ENVIRONMENTAL ANALYSIS OF A CONCENTRATED SOLAR POWER (CSP) PLANT HYBRIDISED WITH DIFFERENT FOSSIL AND RENEWABLE FUELS.

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Abstract

The environmental performance of a 50 MW parabolic trough Concentrated Solar Power (CSP) plant hybridised with different fuels was determined using a Life Cycle Assessment methodology. Six different scenarios were investigated, half of which involved hybridisation with fossil fuels (natural gas, coal and fuel oil), and the other three involved hybridisation with renewable fuels (wheat straw, wood pellets and biogas). Each scenario was compared to a solar-only operation. Nine different environmental categories as well as the Cumulative Energy Demand and the Energy Payback Time (EPT) were evaluated using Simapro software for 1 MWh of electricity produced. The results indicate a worse environmental performance for a CSP plant producing 12% of the electricity from fuel than in a solar-only operation for every indicator, except for the eutrophication and toxicity categories, whose results for the natural gas scenario are slightly better. In the climate change category, the results ranged between 26.9 and 187 kg CO_2 eq/MWh, where a solar-only operation had the best results and coal hybridisation had the worst. Considering a weighted single score indicator, the environmental impact of the renewable fuels scenarios is approximately half of those considered in fossil fuels, with the straw scenario showing the best results, and the coal scenario the worstones. EPT for solar-only mode is 1.44 years, while hybridisation scenarios EPT vary in a range of 1.72 -1.83 years for straw and pellets respectively. The fuels with more embodied energy are biomethane and wood pellets.

Keywords: Life Cycle Assessment, Cumulative Energy Demand, Energy Payback Time, biomass, biogas, natural gas, fuel oil, coal.

1. Introduction

Concentrated Solar Power (CSP) is receiving increasing attention as a technology capable of transforming solar radiation into electricity in a sustainable and cost effective way. Spain and the USA are world leaders in the deployment of CSP technology, accumulating more than 90 % of the installed capacity worldwide. Spanish installed capacity of CSP plants amounts to 2300 MW, distributed into 50 power plants [1]. At present, other countries with high solar Direct Normal Irradiance (DNI) such as India, Chile and South Africa are also significantly increasing their CSP installed capacity. Parabolic trough solar collectors are the most mature and widely deployed of the CSP technologies, representing over 85 % of the installed capacity worldwide. Forty five of the fifty power plants installed in Spain are based on parabolic trough technology. These plants use parabolic mirrors with sun tracking systems to concentrate direct solar irradiation into a tube receiver that runs along the focal point of the collector. A Heat Transfer Fluid (HTF) circulating inside the receiver absorbs the solar energy to increase its temperature from around 295 ºC in the cold end of the system to 395 ºC at the exit of the solar field. The hot HTF is circulated through a series of heat exchangers that result in the production of a superheated steam (typically at 100 bars/375 ºC) which is used to drive a steam turbine for electricity generation, following a conventional Rankine cycle. Modern CSP plants also incorporate thermal energy storage systems, usually based on molten nitrate salt mixtures to increase the number of operating hours and their capacity factor [2].

Hybrid CSP integrates an auxiliary boiler operated with fuel to facilitate start-up operations, provide system stability, avoid freezing of HTF and increase power generation. Natural gas is used most frequently as a backup fuel due to its low cost, clean combustion and rapid response, although the use of fuel oil, mineral coal and biomass has also been reported [2-4].

The Spanish legislation regulating the feed-in tariff for electricity from sustainable resources allowed CSP plants to produce up to 12 % of their electricity from fossil auxiliary fuels [5]. Hence, most of commercial CSP plants in Spain have been operating according to this strategy in order to maximize economic revenues. This legislation was superseded by Royal Decree Law 1/2012 and Royal Decree Law 413/2014 [6], which changed the retribution system for electricity generation from renewable sources. However, for the sake of this study, we have decided to maintain the same proportion of hybridisation (12%), since most of the CSP plants currently operating in Spain generate between 12 and 15% of the electricity from natural gas combustion.

Hybridisation with fossil fuels can significantly improve the performance and profitability of a CSP plant; however, it increases its carbon footprint, reduces its share of renewable energy and, in the case of Spain, it increases its dependence on foreign natural gas and fuel oil. On the contrary, a biomass alternative allows an electricity to be produced that is fully renewable and locally available.

