Life Cycle Assessment and Environomic Optimization of Concentrating Solar Thermal Power Plants

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Abstract: The number of Concentrating Solar Power (CSP) plants in operation and under planning is currently growing. The assessment and the optimization of their performances are required both at the economic level and at the environmental level. Life Cycle Assessment (LCA) has been proven to be suitable for the environmental assessment of renewable energy technologies, since it accounts for the impacts generated over the full life cycle. This paper presents first a comparative LCA of four different CSP plants using data of recently built power plants: parabolic trough (Andasol), tower (Gemasolar), Fresnel (PE2) and dishes (Maricopa). The Impact2002+ method is used to assess their impacts on human health, ecosystem quality, climate change and resources. A sensitivity analysis on the key design parameters of CSP plants is as well performed. Subsequently, a multi-objective environomic optimization is run with selected decision variables to minimize simultaneously the levelized cost of electricity and the environmental impacts. The hybridization with natural gas is considered. The issue of the optimal value of the CO_2 tax ensuring the competitiveness of CSP over its fossil competitors is as well addressed. The results of the LCA demonstrate that more than 86% of the impact is due to the construction phase. In general, the solar field construction has the highest contribution to the impact. In addition, the storage system and the heat transfer fluid (HTF) may have as well a significant impact, in particular for trough plants. However, when compared with its fossil competitors, CSP has a much lower impact for most of the impact categories. The optimization highlights the trade-off between the investment costs of the CSP plant and its environmental impacts. The optimal range for the hybridization ratio is between 70% and 20%. The breakeven value of the CO_2 tax favoring CSP over coal or natural gas is between 54 and 174 $/ton of CO_2-eq, depending on the CSP technology and the hybridization ratio.

Keywords:

Concentrating Solar Power, Life Cycle Assessment, Multi-Objective Optimization, Environomic.

1. Introduction

At the beginning of 2012, the solar thermal power plants in operation worldwide achieved a total capacity of 2’103 MW_e [1], while new plants were under construction for 2’662 MW_e of additional capacity. Besides, more than 13’000 MW_e were under planning, which means with signed agreement or within short-term national programmes.

Despite this high growth rate, the sector is still at an early stage of its learning curve in comparison with other renewable technologies such as photovoltaic (70 GW_e) and wind (250 GW_e). Therefore the continuous assessment and optimisation of the energy performance, the economic performance and the environmental impact of solar thermal power plants are required. In a simplified statement, solar thermal power plants have to convert solar radiation into as much electricity as possible, and at the same time cost as less money as possible, with lower environmental impacts than fossil-based or other renewable-based power plants.

The literature on LCA of CSP technologies shows three levels of analysis: first, the entire CSP industry sector, second, a given CSP technology (trough, tower, …), and third, specific elements of a CSP plant (mirrors, structure, tubes, …). Regarding the entire CSP sector, for example Lechòn [2] performed the LCA of the Spanish sector, resulting in around 1 yr of energy payback time and 200 g of CO_2-eq per kWh_e over the plant lifetime (see also review by Varun [3]). Then looking at given CSP technologies, Burkhardt [4,5] performed the LCA of a trough plant, as well as the review of LCA analyses of both trough and tower plants: for instance, the studied trough plant showed a much lower emission of 26 g of CO_2-eq per kWh_e and a water consumption of 4.7 L/kWh_e. Third, the

LCA of specific elements of the plant, such as the heliostats, has been proposed by Heath [6] and resulted in 5300 kg of CO_2-eq and 274 m^3 of water for a 148 m^2 heliostat.

This paper presents first a comparative LCA of four different CSP plants using data of recently built power plants: parabolic trough (Andasol), tower (Gemasolar), Fresnel (PE2) and dishes (Maricopa). The Impact2002+ method is used to assess their impacts on human health, ecosystem quality, climate change and resources. A sensitivity analysis on the key design parameters of CSP plants is as well performed. Subsequently, a multi-objective environomic optimization is run with selected decision variables to minimize simultaneously the levelized cost of electricity and the environmental impacts. The hybridization with natural gas is considered. The issue of the optimal value of the CO_2 tax ensuring the competitiveness of CSP over its fossil competitors is as well addressed.

