Life Cycle Environmental Impacts of Electricity Production by Solarthermal Power Plants in Spain

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The objectives of the analysis reported in this paper are to evaluate the environmental impacts of the electricity produced in a 17 MW solar thermal plant with central tower technology and a 50 MW solar thermal plant with parabolic trough technology, to identify the opportunities to improve the systems in order to reduce their environmental impacts, and to evaluate the environmental impact resulting from compliance with the solar thermal power objectives in Spain. The methodology chosen is the life cycle assessment (LCA), described in the international standard series ISO 14040-43. The functional unit has been defined as the production of 1 kW h of electricity. Energy use needed to construct, operate, and dismantle the power plants is estimated. These results are used to calculate the "energy payback time" of these technologies. Results were around 1 yr for both power plants. Environmental impacts analyzed include the global warming impacts along the whole life cycle of the power plants, which were around 200 g/kW h generated. Finally, the environmental impacts associated with the compliance of the solar thermal power objectives in Spain were computed. Those figures were then used to estimate the avoided environmental impacts including the potential CO_2 emission savings that could be accomplished by these promotion policies. These savings amounted for 634 kt of CO_2 equiv./yr. [DOI: 10.1115/1.2888754]

Keywords: life cycle analysis, solar energy, greenhouse gas emissions, energy payback time

Introduction

Concentrating solar thermal energy has become one of the most promising sources of energy in the past years. Its renewable and almost carbon neutral nature, the fact that it can provide energy on a large scale and its near-to-commercial technological development, has created a growing interest in this technology. There are different configurations of solar thermal power plants being the most developed ones the parabolic trough technology and the central receiver technology also called solar tower. Both are at the stage of a commercial deployment, although for the parabolic trough technology, up to 354 MW of hybrid solar thermal plants (solar electric generating system (SEGS) plants) have been successfully operated in California since 1983.

In Spain, the development of the solar thermal technology has risen due to a favorable regulatory framework, established in Royal Decree 661/2007. Two of the promotion measures regulated by this decree are around 0.25 €/kW h premium for the electricity generated by solar thermal technologies and the possibility to use some amounts of gas (in a proportion of 12–15% of total output). As a consequence, several solar thermal power plant construction projects—in different development stages—are currently being developed. The projected capacity reaches now more than 500 MW_e, which is also the goal established in the Spanish Renewable Energy Plan 2005-2010 (REP).

Given this situation, it becomes necessary to accompany this development with detailed analysis of the environmental impacts in order to show the potential benefits of this technology as well as to acknowledge which stages of the electricity production process can be improved.

There exist several environmental assessments of solar thermal technologies in the scientific literature. Weinrebe et al. [1] performed a life cycle assessment (LCA) of two plants, an 80 MW SEGS plant and a 30 MW Phoebus power tower. Viebahn [2,3] within the SOKRATES [2] and INDITEP [3] projects also conducted LCAs of different configurations of solar thermal plants, a direct steam generation (DSG) plant, a SEGS plant, and a FRESNEL-type plant. All of these studies show important benefits in terms of reduced environmental impacts for solar thermal power plants compared to other competing electricity generation technologies, especially in terms of emissions of greenhouse gases.

This study enlarges the current body of knowledge by analyzing the construction and operational environmental impacts of Spanish ongoing solar thermal power plant projects, and comparing them to those of other competing energy options. Moreover, this study analyzes the compliance of the Renewable Energy plan objectives estimating the environmental impacts avoided using these LCA results.

Methodology, Goal, and Scope

The methodology used to evaluate the environmental impact of solar thermal power plants is the so called LCA, which is a method for systematic analysis of environmental performance from a cradle to a grave perspective. This analytic tool systematically describes and assesses all flows that enter into the studied systems from nature and all those flows that go out from the systems to nature, all over the life cycle.

The practice of LCA is normalized by the series of ISO standards 14040.