Biomass combustion plants' efficiency increases when operating at large scales [7]. However, this involves large amounts of available biomass and high capital investments, which so far have been the main setbacks in the implementation of this technology in Spain [8]. One alternative to solving this problem is to hybridise CSP with biomass: a large scale facility can be used to produce renewable electricity from biomass and at the same time increase power generation of the plant with transient clouds or at night. Another solution which is having increasing attention is biomass co-firing [10, 11] which usually consists of the co-combustion of biomass in coal fired power plants. However, this operation decreases the boiler efficiency and needs biomass pre-treatments.

Biomass resources from the forest and agriculture industrial sector (by-products and wastes) are some of the cheapest and most used resources. Facilities around the world are increasing the generation of electricity from these recourses, especially straw, which is one of the most abundant and utilised in the bioenergy sector [11].

The international pellet market is also growing, and it is expecting an increase of wood pellet combustion for power generation in Europe [10, 12]. In 2010 Spain produced 100,000 tons of pellets, just 1% of the European production; however, it has the potential to produce three times as much [13].

Life Cycle Assessment (LCA) is a methodology used to assess the environmental impacts of a product or system attending to all the stages of its life cycle, from extraction of raw materials to disposal of components. It evaluates the data collected in a comprehensive inventory of all the processes and the materials involved in its life cycle and determines the impacts of such activities in the form of environmental categories, such as climate change (analogue to global warming), acidification, eutrophication, depletion of fossil fuels, human toxicity or environmental ecotoxicity. LCA has been largely used to evaluate energy systems, allowing a comparison of different energy technologies and different configurations of the same technology to occur [14-17].

The environmental performance of CSP plants have been analysed before, including different configurations for thermal storage, cooling systems and hybrid modes [18-25]. Although the hybridisation of CSP plants with natural gas and biogas has been previously analysed [21, 22], never was the environmental performance of the hybridisation with coal, oil, wood pellets and straw determined; neither was an environmental comparison of these fuels analysed, assuming the same scope and methodological choices.

In this study, the environmental performance of a hybrid CSP operating in 6 different scenarios (12% of hybridization with coal, natural gas, fuel oil, biomethane, wood pellets and wheat straw) was evaluated and compared to a solar-only scenario where no hybridisation took place.

2. Methodology

An LCA model was produced for a 50 MWe commercial CSP parabolic trough plant located in the Ciudad Real (Spain). The analysis was conducted according to ISO 14040 [26] and included a flow diagram and a complete inventory of the life cycle of the process, including extraction of raw materials and manufacturing of components, construction, operation and dismantling phases. Quantification and aggregation of environmental impacts was performed using standard method ReCiPe Midpoint and Endpoint Europe (H) v1.09, with 1 MWh as the functional unit.

Cumulative Energy Demand (CED) accounts for the primary energy source consumed throughout the life cycle of the technology. CEDs were determined for different scenarios using the Cumulative Energy Demand v1.08 evaluation method, based on the method published by ecoinvent version 2.0 and expanded by PRé Consultants. Energy payback time (EPT) describes the time required by the CSP plant to generate (as net electricity output) the primary energy consumed in the construction (including extraction of raw materials and manufacturing of plant elements) and dismantling of the installation. EPTs were determined for different operating scenarios using an equation described by Lechon et al. [25].

2.1. Characteristics of the CSP plant

The installation has a lifetime of 25 years, uses synthetic oil as HTF and incorporates a 7.5 hour molten salt thermal energy storage based on a two tank configuration. The power plant location (Ciudad Real, Spain) receives a direct normal irradiance of 2030 kWh/m2/yr. The plant allows 2,800 h/yr of full load equivalent operation when operated using solar energy only for a gross electricity output of 165,687 MWh/yr. Since 16% of this electricity is consumed onsite for operation and maintenance, net energy injected into the grid amounts to 139,725 MWh/yr. The hybrid mode operation was assumed to involve an additional 12 % gross power generation from the auxiliary fuel, producing 158,703 MWh/yr of net energy. Thermal efficiency of the steam cycle is 37 %.

The minimum amount of backup energy required to operate the CSP plant (for start-up operations and anti-freezing purposes) has been estimated to be around $6.28 \cdot 10^6$ MJ/yr. This energy input is generated in a 10MWth boiler, and does not have a net contribution to electricity generation.

