manufacturing	0.01%	0.01%	0.01%	0.01%	0.01%
Electricity	86.86%	90.15%	78.61%	85.21%	79.30%
Construction	0.12%	0.12%	0.08%	0.11%	0.13%
Services	3.36%	2.74%	8.00%	4.70%	3.26%
Transport	1.25%	0.99%	2.11%	1.45%	1.30%
Waste management disposal	0.29%	0.28%	0.48%	0.35%	0.28%

Table 27. Hotspot analysis of the employment impact of installation of CSP plants.

Sector	Plant in Spain	Plant in Italy	Plant in Greece	Plant in Europe	Plant in China
Agriculture	8.79%	9.36%	8.95%	9.03%	16.33%
Mining	5.88%	4.86%	5.23%	5.32%	5.26%
Food and Tobacco	0.83%	0.82%	0.82%	0.82%	0.77%
Textile	0.37%	0.37%	0.31%	0.35%	0.57%
Furniture and timber	0.71%	0.68%	1.20%	0.86%	0.77%
Paper Products	0.65%	0.64%	0.61%	0.63%	0.72%
Petroleum	0.83%	0.92%	0.92%	0.89%	0.79%
Chemical	5.71%	6.06%	5.34%	5.70%	6.04%
Non-metallic mineral products	5.27%	5.07%	7.41%	5.92%	4.57%
Metal Products	10.66%	12.20%	11.74%	11.53%	7.88%
General and special machinery	11.53%	11.33%	11.70%	11.52%	11.67%
Electrical, electronic and measuring equipment	3.79%	3.68%	3.55%	3.67%	4.63%
Transport equipment	0.57%	0.49%	0.35%	0.47%	0.46%
Other manufacturing	0.20%	0.20%	0.18%	0.19%	0.27%
Electricity	1.06%	1.12%	1.02%	1.07%	1.07%
Construction	7.61%	7.41%	8.13%	7.72%	9.15%
Services	30.49%	30.10%	28.15%	29.58%	25.58%
Transport	4.50%	4.12%	3.90%	4.17%	3.22%
Waste management disposal	0.56%	0.56%	0.48%	0.53%	0.25%

Table 28. Hotspot analysis of the employment impact of the O&M phase of CSP plants.

Sector	Plant in Spain	Plant in Italy	Plant in Greece	Plant in Europe	Plant in China
Agriculture	9.50%	9.37%	10.69%	9.85%	21.69%
Mining	1.83%	1.79%	2.03%	1.88%	2.09%
Food and Tobacco	1.08%	0.93%	1.22%	1.08%	0.88%
Textile	0.34%	0.31%	0.32%	0.33%	0.63%
Furniture and timber	0.46%	0.39%	0.41%	0.42%	0.38%
Paper Products	0.70%	0.64%	0.79%	0.71%	0.80%
Petroleum	0.55%	0.61%	0.63%	0.59%	0.55%
Chemical	3.06%	3.00%	3.02%	3.03%	3.24%
Non-metallic mineral products	1.16%	1.11%	1.88%	1.39%	0.98%
Metal Products	1.17%	1.23%	1.25%	1.22%	1.11%
General and special machinery	0.41%	0.44%	0.41%	0.42%	0.65%
Electrical, electronic and measuring equipment	1.66%	1.57%	1.81%	1.68%	2.11%
Transport equipment	0.35%	0.39%	0.30%	0.34%	0.41%
Other manufacturing	0.06%	0.06%	0.07%	0.06%	0.23%
Electricity	5.84%	6.43%	4.24%	5.50%	4.30%
Construction	0.93%	1.00%	0.89%	0.94%	0.82%
Services	67.29%	67.03%	66.39%	66.90%	57.02%
Transport	3.10%	3.17%	3.15%	3.14%	1.89%
Waste management disposal	0.52%	0.53%	0.50%	0.52%	0.23%

Table 29. Life cycle carbon emissions for different energy technologies. Personal elaboration. Published data year is taken as reference year when it is not mentioned in the paper.

Technology	Carbon intensity [gCO2/kWh]	Geographical Reference	Reference year	Reference
Coal	541	UK	2006	(Odeh & Cockerill, 2008)
	243	The Netherlands	2008	(Koornneef et al., 2008)
	800 - 970	China	2013	(Liang et al., 2013)
	980	China	2011	(Chang et al., 2015)
	662 - 849	Germany	2020	(Viebahn et al., 2007)
Natural gas	485 - 990	Europe	2000	(Dones et al., 2007)
	380 - 1000	Global	2013	(Turconi et al., 2013)
	675	China	2011	(Chang et al., 2015)
	337	Germany	2020	(Viebahn et al., 2007)
PV	210		2007	(Yao et al., 2014)
	68	Hong Kong	2008	(L. Lu & Yang, 2010)
	5.60 - 12.07	China	2010	(Chen et al., 2016)
	30	Spain	2011	(Bensebaa, 2011)
	27.2 - 81	South-Europe	2011	(De Wild-Scholten, 2013)
	38	Europe	2012	(Louwen et al., 2015)
	18.8	Italy	2012	(De Feo et al., 2016)
	60 - 87.3	China	2013	(Hou et al., 2016)
	50.90	China	2015	(Fu et al., 2015)
Nuclear	3.90 - 6.10	Europe	2007	(Lecointe et al., 2007)
	5.10 - 5.70	Sweden	2008	(Vattenfall, 2010)
	17	China	2008	(Feng et al., 2014)
Wind	46.4	China	2008	(Feng et al., 2014)
	6.2 - 6.6	Spain	2009	(Martínez et al., 2009)
	9 - 11	Europe	2010	(Neves et al., 2016)
	13.4	UK	2011	(Wiedmann et al., 2011)
	8.8 - 9.7	Germany, Denmark, China	2012	(Guezuraga et al., 2012)
	5.2 - 11.1	Europe	2013	(Bonou et al., 2016)
Hydro	13.2	China	2008	(Feng et al., 2014)
	10 - 13	Europe	2010	(Neves et al., 2016)
	5.1	China	2012	(Q. Zhang et al., 2007)
	7.3 - 9.1	China	2012	(Li et al., 2017)