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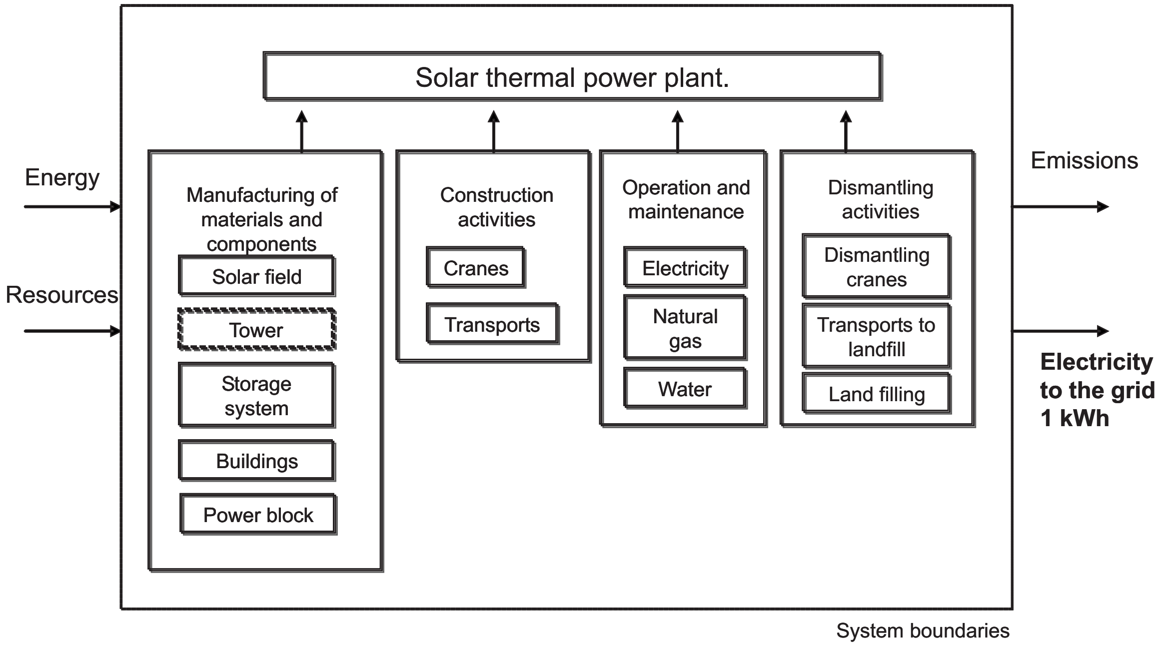

Fig. 1 Life cycle of a solar thermal power plant

A LCA study consists of four steps:

1. definition of the goal and scope of the study
2. life cycle inventory (LCI) phase: collection of all the environmental inflows and outflows
3. life cycle impact assessment (LCIA) phase and
4. interpretation of the study results

The first step is then the definition of the objectives of this study. These objectives are as follows:

- to evaluate the environmental impacts derived from the electricity production of a 17 MW solar thermal plant with central tower technology and a 50 MW solar thermal plant with parabolic trough technology, both of them hybrid operation power plants
- to identify the opportunities to improve the systems in order to reduce those environmental impacts
- to evaluate the environmental impacts derived from the compliance of the solar thermal power objectives stated by the Spanish Renewable Energies Plan 2005-10. Based on these objectives, the installed capacity in 2010 would reach 500 MW. In the considered scenario, it has been assumed that 80% of such capacity would be met by parabolic trough plants while 20% would be met by solar tower power plants.

The geographic reference of this assessment is Spain, and the time reference is 2006. The functional unit used is 1 kW h_{el} produced at the power plant. The processes modeled are the manufacturing of materials and components of the power plant, construction activities, operation and maintenance, as well as decommissioning of the power plant and the disposal of all the waste materials. Processes modeled in the life cycle of the solar thermal power plants are depicted in Fig. 1.

Data needed to perform the LCI were provided by firms investing in solar thermal power plants in Spain, complemented with data obtained from the most up-to-date LCA databases mainly from ECOINVENT V1.2 [4].

At the time of performing this LCI, some data related to the weight of materials of some parts of the power plants were missing. Consequently, the following assumptions were made.

- Weight of steel in the steam generator. Data for our plants were missing. Therefore, data from literature [5] were considered for our analysis (17.767 kg/kW_e for the central tower power plant and 9.144 kg/kW_e for the parabolic trough power plant).
- Weight of steel in the steam turbine of the parabolic trough power plant. There were no data available, and therefore data from the literature were used [5].
- Weight of molten salts in the storage system of the central receiver power plant. Only the cost of the salts was available. Based on that, and considering a unit cost of