The plant operating in hybrid mode has two auxiliary boilers, each having a capacity of 20 MWth, with 95 % efficiency when operating with fossil fuels and 90 % with biomass. The total fuel cycle efficiency, calculated as the product of multiplying the steam cycle by the boiler efficiencies, is 33 % for straw and pellets, and 35 % for the rest of the scenarios.

Operating the CSP plant in hybrid mode would require the provision of 2.39·108 MJ/yr of auxiliary energy input. Quantities of fuel consumed in the operation phase were determined considering the low heating value of each gas as follows: natural gas 39 MJ/Nm3; coal 22.0 MJ/Kg [27], fuel oil 41.2 MJ/kg [28], mixed manure (upgraded to methane) 24.0 MJ/Nm3 [28], wood pellets 12164 MJ/m3 DM [29] and wheat straw 16.73 MJ/kg DM [9].

2.2. Life Cycle Inventories

The inventory related to the CSP plant was obtained mainly from engineers specialised in this technology, and whenever it was not possible, data was taken from established databases and scientific literature. Ecoinvent database v2.2 was used for background data.

Full inventory of the solar-only CSP plant base case, including data sources, is available in Corona et al. [22].

Boiler inventory for the operation of each hybridisation scenario have been assumed to be the same as in a natural gas combustion, considering that impacts derived by differences in design or manufacturer were negligible compared to the whole life cycle of the plant. This assumption is based on the small environmental effect of this component detected in previous studies by the authors [22]. LCA inventory of fuels was mainly obtained from the ecoinvent 2.2 database, with data adapted to the Spanish system. Specifications for each fuel are as follows:

- The impacts derived from a *natural gas* life cycle were determined by the ecoinvent database, adapting the CORES percentages of Spanish natural gas imports [30] to the following composition: 69% from Algeria, 16% Nigeria, 10.9 % Norway and 3.9% Netherlands.
- *The coal* and *fuel oil* life cycles were taken from the corresponding Spanish process available in the Ecoinvent database.
- *Mixed slurry biogas* derives from the co-fermentation of slurry from swine and cattle mixed with 20 wt% biowaste substrate made of paunch, oil and vegetable waste, (“Biogas, from slurry, at agricultural co-fermentation, covered, CH” process from Ecoinvent 2.2 detailed in Jungbluth et al. [28]). Slurry digestion usually fulfils three functions: livestock farming waste disposal, biogas production, and the production of digested matter as fertiliser. It has been reported that the storage and application of digested matter is a source of emissions of CH_4, NH_3 and N_2O, which are responsible for impacts in climate change and acidification categories. In the ecoinvent database, it is assumed that digested matter is covered to avoid such emissions, but NH_3 and N_2O are still emitted due to the application of digestate (even if the emissions which occur in addition to those that would occur with undigested manure are only reported). However, some studies analysing these emissions for digested and undigested manure, report higher emissions for these gases in undigested manure [31,32], presenting a positive impact for the digestion process. Some consequential LCA also present positive impacts for this process because of the avoided impacts when applying digestate instead of chemical fertilisers [33]. Due to these differences, for the sake of this study, the ecoinvent process was modified and a cut-off allocation method was applied [34], considering that only the impacts and benefits of biogas production are included (and not the ones of digestate application as fertilizer). Operating the CSP with mixed manure biogas would require the provision of $9.9 \cdot 10^6$ Nm^3/yr of biogas. This volume of raw biogas may only be produced in a very large centralised biogas facility, which does not exist in the place studied (Ciudad Real). Hence, operation of the CSP plant in hybrid mode was investigated assuming the upgrading of biogas to biomethane (and injected into the gas grid from different locations), which in the proposed conditions would require $6.93 \cdot 10^6$ Nm^3/yr of biomethane. The impact associated with upgrading the biogas to biomethane, as well as its injection and transportation through the gas grid was also incorporated into the model.
- *The wood pellets* were manufactured out of dried industrial residual wood with 10 % moisture content. Manufacturing processes have been taken from the ecoinvent database [28]. An average transport distance (by lorry) of 300 km from pellet mills to the CSP plants was assumed. The only data for the combustion of wood pellets available in established databases

was found to be for a 50 kW furnace. It has been reported that emissions in large-scale industrial boilers are lower than in small combustors due to the higher combustion efficiency in the former [35]. Hence, taking a precautionary perspective, NOx and particulate emission values from a 50 kW furnace (as included in ecoinvent 3.0 database) were reduced by 90 %. It is assumed that 50 % of the combustion ashes were disposed of in a landfill and 50 % was spread in soil, as assumed in the corresponding ecoinvent process.