Table 30. Life cycle carbon emissions for CSP. Personal elaboration. Published data year is taken as reference year when it is not mentioned in the paper.

Technology	Carbon intensity [gCO2/kWh]	Geographical Reference	Reference year	Reference
CSP	200	Spain	2004	(Lechón et al., 2008)
CSP	31	Algeria and Spain	2007	(Viebahn et al., 2011)
CSP	72	Spain	2010	(Corona et al., 2014)
CSP	129.65	Spain	2010	(Corona et al., 2016)
CSP	36.3	China	2011	(M. Zhang et al., 2012)
CSP	26.6	USA	2013	(Klein & Rubin, 2013)
CSP	24.3	South Africa	2018	(Ko et al., 2018)
CSP	26 - 184	Europe	2020	This work
CSP	54-181	China	2020	This work

Table 31. Jobs creation for different energy technologies. Personal elaboration. Published data year is taken as reference year when it is not mentioned in the paper.

Technology	Employment intensity [person-year/MW]	Geographical Reference	Reference year	Reference
Coal	8.5	USA	2001	(Singh & Fehrs, 2001)
Natural gas	1.02	USA	2002	(Heavner et al., 2002)
	4.1	Portugal	2008	(Henriques et al., 2016)
PV	32.35	USA	2001	(Singh & Fehrs, 2001)
	7.14	USA	2001	(Simons & Peterson, 2001)
	37	Global	2006	(EPIA & Greenpeace, 2008)
	25.17	Portugal	2008	(Henriques et al., 2016)
Wind	2.57	USA	2001	(Simons & Peterson, 2001)
	7.4	USA	2002	(Heavner et al., 2002)
	10.1	EU	2007	(Blanco & Kjaer, 2009)
	5.04	Portugal	2008	(Henriques et al., 2016)
Hydro	5.71	USA	2001	(Simons & Peterson, 2001)
	10.50-17.22	Portugal	2008	(Henriques et al., 2016)

Table 32. Jobs creation for CSP. Personal elaboration.

Technology	Employment intensity [person-year/MW]	Geographical Reference	Reference year	Reference
CSP	191.67	Spain	2007	(Caldés et al., 2009)
CSP	323	Spain	2007	(Caldés et al., 2009)
CSP	39.55	USA	2008	(Sargent & Lundy, 2003)
CSP	65.86	Spain	2010	(Corona et al., 2016)
CSP	48 - 134	Europe	2020	This work
CSP	111 - 164	China	2020	This work

Table 33. Specific installation and O&M costs for different low carbon energy technologies. Personal elaboration.

Technology	Installation costs [€/kW]	O&M costs [€/kW]	O&M costs ratio [%]	Reference
PV	1953	20	1.01	(Handayani et al., 2017)
	4430	9	0.20	(Henriques et al., 2016)
Nuclear	3967	164	3.97	(Anderson, 2007)
	1770	105	5.60	(Henriques et al., 2016)
Wind	800	25	3.03	(Anderson, 2007)
	1330	20	1.48	(Anderson, 2007)
	1756	44	2.44	(Handayani et al., 2017)
	1152	15	1.29	(Henriques et al., 2016)
Hydro	n.a.	n.a.	1.5 – 5	(European Small Hydropower Association, n.d.)
	2200	56	2.48	(Handayani et al., 2017)
	1232	16	1.28	(Henriques et al., 2016)
	1756	16	0.90	(Henriques et al., 2016)
CSP	-	-	3.17	This work

Table 34. The projected carbon intensity of installation under different scenarios [Mt CO_2/GW]. Values for CSP are obtain in this work. Values for other technologies are retrieved from (Yuan et al., 2018).

Scenarios	**Hydro**	**Nuclear**	**Wind**	**Solar**	**CSP - Europe**	**CSP - China**
IEA-Current						
2015	0.65	2.14	1.7	1.54		
2020	0.58	1.68	1.48	1.23	2.32	4.29
2030	0.49	1.3	1.31	1.14	1.84	3.39
2040	0.44	1.18	1.22	1.09	1.55	2.86
2050	0.38	1.05	1.15	1.07	1.44	2.65
IEA-New						
2015	0.65	2.14	1.7	1.54		
2020	0.58	1.68	1.43	1.22	2.32	4.29
2030	0.48	1.27	1.22	1.08	2.32	4.29
2040	0.43	1.14	1.11	1.01	1.89	3.49
2050	0.36	1.01	1.05	0.98	1.76	3.25
IEA-450						
2015	0.65	2.14	1.7	1.54		
2020	0.58	1.68	1.48	1.23	2.32	4.29
2030	0.45	1.11	1.17	1.09	1.22	2.41
2040	0.4	0.97	1.07	1.03	0.92	1.77
2050	0.35	0.85	0.99	0.98	0.77	1.62
NDRC-High RE						
2015	0.65	2.14	1.7	1.54		
2020	0.54	1.73	1.32	1.27	2.32	4.29
2030	0.48	1.55	0.94	0.96	1.12	2.07
2040	0.45	1.46	0.79	0.86	0.85	1.56
2050	0.38	1.32	0.76	0.87	0.72	1.34

Table 35. The projected employment intensity of installation under different scenarios [1000p/GW]. Values for CSP are obtain in this work. Values for other technologies are retrieved from sources in Table 32 and learning rates in (Yuan et al., 2018) are applied.