Table 1 Impact categories assessed

Impact category	Impact indicator
Global warming	kg CO_2eq
Abiotic depletion	kg Sb eq
Ozone layer depletion	kg CFC-11 eq
Human toxicity	kg 1,4-dichlorobenzene eq
Fresh water aquatic ecotoxicity	kg 1,4-dichlorobenzene eq
Marine aquatic ecotoxicity	kg 1,4-dichlorobenzene eq
Terrestrial ecotoxicity	kg 1,4-dichlorobenzene eq
Photochemical oxidation	kg C_2H_4
Acidification	kg SO_2 eq
Eutrophication	kg PO_4 eq

Table 2 Contribution to the electricity generation system and primary energy conversion factors [8]

	%	Primary energy conversion factor
Hydro	16.21	1
Nuclear	23.87	3.03
Coal	30.23	2.81
Fuel and gas (–CC)	6.86	2.70
Gas in combined cycle	11.18	1.96
Wind	11.65	1

Table 3 Characteristics of the studied solar thermal power plants

Technology	Central tower	Parabolic trough system
Installed capacity	17 MW	50 MW
Direct normal irradiation	1997 kW h/m^2 yr	2016 kW h/m^2 yr
Number of heliostats or solar collector assemblies	2750	624
Aperture	264,825 m^2	510,120 m^2
Full load hours	6230	3220
Plant load factor	71.1%	43.6%
Technical lifetime	25 years	25 years
Energy generated per year	104,014 MW h	187,581 MW h
Energy generated in the lifetime	2600 GW h	4690 GW h
Storage capacity	16 h	7.5 h
Storage medium	Molten salts (calcium nitrate, sodium nitrate, and potassium nitrate 42:15:43)	Molten salts (sodium nitrate and potassium nitrate 60:40)
Area occupied	1,500,000 m^2	2,000,000 m^2
Natural gas consumption	48,206 MW h/yr	97,691 MW h/yr
Electricity consumption from the grid	10,757 MW h/yr	16,338 MW h/yr
Annual average solar field efficiency	45.6%	47.6%
Thermal efficiency of the cycle	39.09%	35.72%
Net efficiency	16.7%	15.7%

Table 5 EPT calculated for solar thermal power plants and some other reference values; sources for reference plants: [3,10–12]

Technology	EPT (months)
Central tower 17 MW solar thermal power plant	12.2
Parabolic trough 50 MW solar thermal power plant	12.5
Solar thermal SEGS plant	4.5
Solar thermal Fresnel-type plant	6.7
Solar thermal DSG-type plant	2.7
Wind power	3–7
Photovoltaics	0.21–8 years

Table 6 Global warming emissions in the life cycle of the solar thermal power plants in g CO_2 equiv./kW h

g CO_2 equiv./kW h	Central tower	Parabolic trough
Solar field	5.61	7.88
Power block	0.64	0.50
Storage system	9.49	14.60
Tower	0.04	
Buildings	1.03	0.46
Construction	0.18	0.34
Decommissioning	4.31E−04	1.98E−02
Subtotal	17	24
Operation	186	161
Total	203	185

0.18 €/kg, the weight of salts was estimated.

- Weight of steel in the storage system tanks. Data were missing as well. For this analysis, it was considered that, in both plants, the salts are stored in two tanks of diameter 38.2 m. Based on that, a total weight of steel was then estimated.
- There were no data available for the natural gas boilers that exist in both plants. Given this limitation, the manufacturing of this component was excluded from the analysis.

A recycling scenario in which some part of the materials is recycled after decommissioning has been considered: 40% of the steel, 40% of aluminum materials, 40% of iron, 4.57% of polyethylene terephthalate (PET), and 4.57% of polyvinyl chloride (PVC). These percentages are taken from the actual values recycled in Spain in year 2004 [6].

The LCI is performed using the software tool SIMA PRO [7].

In the LCIA the impact assessment method developed by the Leiden University Institute of Environmental Sciences (CML) was selected. This is a well known impact assessment method including many of the relevant impacts. Other impacts that could be assessed such as land or water use has not been included due to their very site specific nature that precluded a viable comparison with other electricity generation technologies. These impacts could be important in solar thermal technologies and this fact should be kept in mind. In this impact assessment method, the following impact categories are assessed (Table 1):

Furthermore, the cumulative energy consumption or demand in megajoule has been assessed. Based on this parameter, the "energy payback time" (EPT) has been calculated. EPT is defined as the time it takes for a renewable energy system to save the same amount of primary energy as is consumed for its production, operation, and dismantling. The EPT is calculated using the following formula [3]:

$$\mathrm{EPT} = \frac{\mathrm{CED}_c}{\left(\frac{E_{\mathrm{net}}}{g} - \mathrm{CED}_0\right)}$$

where CED_c is the cumulative primary energy demand for construction of the power plant, E_{net} is the yearly produced net electricity (MJ/yr), and g is the utilization grade of primary energy source to produce electricity. Since most products are assumed to be produced in Spain, this utilization grade is taken as 44.28%. This utilization grade has been calculated considering the contri-