- *Wheat straw* is transported and burned in the form of bales with a moisture content of 10 %. Soil cultivation, harvesting and the processing of straw were included in the study with an economic based allocation for cultivation and harvesting of 7.5 % [36]. A wheat straw yield of 2300 kg/ha, according to Spanish values, was assumed [11]. The average distance for transportation of straw bales to the CSP plant was assumed to be 70 km (by lorry), transporting in each trip a maximum of 25 bales of 700 kg each. Emissions data for the combustion of straw bales were taken from Nielsen et al. [37], taking into account the reduction due to the gas treatment system defined for the wood scenario. Straw is known for producing high amounts of ash during combustion compared to other forms of biomass. Different values for ash generation are reported in scientific literature, varying from 3 to 11 %. In this study, an ash production of 6.3 % (of dry fuel mass) was assumed as an average of the values reported in 6 different studies [9, 38-42]. Composition of ash was extrapolated from data about solid straw biofuel composition in standard UNE EN 14961:2011 [43]. Straw ashes are disposed of by landfarming.

3. Results and discussion

The life cycle impact associated with the generation of 1 MWh of electricity in the solar-only mode CSP plant and the hybrid CSP plant operating on different fuels is described in Table 1.

The characterised results suggest that the operation of the CSP plant in solar-only mode produced the lowest environmental impact in almost every category. This was especially relevant in regards to climate change (26.9 kg CO2 eq), terrestrial acidification (168 g SO2 eq) and photochemical oxidant formation (160 g NMVOC) categories. Utilization of different auxiliary fuels had a determinant effect on the environmental performance of the plant. The coal scenario produced the highest scores in every category except for natural land transformation (whose highest score was found in the fuel oil scenario).

Table 1 Characterised values for a CSP plant operating on different fuels compared to a solar-only operation.

		Hybrid CSP (12% fuel)						Solar-only
		Natural gas	Coal	Fuel oil	Biomethane	Wood pellets	Wheat straw	
Climate change	kg CO_2 eq	125	187	159	64.1	37.5	34.2	26.9
Terrestrial acidification	g SO_2 eq	216	1686	1024	284	277	286	168
Freshwater eutrophication	g P eq	9.4	84.7	12.6	14.9	14.9	11.3	10.0
Human toxicity	kg 1,4-DB eq	12.1	64.3	20.1	20.0	21.4	19.4	13.0
Photochemical oxidant formation	g NMVOC	300	892	844	276.1	242	213	160
Particulate matter formation	g P eq	89.1	524	323	107	105	96.9	68.3
Freshwater ecotoxicity	g 1,4-DB eq	306	1600	420	480	428	355	329

Marine ecotoxicity	g 1,4-DB eq	324	1579	549	495	461	348	340
Natural land transformation	m^2	0.020	0.011	0.070	0.010	0.011	0.006	0.005

Figure 1 shows the normalised profile for each case scenario. The represented values show the differences between the normalised results for each case and the corresponding solar-only value. The negative values for a natural gas scenario (in freshwater eutrophication and toxicity) indicate a better performance for that scenario than in a solar-only operation, due to the increase of electricity generation and the low impact of this life cycle fuel on those categories (as indicated in Corona et al. [22]).

Results of each category of the hybrid scenarios are described in the following sections.

3.1. Climate Change

The hybrid scenario with the lowest impact on climate change, after the solar-only scenario, is wheat straw (34.2 kg CO_2 eq), followed closely by wood pellets (37.5 kg CO_2 eq). The biomethane scenario impact (64.1 kg CO_2 eq) almost doubles the one for the straw and pellets scenarios, but it is also half of the impact of a natural gas scenario (125 kg CO_2 eq). Impacts in coal and fuel oil scenarios are even higher (187 and 159 kg CO_2 eq). These higher impacts in fossil fuels are mainly due to the emissions given off during fuel combustion. In the case of a biomethane scenario some methane leakage takes place due to the upgrading process (from biogas to biomethane).

3.2. Acidification

The highest impact in acidification is found with the coal and fuel oil scenario, whose value is almost one order of magnitude greater than in other scenarios. This high impact in both cases is due to the combustion emissions given off during the operation of the power plant.