Scenarios	Hydro	Nuclear	Wind	Solar	CSP - Europe	CSP - China
IEA-Current						
2015	21.78	28.88	12.63	48.27		
2020	19.44	22.67	10.99	38.56	90.67	161.53
2030	16.42	17.54	9.73	35.74	71.74	127.80
2040	14.75	15.92	9.06	34.17	60.52	107.82
2050	12.73	14.17	8.54	33.54	56.03	99.81
IEA-New						
2015	21.78	28.88	12.63	48.27		
2020	19.44	22.67	10.62	38.24	90.67	161.53
2030	16.09	17.14	9.06	33.85	90.67	161.53
2040	14.41	15.38	8.24	31.66	73.85	131.56
2050	12.06	13.63	7.80	30.72	68.77	122.51
IEA-450						
2015	21.78	28.88	12.63	48.27		
2020	19.44	22.67	10.99	38.56	90.67	161.53
2030	15.08	14.98	8.69	34.17	47.70	84.98
2040	13.41	13.09	7.95	32.29	35.74	63.66
2050	11.73	11.47	7.35	30.72	30.21	53.82
NDRC-High RE						2
2015	21.78	28.88	12.63	48.27		
2020	18.10	23.35	9.80	39.81	90.67	161.53
2030	16.09	20.92	6.98	30.09	43.65	77.76
2040	15.08	19.70	5.87	26.96	33.07	58.92
2050	12.73	17.81	5.64	27.27	28.27	50.37

Appendix B. Figures

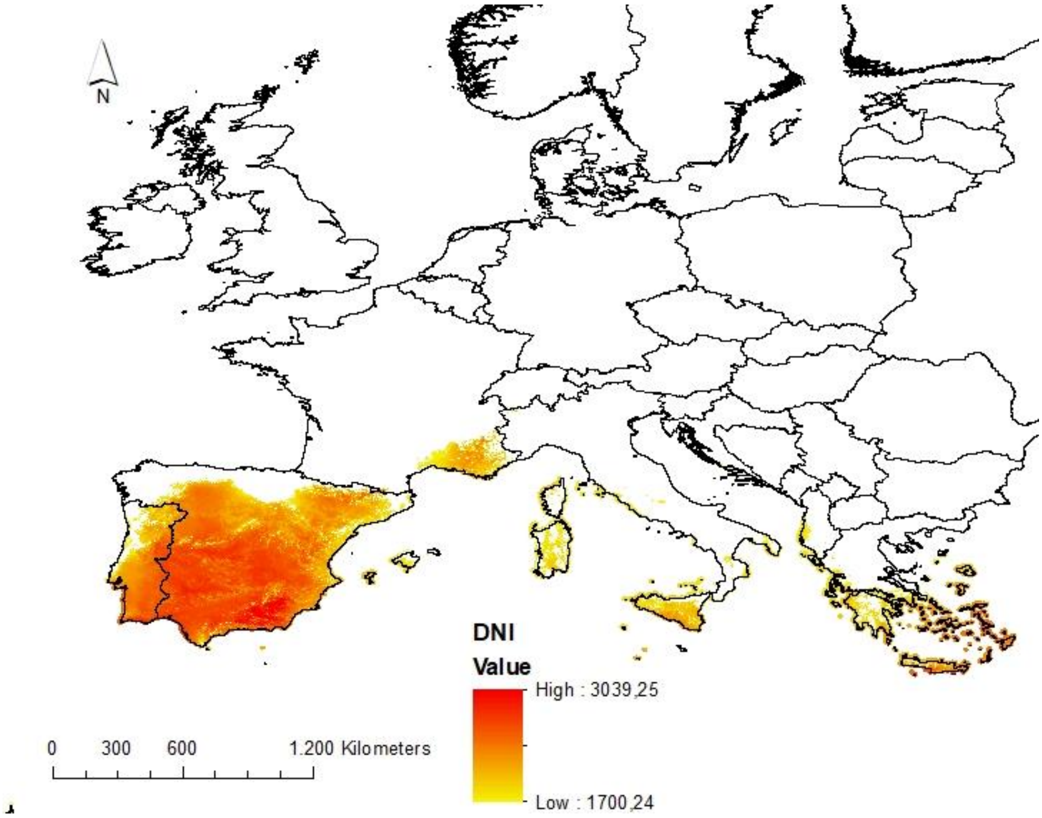


Figure 13. Solar average annual Direct Normal Irradiation (DNI) in Europe. Personal elaboration Data collected from (SolarGIS, 2020).