Table 4 Cumulative energy demand in the life cycle of the solar thermal power plants in MJ/kW h

MJ/kW h	Central tower	Parabolic trough
Solar field	0.08	0.09
Power block	0.007	0.004
Storage system	0.05	0.08
Tower	3.95E−04	
Buildings	0.024	0.004
Construction	0.004	0.006
Decommissioning	−6.68E−08	−2.87E−04
Subtotal	0.17	0.19
Operation	2.62	2.26
Total	2.79	2.45

Table 7 Global warming emissions for solar thermal power plants reported in literature

g CO_2 equiv./kW h	Central tower	Parabolic trough
Weinrebe et al. [1]	23–25	17
Hybrid operation of Weinrebe et al. [1]	345	234
Kreith et al. [14]	43	
Vant-Hull [15]	11	
Uchiyama [13]	213	
Norton et al. [16]	21–48	30–80
Viehban [3]		12
Viebahn [5]	24	10
ETSU [17]	26	38

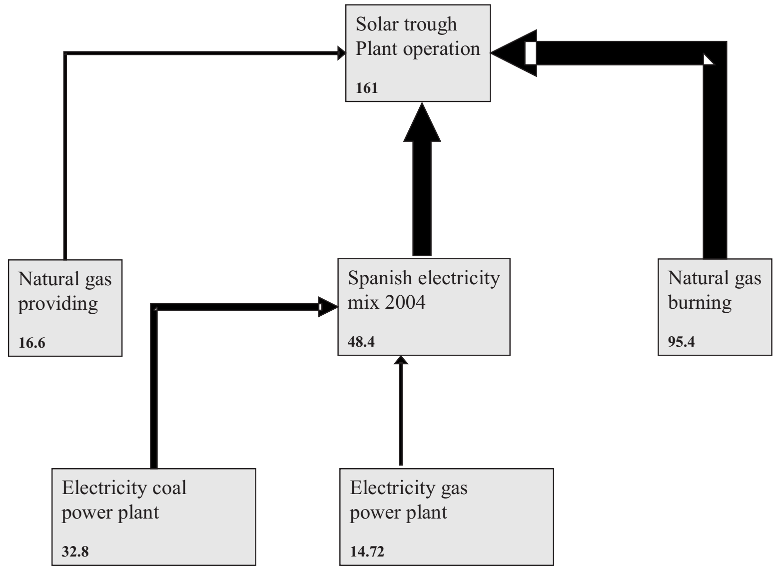

Fig. 2 Global warming emissions (g/kW h) in the operation of the parabolic trough solar thermal plant, contribution of different parts

bution to the overall production of electricity in the country and the primary energy conversion factors of the different electricity generation technologies shown in Table 2. CED_0 is the annual primary energy demand for operation and maintenance (MJ/yr).

Description of the Solar Thermal Power Plants

The characteristics of the power plants analyzed are summarized below. Details can be seen in Table 3.

A 17 MW solar thermal power plant with central tower technology and 2750 heliostats. The plant uses molten salts as heat transfer fluid. The storage system also uses molten salts and provides 16 h of stored energy. The power plant occupies a total area of 150 has. The power plant uses natural gas to produce up to 15% of the total electricity generated.

A 50 MW solar thermal power plant with parabolic trough technology consisting of 624 parabolic trough collectors. This plant uses synthetic oil as transfer fluid and molten salts to create a 7.5 h storage system. The total area occupied by the plant is 200 has. As the former plant, 15% of total output is generated by natural gas.

Both plants are located in the south of Spain, in the area of Andalucía but not in the same location. This is why direct normal irradiation is not exactly the same, and this fact has to be taken into account when comparing the results of both plants.

Results

Cumulative Energy Demand and Energy Payback Time. The estimated cumulative fossil energy demand for the life cycle of the solar thermal power plants studied is shown in Table 4.

Most of the fossil energy required comes from the operational stage and it is mainly due to the natural gas and electricity consumption. Without taking into account these energy expenses, the energy required to build and dismantle the power plants is 0.17 MJ/kW h for the central tower technology and is 0.19 MJ/kW h for the parabolic trough technology.