The biomethane scenario result in acidification is quite similar to the wood and straw ones, and its main contributing activity is the upgrade from biogas to biomethane (34% of the acidification impact in the whole life cycle of the plant). However, it has been detected that the acidification results could change significantly depending on the end of life allocation method used for the digestate (as introduced in the methodology section). When using data provided by ecoinvent, the digestate emissions are responsible for increasing the acidification potential of the system studied to 1320 g SO_2 eq (instead of 283 g SO_2 eq), and the global warming potential to 102 kg CO_2 eq (instead of 63.4 kg CO_2 eq). However, when considering the benefits of substituting the digestate for chemical fertilisers, impacts reported in biogas production literature for acidification are below zero [33].

In the case of the wood scenario, the main activity contributing to acidification impacts is the pellets manufacturing (34%), and for the straw scenario, the main contributor is the wheat cultivation (35%).

3.3. Toxicity categories (human, marine and freshwater) and eutrophication

The coal scenario result in the human toxicity category more than triples the impact of the other scenarios. Impacts in toxicity from the coal case scenario derive primarily from the disposal of coal mining spoil, which is associated with high concentrations of contaminants, especially heavy metals [44, 45]. That activity is associated with 65% of the marine ecotoxicity impact for the whole life cycle of the plant and 66% of human toxicity, but also the disposal of coal combustion ash contributes to the toxicity categories with 8.8% and 6.1% respectively. Eighty seven percent of the freshwater eutrophication impact for the coal scenario (which is more than five times higher than in the others scenarios) is also derived from the disposal of mining spoil.

Wood pellets are the second scenario and have the highest impacts on human toxicity. This is mainly due to the emission of contaminants during pellets combustion, which contributes to 46% of the impact in the human toxicity category (for the whole life cycle of the plant), but also because of the manufacturing of pellets, with a contribution of 15%. This last process is also responsible for 24% of the impact in marine ecotoxicity.

The biomethane scenario presents similar impacts than the wood one in marine ecotoxicity and freshwater eutrophication. Main impacts in these categories for the biomethane scenario are due to the upgrading of biogas to biomethane, which contributes to a 34% (in marine ecotoxicity) and 35% (in freshwater eutrophication).

3.4. Photochemical oxidant formation and particulate matter formation

Coal and fuel oil scenarios again have the highest impact in photochemical oxidant formation and particulate matter formation. In both cases, the main impact is due to the emissions during combustion, which contributes to more than 65% of the life cycle impact in both scenarios and categories.

The results for other scenarios are higher than in the solar-only scenario mainly due to the emissions given off during combustion and production of each fuel, except for wood pellets whose impact is mainly attributed to the electricity consumption during its manufacturing.

3.5. Natural land transformation category

The results suggest that natural land transformation is the category with the biggest differences regarding the solar-only operation, and it also has the highest values in almost all the scenarios except for wheat straw and coal, whose main impact is associated with toxicity and eutrophication respectively. The fuel oil scenario has four times the impact on natural land transformation than the natural gas scenario (the next scenario most impacted in this category), due to the high level of transformation of natural land when building the extraction wells. Wood pellets have more impact in this category due to the land used in the production of wood, even if it comes from industrial wood waste with an allocation of 1%.