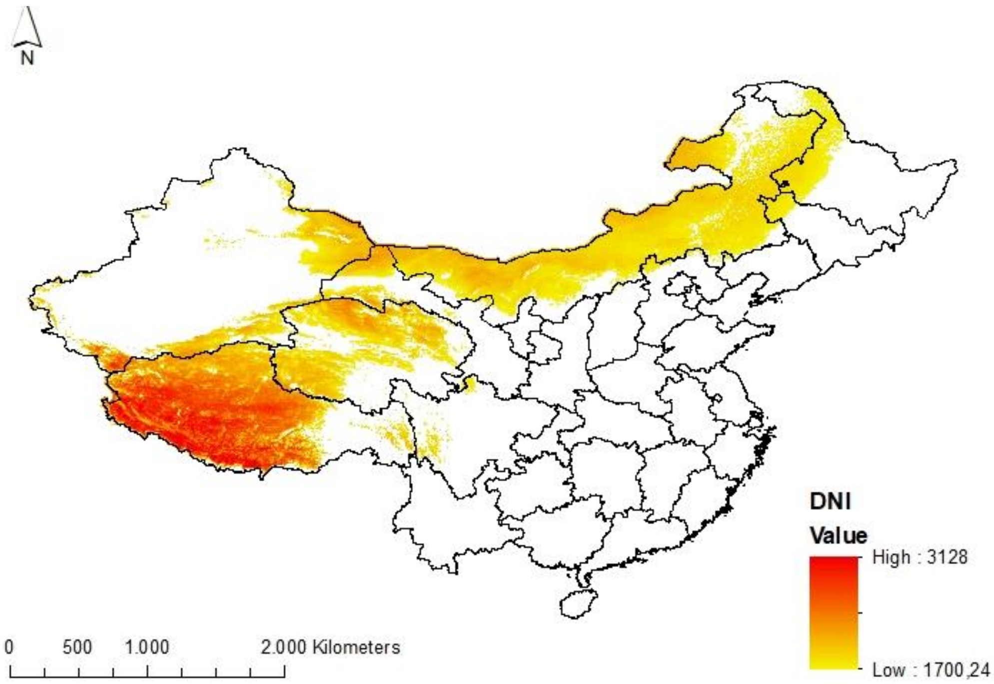


Figure 14. Solar average annual Direct Normal Irradiation (DNI) in China. Personal elaboration Data collected from (SolarGIS, 2020).

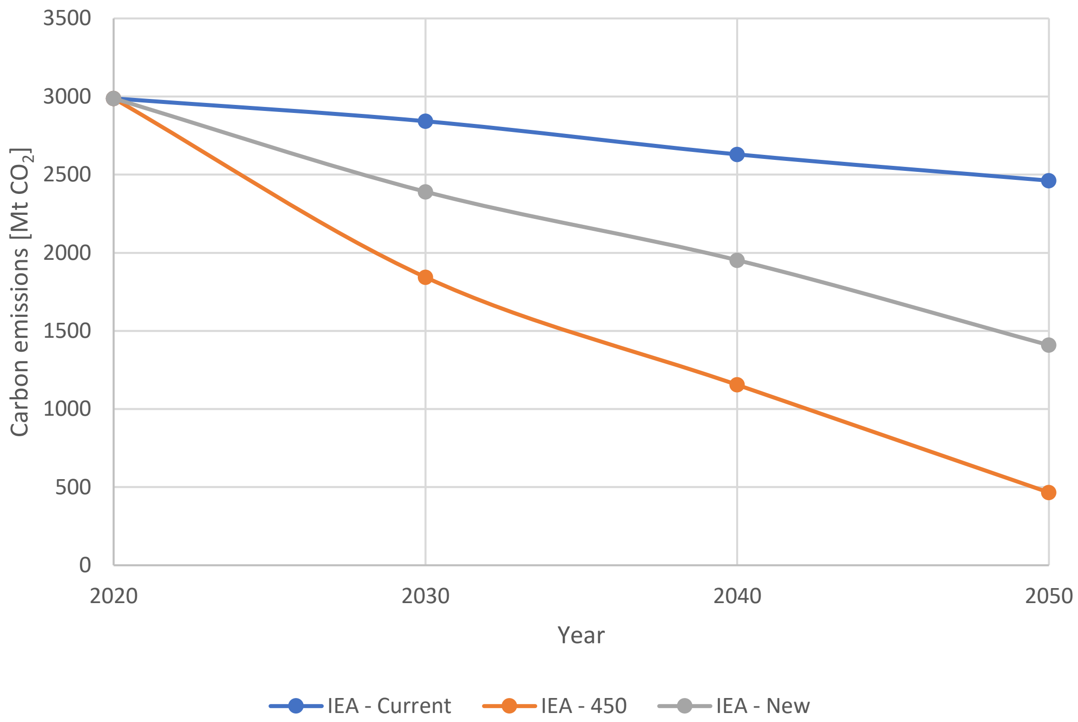


Figure 15. Carbon emission trajectories in Europe by scenario. Personal elaboration. Data collected from (International Energy Agency, 2016)