Results from other LCAs give values of 0.14–0.16 MJ/kW h for a SEGS-type plant [3,9]. For the central tower technology, the cumulative energy demand was not found in the available references.

Our estimated EPTs are shown in Table 5 (first two rows), in comparison with those of other technologies. Comparability of the values between our studies and those of other solar thermal plants is not straightforward. Irradiation levels are different. The values are only shown for illustration purposes. EPTs calculated for the studied plants are higher than the values reported for solar thermal power plants in the literature due to the energy consumption in operation (mainly natural gas and electricity consumption). EPTs for photovoltaic technology are very dependent on the selected technology. Very reduced EPT values have been reported recently [12].

Global Warming Emissions. Global warming emissions produced during the life cycle of the analyzed solar thermal power plants are shown in Table 6. Values are around 200 g/kW h, and most of them come from the operational stage. Emissions due to the construction and dismantling of the power plant range from 17 g/kW h to 24 g/kW h, which are similar to the values reported in the literature (see Table 7).

Values of global warming emissions reported in the literature range from 11 g/kW h to 48 g/kW h and from 10 g/kW h to 80 g/kW h for central tower and parabolic troughs, respectively, with the exception of the values reported by Weinrebe et al. [1] for hybrid operation and the values reported by Uchiyama [13]. Emissions are higher in hybrid operation for the obvious reason of natural gas consumption, which is also the case of the Spanish studied plants. Values reported in the Uchiyama study are more

Table 8 Impact analysis results

Impact category	Central tower	Parabolic trough
Abiotic depletion g Sb equiv./kW h	1.6	1.4
Ozone layer depletion mg CFC-11 equiv./kW h	0.01	0.01
Human toxicity g 1,4-DB equiv./kW h	88.3	90.2
Fresh water aquatic ecotoxicity g 1,4-DB equiv./kW h	8.7	9.3
Marine aquatic ecotoxicity kg 1,4-DB equiv./kW h	114.7	111.6
Terrestrial ecotoxicity mg 1,4-DB equiv./kW h	528.0	506.0
Photochemical oxidation mg (C_2H_4 equiv.)/kW h	28.3	26.4
Acidification mg SO_2 equiv./kW h	612.0	590.1
Eutrophication mg PO_4 equiv./kW h	49.6	49.7