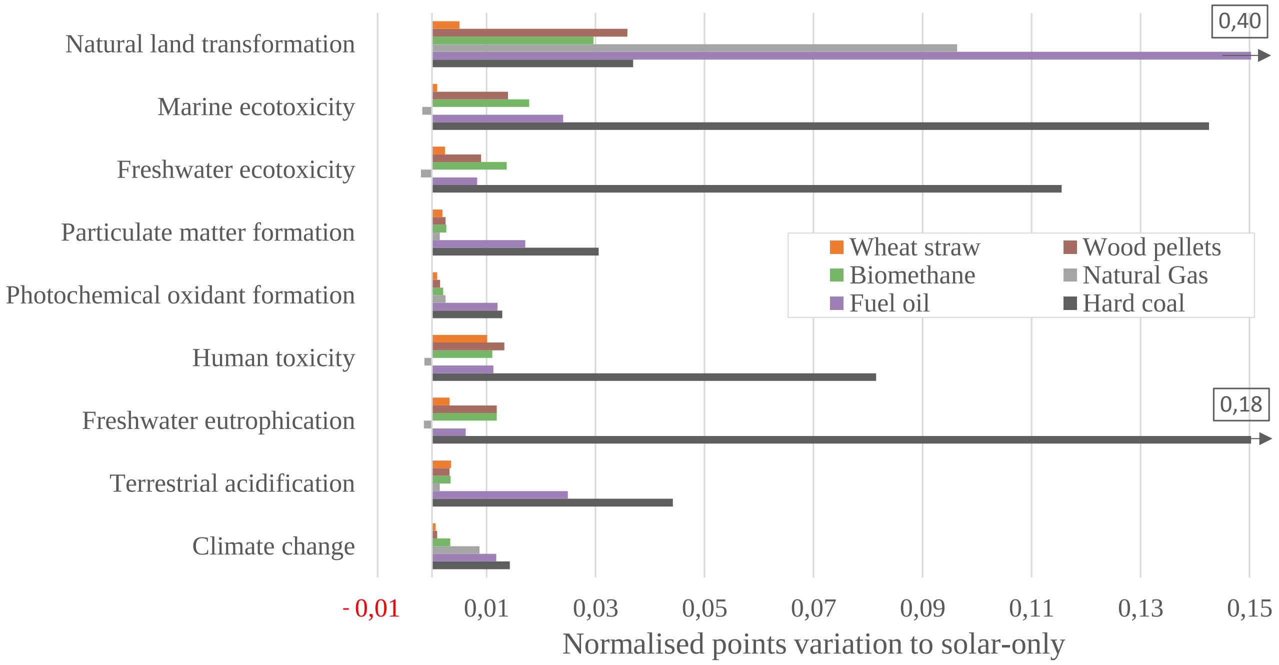

Figure 1 Variations in the normalised profile of the CSP technology hybridised with different fuels with respect to solar-only scenario

3.6. Single score

As shown in Figure 2, the single score (sum of weighted results according to ReCiPe Endpoint Europe H) evidences that solar-only configuration is the best environmental option, followed by biomass derived fuels. Fossil fuels more than double the single score value compared to renewable fuels.

In the case of biomass derived fuels, the biomethane scenario performs better in ecosystems than straw and wood, however it has more impacts on human health (mainly due to the sulphur dioxide and hydrogen sulphide emitted during the upgrading process). The wood scenario's higher impact on ecosystems is due to a greater electricity consumption in pellets manufacturing. Main impacts in the straw scenario are derived from the wheat cultivation (25% contribution of this process to the single score indicator).

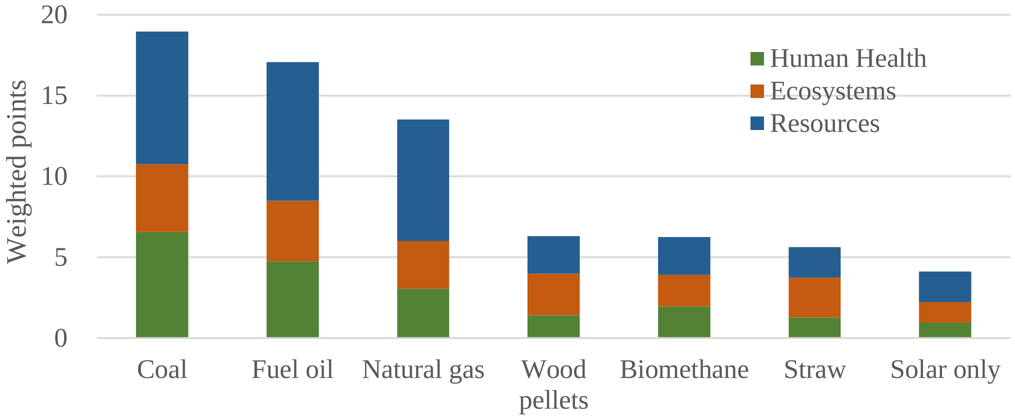

Figure 2 Weighted LCA profiles of the CSP plant operating on different fuels and in solar-only configuration

3.7. Energy indicators

The cumulative energy demand associated with the manufacturing, construction and dismantling phases (CEDc) and the Cumulative Energy Demand associated with the operation and maintenance phase (CEDo) were calculated for each scenario and compared to the solar-only operation. Raw energy from renewable resources (solar, wind, hydro energy) is not included in the calculations.