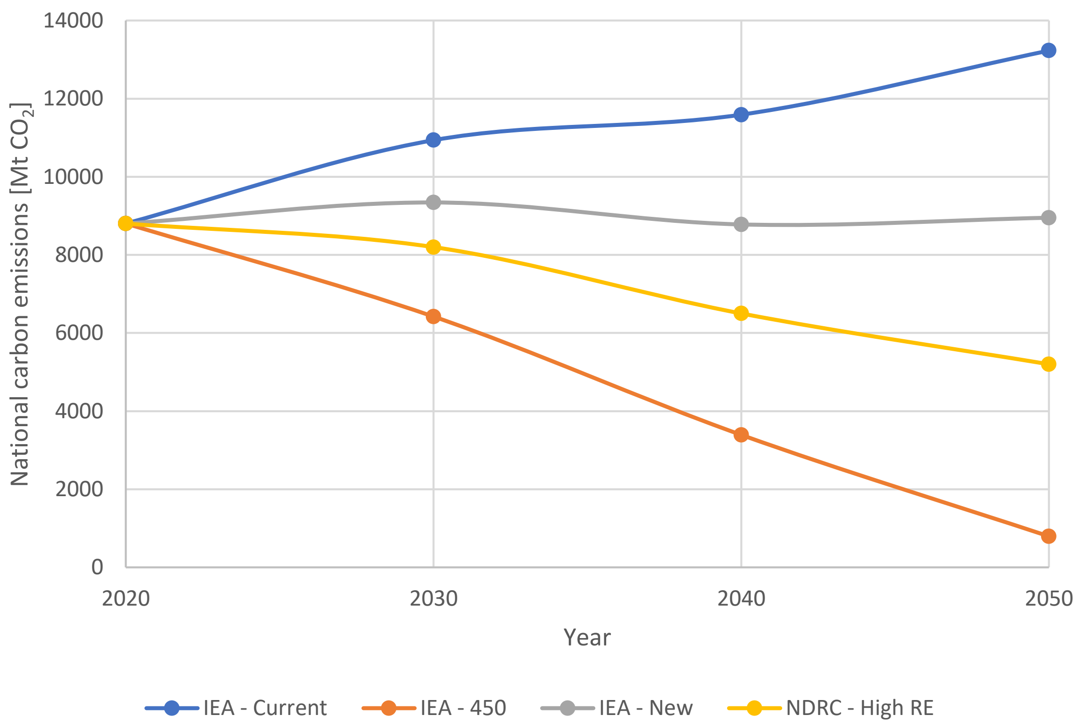


Figure 16. Carbon emission trajectories in Europe by scenario. Personal elaboration. Data collected from (International Energy Agency, 2016; National Development and Reform Commission, 2015).

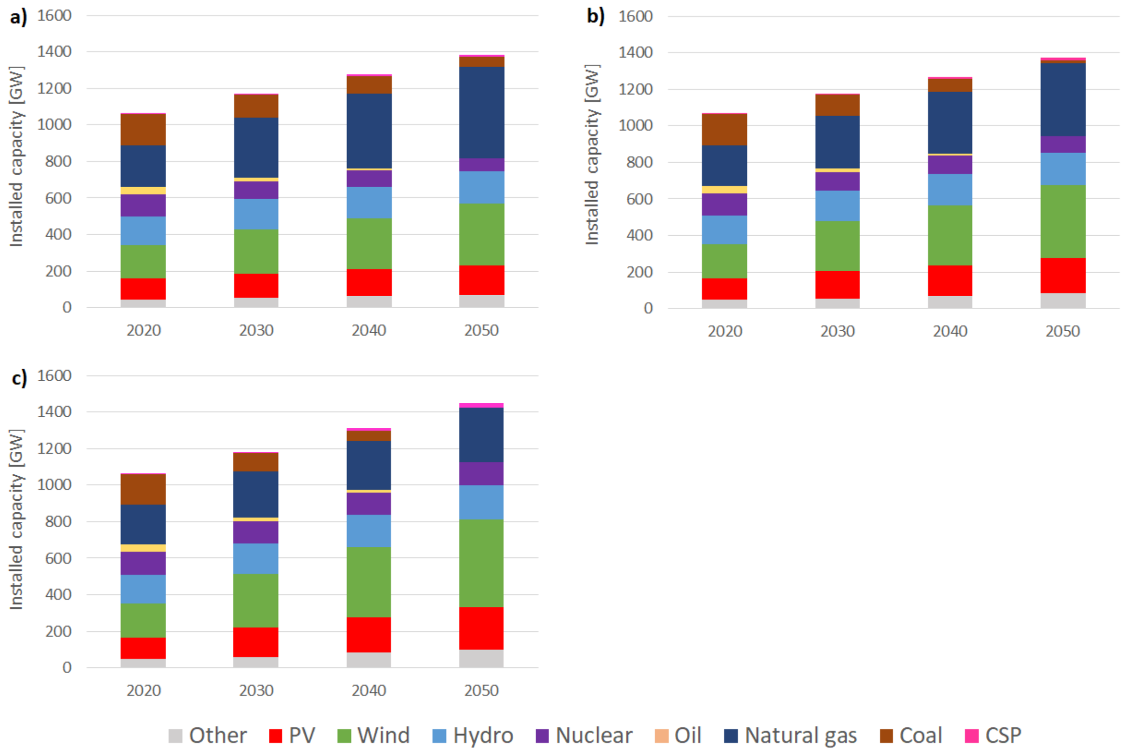


Figure 17. Different scenarios for growth in installed capacity of electricity technologies in Europe. (a) IEA - Current Scenario, (b) IEA - New, (c) IEA - 450. Personal elaboration based on the values from (International Energy Agency, 2016).