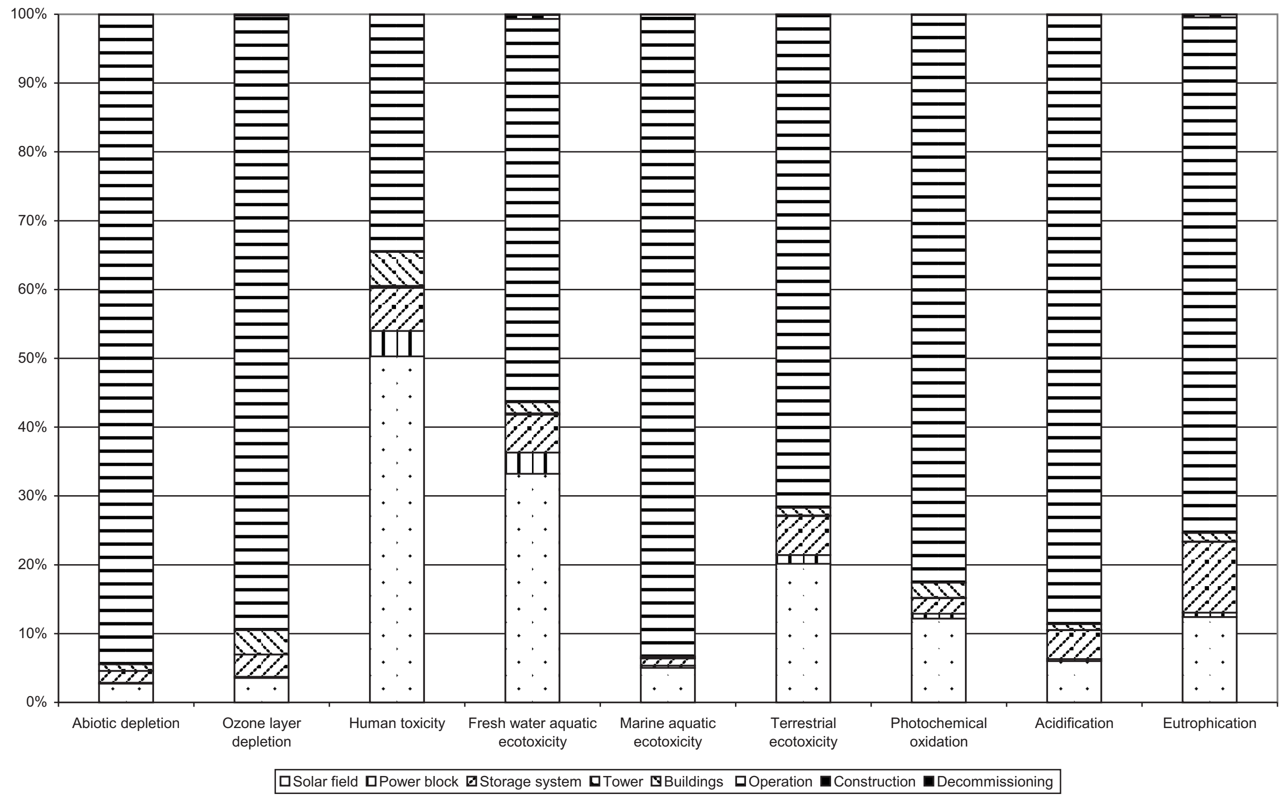

Fig. 3 Impact analysis results for the central tower solar thermal power plant

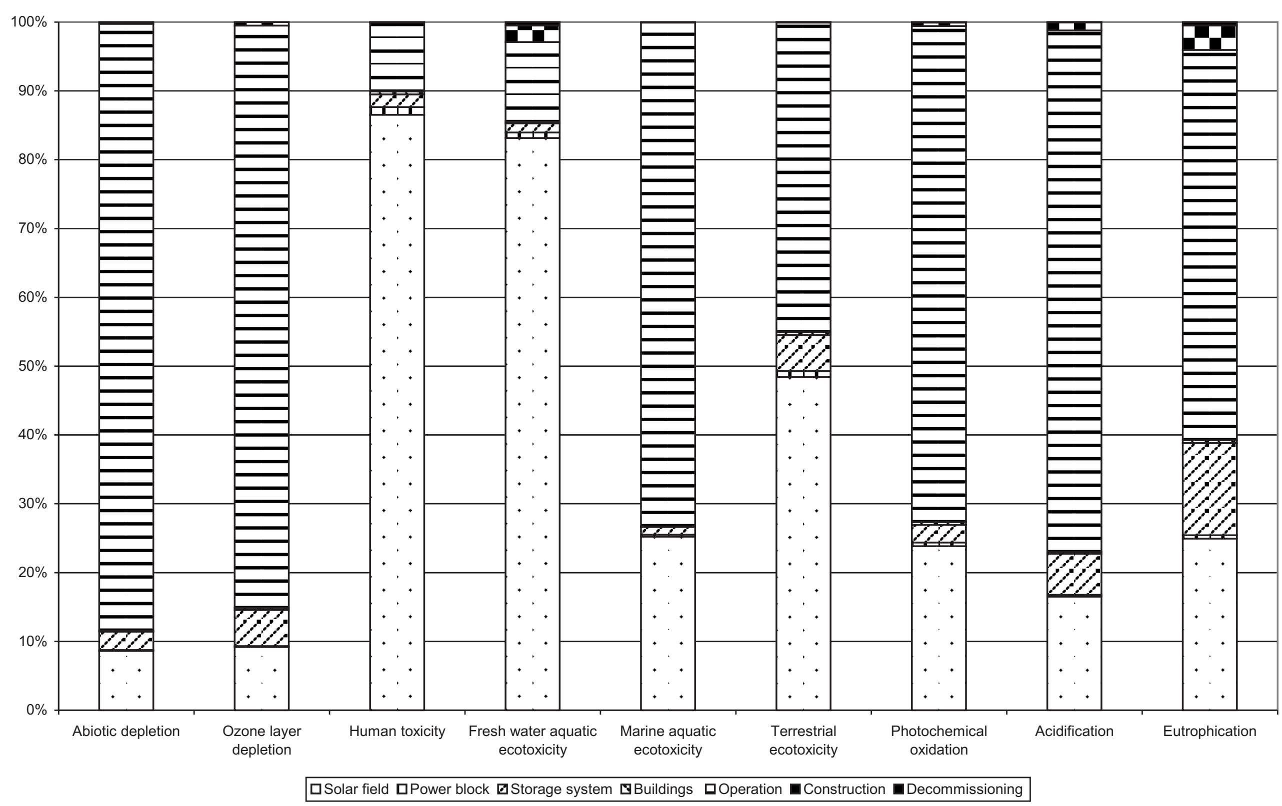

Fig. 4 Impact analysis results for the parabolic trough solar thermal power plant

difficult to explain and could be related to the more stringent building regulations for foundations and structures established in Japan, as commented by Weinrebe et al. [1].