2. LCA of CSP technologies

Life Cycle Assessment (LCA) is a standardized method [7,8] to quantify the environmental impacts of a product, a system or a service, from cradle-to-grave and related to its function. It consists in four different stages: the goal and scope definition, the life cycle inventory (LCI), the impact assessment and the interpretation.

2.1. Goal and Scope

The goal of the following LCA is to analyze and compare the ecological impacts of the different CSP technologies, based on the data from existing power plants: Andasol (trough), Gemasolar (tower), PE2 (fresnel) and Maricopa (dish) power plants. Therefore, the environmentally most competitive power plant can be identified, as well as the processes and materials that are critical for the environmental performance of the different CSP technologies. Moreover, the power plants are as well compared with their fossil competitors, coal, natural gas and nuclear, respectively.

The functional unit of the LCA is defined as 1 MWh_e electric produced at the power plant with a lifetime of 25 years. Every quantity used in the system is calculated per MWh_e. To perform a fair comparison, the location of the four CSP is supposed identical and is situated near La Luisiana in Spain, 50 km from Seville, which is the precise location of Gemasolar. The direct normal irradiance (DNI) is 2000 $kWh/m^2/yr$ according to the irradiation map of Spain. No hybridation (use of natural gas combustion to support electricity generation) is taken into consideration in this first part of the LCA. Since Gemasolar and Andasol produce 15% of electricity by hybridation, which is the maximum percentage authorized by the Spanish government, this electricity production is deduced from the total electricity generated.