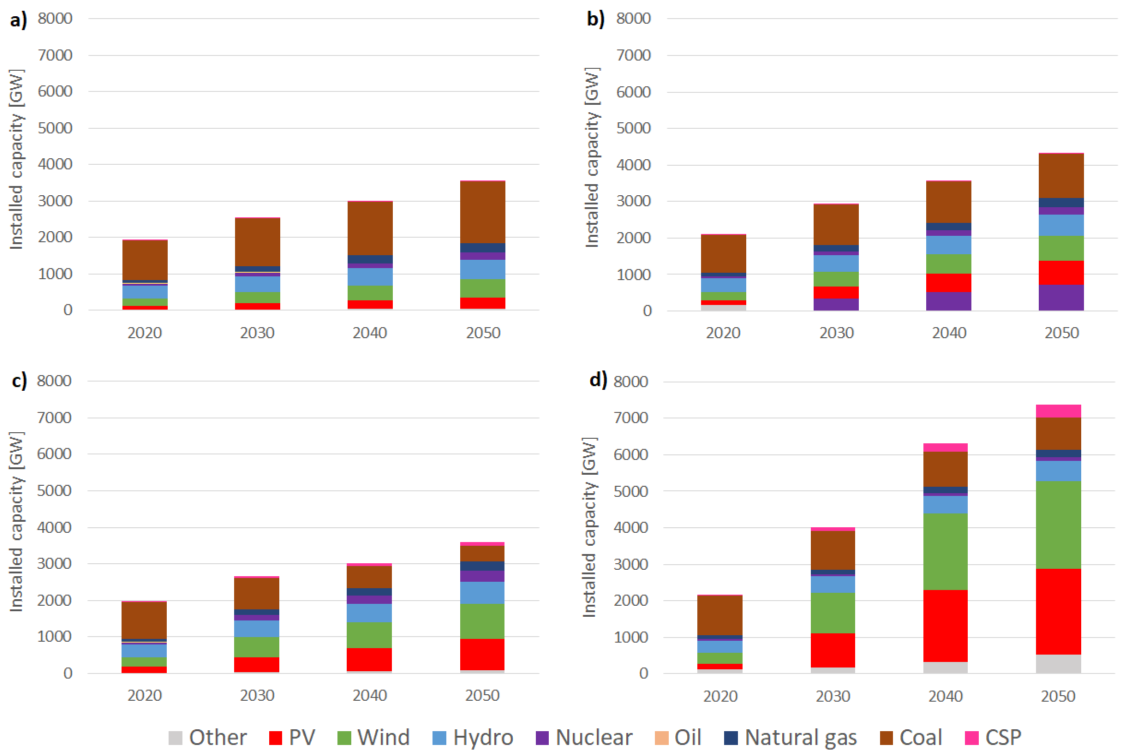


Figure 18. Different scenarios for growth in installed capacity of electricity technologies in China. (a) IEA - Current Scenario, (b) IEA - New, (c) IEA – 450, (d) NDRC – High RE. Personal elaboration based on the values from (International Energy Agency, 2016; National Development and Reform Commission, 2015).

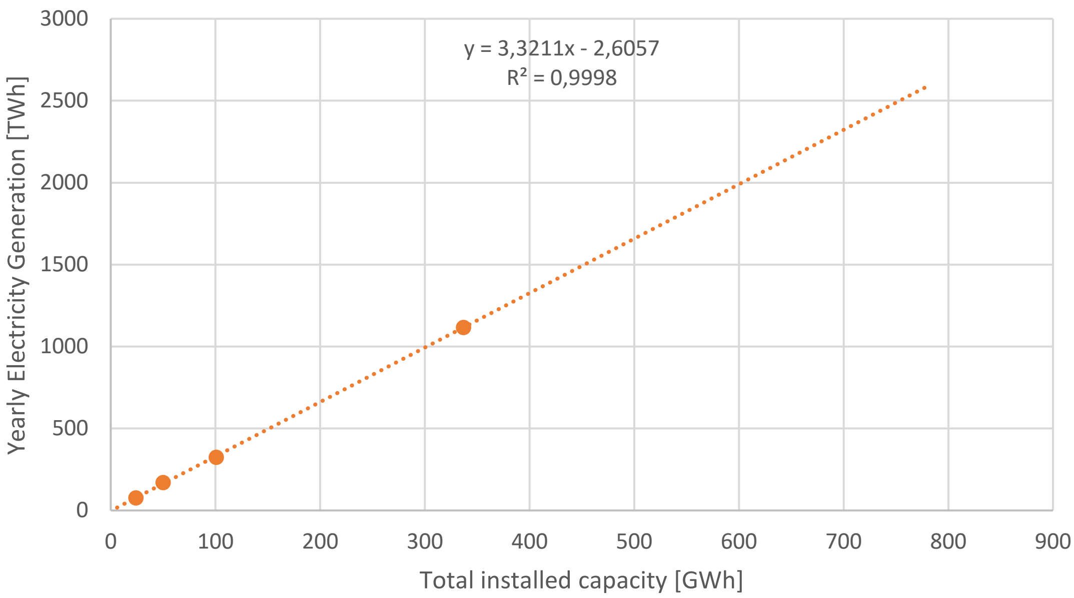


Figure 19. Evolution of the ratio between the total installed capacity and the yearly electricity generation of CSP. Personal elaboration. Data obtained from (International Energy Agency, 2016).