In Fig. 2, the relative contribution of the different parts of the operational stage is depicted. It can be observed that most of the operational stage emissions come from the following:

- natural gas combustion: 95 g/kW h for the parabolic trough receiver power plant and 114 g/kW h for the central tower power plant
- natural gas provision: 16.6 g/kW h for the parabolic trough receiver power plant and 19.9 g/kW h for the central tower power plant
- electricity consumption from the grid: 48.5 g/kW h for the parabolic trough receiver power plant and 50.1 g/kW h for the central tower power plant

It is worthy to note the relevant contribution to the global warming emissions of the electricity consumption of the plants. This contribution is mainly due to the fact that an important part of the electricity generation in Spain is produced in coal power plants with very high associated greenhouse gas emissions. If the self-produced electricity was consumed to meet the electricity requirements of the plants during the operational stage, instead of taking it from the grid, the associated global warming emissions would have been much more reduced.

Other Impacts. Results obtained in the other impact categories analyzed are shown in Table 8. For some of these impact categories, values reported in the literature are lower than the values obtained in this study. Acidification values reported by Viebahn [3] are 69.28 mg SO_2 equiv./kW h for a parabolic trough plant, and eutrophication impacts are 5.69 mg PO_4 equiv. However, it is important to acknowledge that most of the impacts are produced in the operation of the power plant due to the consumption of natural gas and external electricity (as can be observed in Figs. 3 and 4).

In fact, Weinrebe et al. [1] reported similar figures for hybrid operation of solar thermal power plants: 370–510 mg SO_2 equiv./kW h for acidification and 40–56 mg PO_4 equiv./kW h for eutrophication.

Given the obtained results, the assumptions made due to lack of data available are expected to have a negligible effect on them since the most influential process in most of the considered impacts is the plant operation stage.

Table 9 Impacts produced by the Spanish electricity generation system

Impact category	Spanish electricity generation system 2004
Global warming g CO_2 equiv./kW h	485
Abiotic depletion g Sb equiv./kW h	3.96
Ozone layer depletion mg CFC-11 equiv./kW h	0.0842
Human toxicity g 1,4-DB equiv./kW h	274
Fresh water aquatic ecotoxicity g 1,4-DB equiv./kW h	45.3
Marine aquatic ecotoxicity kg 1,4-DB equiv./kW h	996
Terrestrial ecotoxicity mg 1,4-DB equiv./kW h	2340
Photochemical oxidation mg (C_2H_4 equiv.)/kW h	147
Acidification mg SO_2 equiv./kW h	3620
Eutrophication mg PO_4 equiv.	146

Compliance of the Renewable Energies Plan 2005-2010 (REP) Objectives

The last goal of this LCA was to evaluate the environmental impact derived from the compliance of the solar thermal power objectives stated by the Spanish REP.

Based on these objectives, the installed capacity in 2010 would reach 500 MW. In the considered scenario, it has been assumed