Results are described in Table 2. CEDc in hybridisation scenarios is slightly higher (1.3%) than in solar-only mode, due to the inclusion of extra boilers for the fuel's combustion. CEDo results vary significantly in each scenario, since it accounts for the fuel's embodied energy. The energy indicators suggest higher energy intensity for the renewable fuels, except for wheat straw, whose CEDo is the lowest ($3.873 \cdot 10^8$ MJ/yr) followed closely by natural gas ($3.876 \cdot 10^8$ MJ/yr).

Higher embodied energy in biomethane and wood pellets is mainly derived from the electricity consumption in their manufacturing process.

The total cumulative primary energy demand per functional unit of the CSP plant operating with solar energy was only calculated to be 1158 MJ/MWh. Total CED results (per functional unit) for the six hybridisation scenarios more than doubled the result for the solar-only mode, increasing its value from 2.4 to 2.7 times.

Based on CED values, the EPT of each scenario was also calculated. Calculations where made according to the following equation:

$$EPT\ (yr) = \frac{CED_c}{\left(\frac{E_{net}}{g} - CED_o\right)} \qquad [25]$$

E_{net} represents the yearly net electricity output of the plant (in MJ/yr), CEDc is the cumulative primary energy demand associated with extraction, manufacturing, construction and dismantling of the CSP plant (in MJ) and CEDo is the cumulative primary energy demand associated with operation and maintenance (in MJ/yr). The average efficiency in the transformation of primary energy to electricity is represented by g, and has been calculated to be 48.74 %, using data from the Spanish National Energy Report for 2011 [46].

EPT results for solar-only mode were1.44 years, while hybridisation scenarios' EPT vary in a range of 1.72-1.83 years (see Table 2). These results are in accordance with the CED results, since a higher EPT is related with a higher amount of the energy embodied in the fuels considered.

Table 2 E_{net}, CED and EPT of the CSP plant operating in solar-only mode and fuel hybridisation alternatives.

	CEDc (MJ)	CEDo (MJ/yr)	Enet (MJ/yr)	CED (MJ/MWh)	EPT (yr)
Natural Gas	1.348E+09	3.876E+08	5.713E+08	2782	1.72
Hard coal	1.348E+09	4.079E+08	5.713E+08	2910	1.76
Fuel oil	1.348E+09	4.226E+08	5.713E+08	3003	1.80
Biomethane	1.348E+09	4.264E+08	5.713E+08	3026	1.81
Wood pellets	1.348E+09	4.338E+08	5.713E+08	3073	1.83
Wheat straw	1.348E+09	3.873E+08	5.713E+08	2780	1.72
Solar-only	1.331E+09	1.086E+08	5.030E+08	1158	1.44

4. Conclusions

According to the ReCiPe Endpoint evaluation method, the solar-only operation of the Concentrate Solar Power plant produced the best environmental performance from a life cycle point of view, even considering that the power generation is lower than in the hybrid mode. Hybridisation significantly affected the environmental performance of the plant, while renewable fuels were the best environmental option to hybridise, having less than half the impact than that of fossil fuels. The coal scenario, whose main impacts derived from the coal mining spoil, was the worst case.

Single endpoint score impact presented similar results for the three renewable fuel case scenarios; however, their performance in characterised environmental categories presented significant differences in the categories of human toxicity, climate change, marine ecotoxicity and natural land transformation. Terrestrial acidification in the biomethane scenario was similar to the other biomass derived fuels, yet a high sensitivity has been observed in this category as well as in that of climate change, according to the allocation method for manure digestate. The main contributor for environmental impact in the wheat straw scenario was the cultivation of wheat, representing 25% of single score impact. The main environmental impacts in the wood pellets scenario were derived from the pellets manufacturing process and emissions during combustion. However, natural land transformation was the category most affected due to the impact associated with wood acquisition from forests.

Energy results indicated the lowest Cumulative Energy Demand (1158 MJ/MWh) in the solar-only mode, and hence, the lowest Energy Payback Time (1.44 yr). Cumulative Energy Demand results for the six hybridisation scenarios more than doubled the results for the solar-only mode, increasing its value from 2.4 to 2.7 times. The fuels with more embodied energy were biomethane and wood pellets.

The straw scenario had the lowest impacts both in the environmental single point indicator and the energy indicators.

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