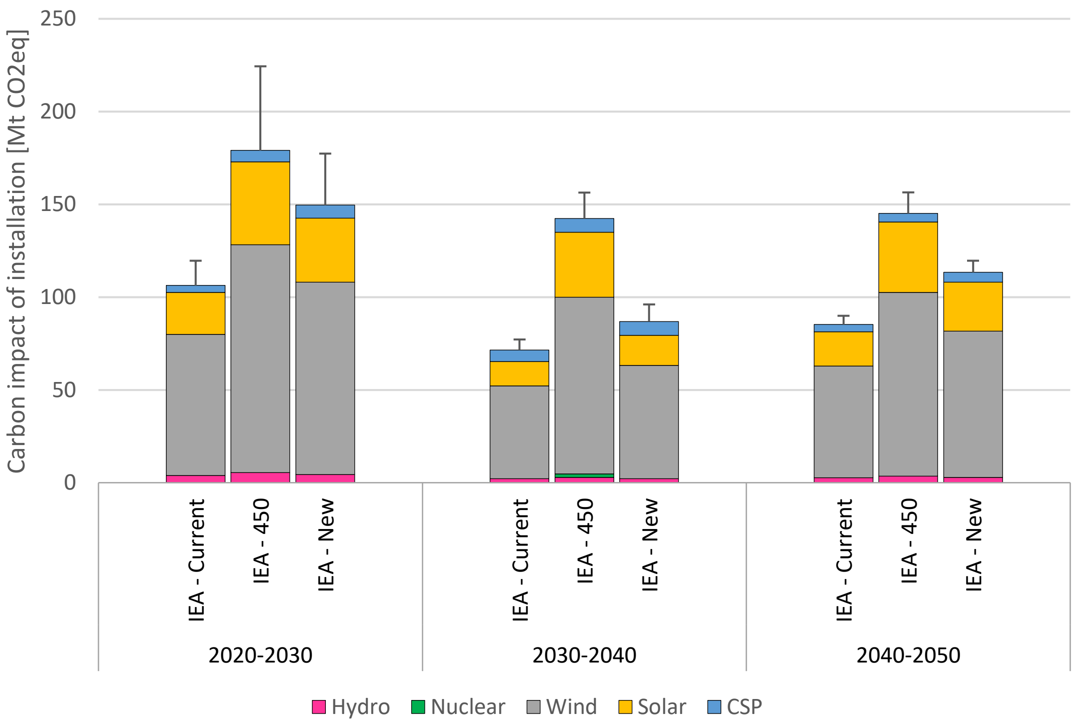


Figure 20. Cumulative carbon impacts of installation of different low carbon technologies in Europe for each ten-year period. Following the methodology in Yuan et al. (2018), error bars indicate the difference between the results obtained taking the intensity for the first year of the period or for the last year of the period. Personal elaboration.

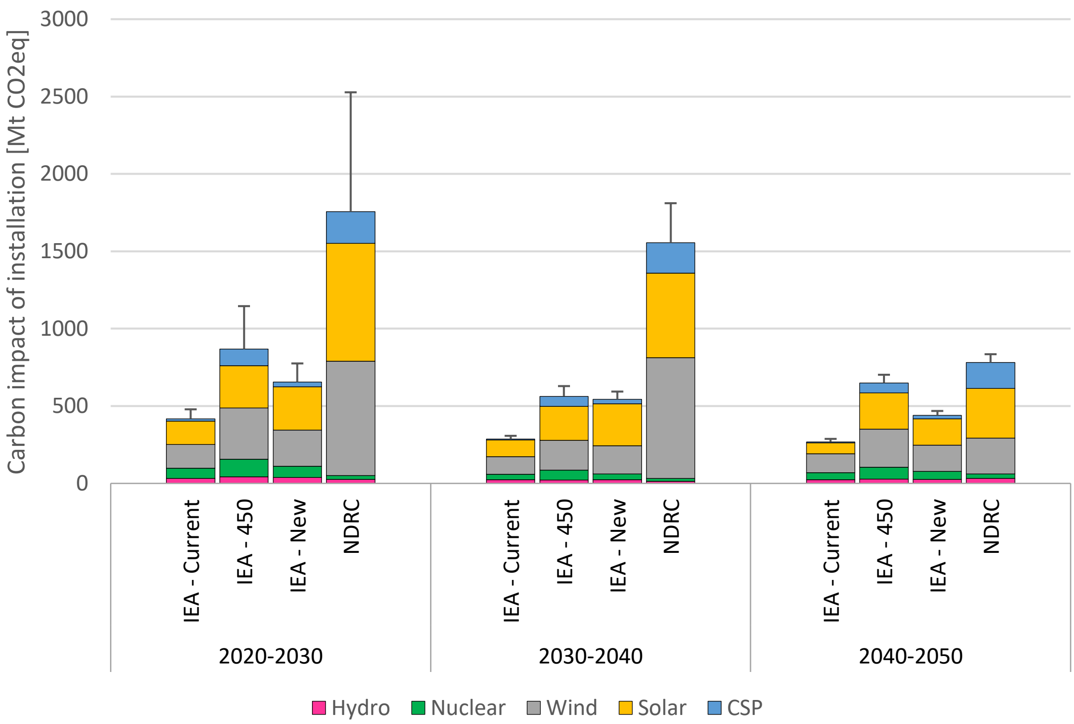


Figure 21. Cumulative carbon impacts of installation of different low carbon technologies in China for each ten-year period. Following the methodology in Yuan et al. (2018), error bars indicate the difference between the results obtained taking the intensity for the first year of the period or for the last year of the period. Personal elaboration.