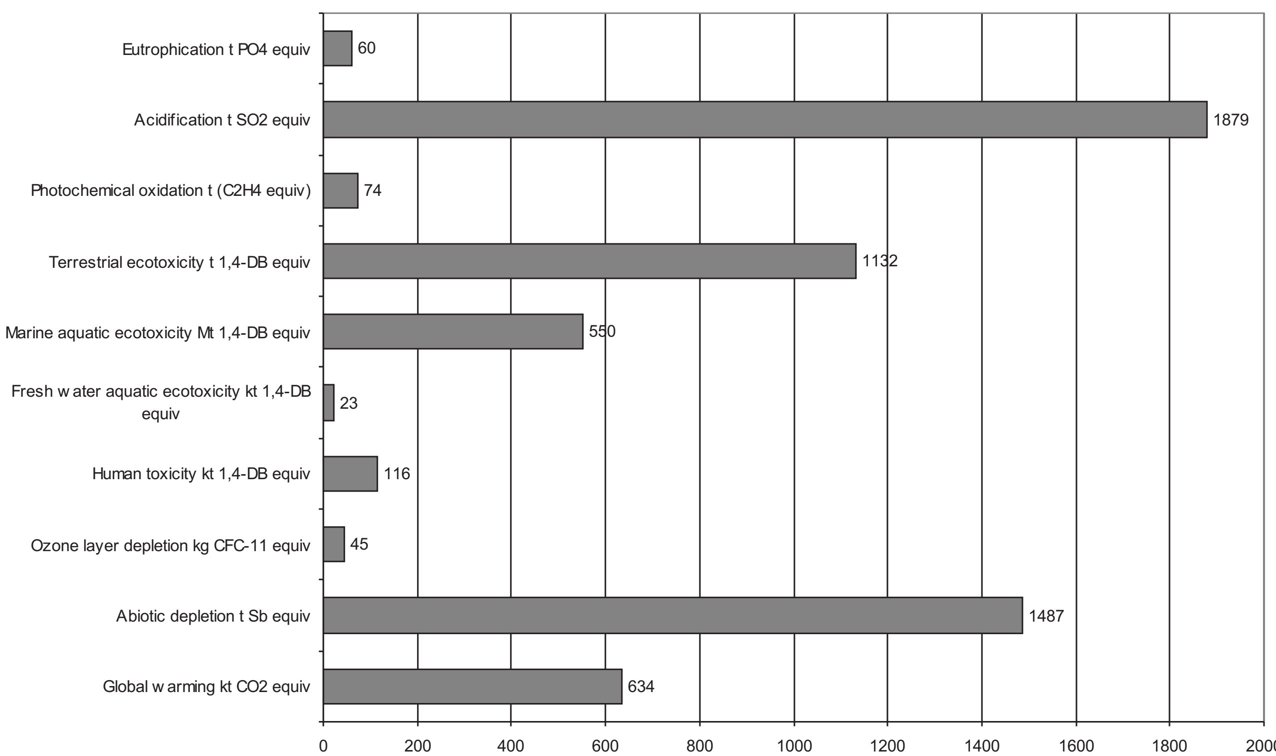

Fig. 5 Avoided impacts per year due to the implementation of the solar thermal objectives of the REP 2005-2010

that 80% of such capacity would be met by parabolic trough plants while 20% would be met by solar tower power plants. Therefore, central tower power plant technology would have a 100 MW installed capacity and parabolic trough power plant technology would have 400 MW installed. Avoided impacts are computed considering that the electricity produced in these plants would replace electricity produced by the Spanish electricity generation system (year 2004). The impacts produced by the electricity generation system are shown in Table 9.

Avoided impacts produced by the implementation of the REP have been quantified and the results are shown in Fig. 5. Avoided greenhouse gas emissions have been quantified in 634 kt/y, which represent a 0.2% of the total greenhouse gas emissions of the energy sector in Spain in year 2002.

Other important impact reductions come from acidification, terrestrial ecotoxicity, and abiotic depletion categories.

Conclusions

From the LCA performed of these two hybrid operation solar thermal power plants, some important conclusion can be drawn.

- First at all, both technologies show an environmental profile much better than the current mix of technologies used to produce electricity in Spain.
- The cumulative energy demand of the life cycle of both plants is lower than the energy produced and the EPT calculated is around 1 yr.
- The global warming emissions are around 200 g/kW h, which are much lower than competing fossil technologies. However, these emissions are mainly due to the use of fossil fuels in the operation of the plant (natural gas consumption and external electricity consumption). The fact that the electricity consumed in the plant is taken from the grid has important environmental consequences due to the high fossil share of electricity generation in Spain. These "imported" impacts could be reduced if the electricity needed in the operation of the plant were taken from the self-produced electricity. If neither natural gas nor external electricity were used, the greenhouse gas emissions would be much lower.
- Other impacts calculated are lower than those produced by the current Spanish electricity generation system, and most of them are produced in the operation of the plant due to the consumption of natural gas and electricity from the grid.
- Impacts that would be avoided by the implementation of the Renewable Energies Plan are important. Regarding global warming emissions, 634 kt of CO_2 equiv./yr would be avoided, which represent a 0.2% of the emissions of the energy sector in Spain in year 2002. Once again, if neither natural gas nor external electricity were used, the CO_2 avoided emissions would be much higher.

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