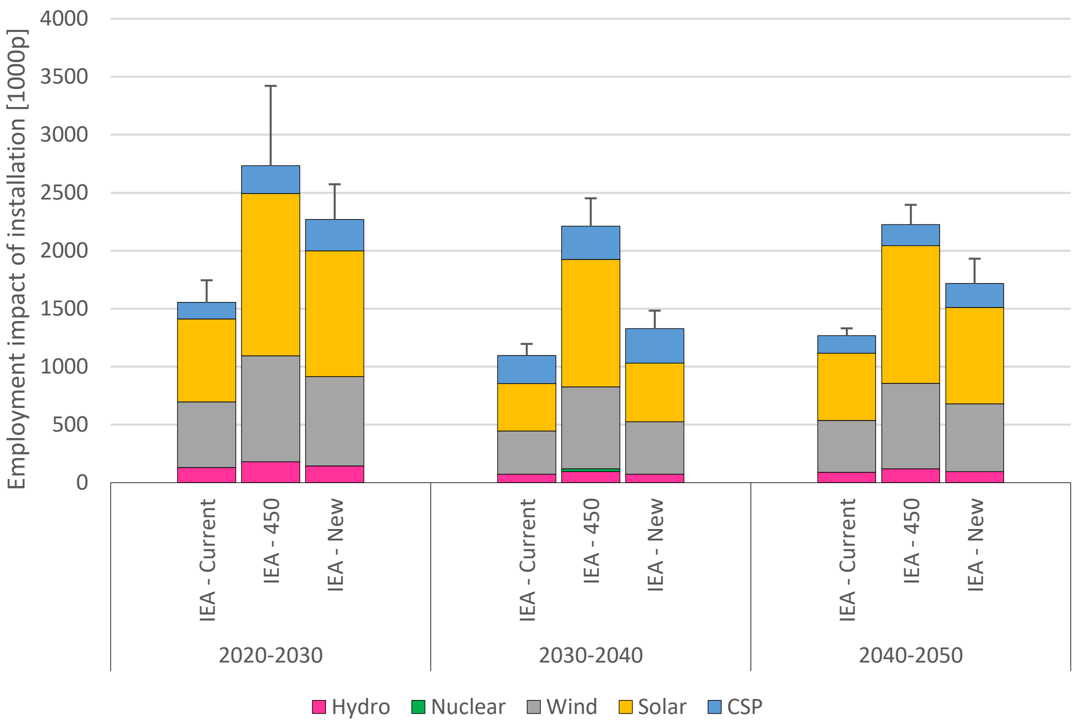


Figure 22. Cumulative employment impacts of installation of different low carbon technologies in Europe for each ten-year period. Following the methodology in Yuan et al. (2018), error bars indicate the difference between the results obtained taking the intensity for the first year of the period or for the last year of the period. Personal elaboration.

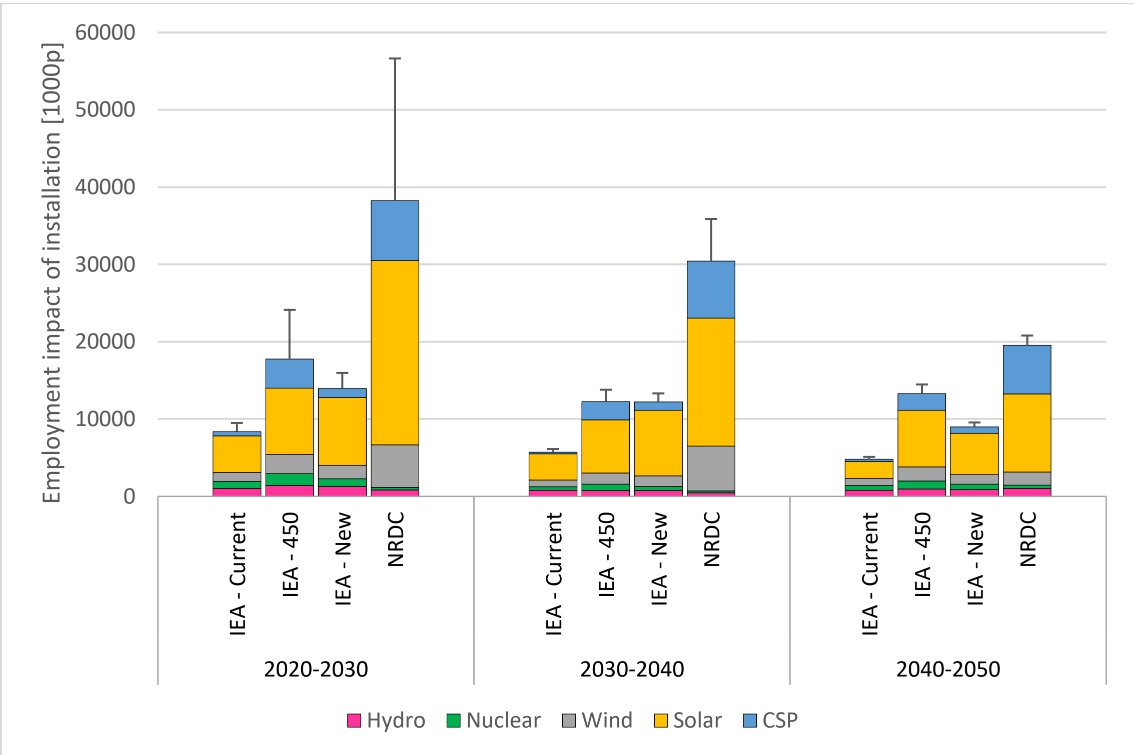


Figure 23. Cumulative employment impacts of installation of different low carbon technologies in China for each ten-year period. Following the methodology in Yuan et al. (2018), error bars indicate the difference between the results obtained taking the intensity for the first year of the period or for the last year of the period. Personal elaboration.