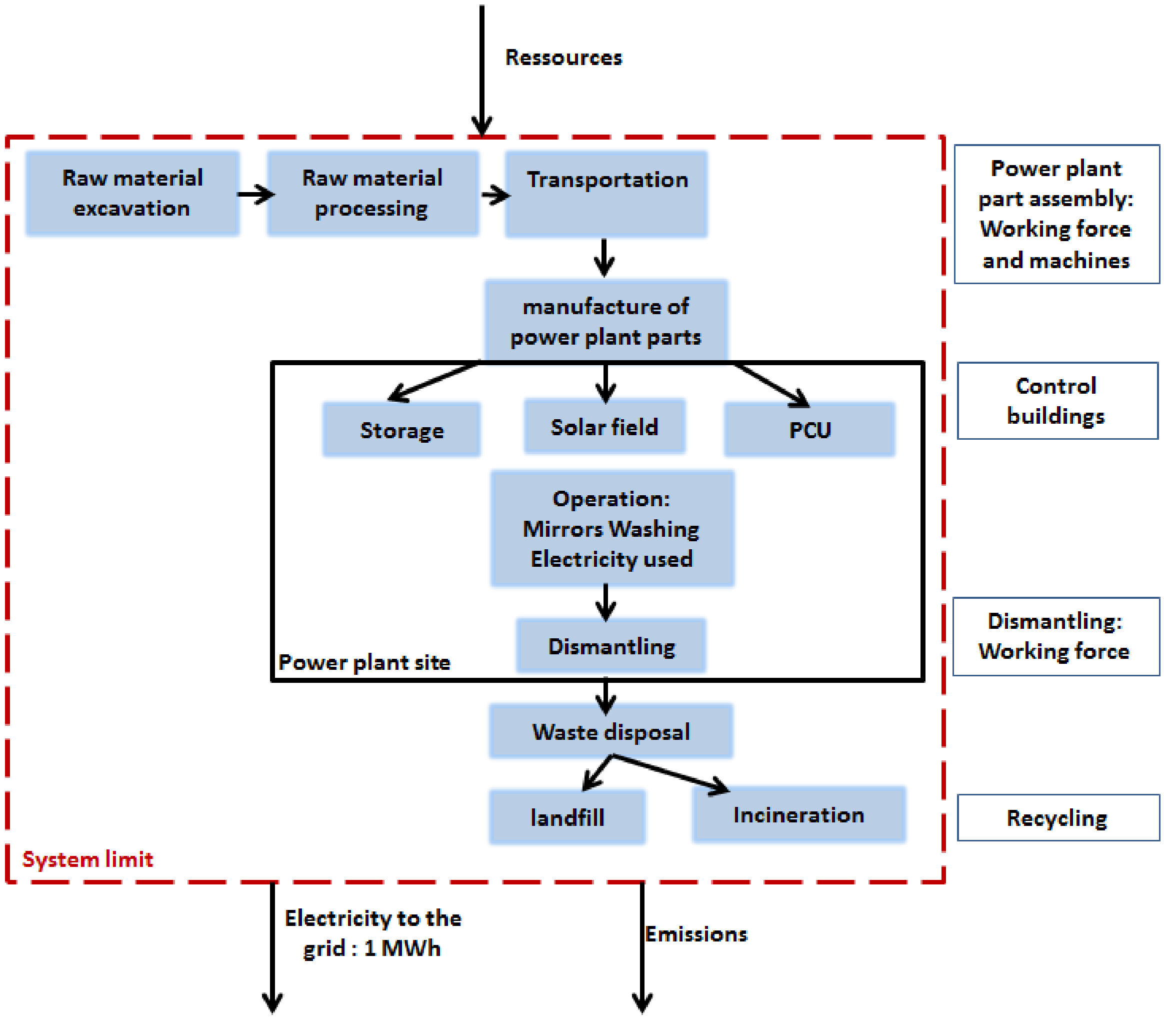

Fig. 1. System limits of the LCA

Fig. 1 shows the system limits of the present study including the stages from cradle-to-grave. During the construction phase, different parts are considered for each type of power plant, which are inventoried in the next section. The operation phase takes into account the water and its transport to clean the mirrors, the electricity used by the pumps, fans and drives and, depending on the power plants, the cooling water used in the condenser. After the use phase, power plants are dismantled. Some materials are brought to landfill or incineration depending on the type of waste. A given percentage for each material is recycled. However, the recycling process itself is not accounted for, since recycled products are not used in this system but in another product cycle. The building and the working force are also out of the system. The land occupation is not included in the system. Indeed, the land occupation impact on ecosystem quality category would be overestimated, most of power plants being located in the middle of a desert where no or few species live.

2.2. Life Cycle Inventory

For each element included in the life cycle inventories, the LCI database ecoinvent©, version 2.2 of 2010, is used [9].

The Andasol inventory is based on direct information provided by the manufacturer and on the information available in [10]. The Gemasolar inventory is based on [11-14]. The PE2 inventory is based on [15,16] and on the information provided by Novatec-Biosol. The Maricopa inventory is based on [17,18] and on the information provided by SES.

The detailed inventories with the quantities of materials and ecoinvent© equivalences are attached in Appendix A, in Tables 1 to 5. For the impact associated with the process equipment, such as turbines, pumps and heat exchangers, the impact scaling methodology developed by [19] is used.

2.3. Impact Assessment and interpretation

The impact assessment aims at converting the emissions and extractions of single substances from the LCI in a reduced number of categories having an environmental significance. In the present study, the Impact2002+ method [20] is used to measure the effects on four endpoint categories: the human health, the ecosystem quality, the climate change and the resources. The normalized damage unit for each category is the eco-point.

2.3.1. Comparison and analysis of the 4 CSP

The results for the impact assessment of the four CSP with the detailed contributions of each part of the power plant over its life cycle are displayed in Fig. 2 for the detailed impact categories. The total impact of the four CSP, obtained by adding the impact categories to each other, is displayed in Fig. 3.

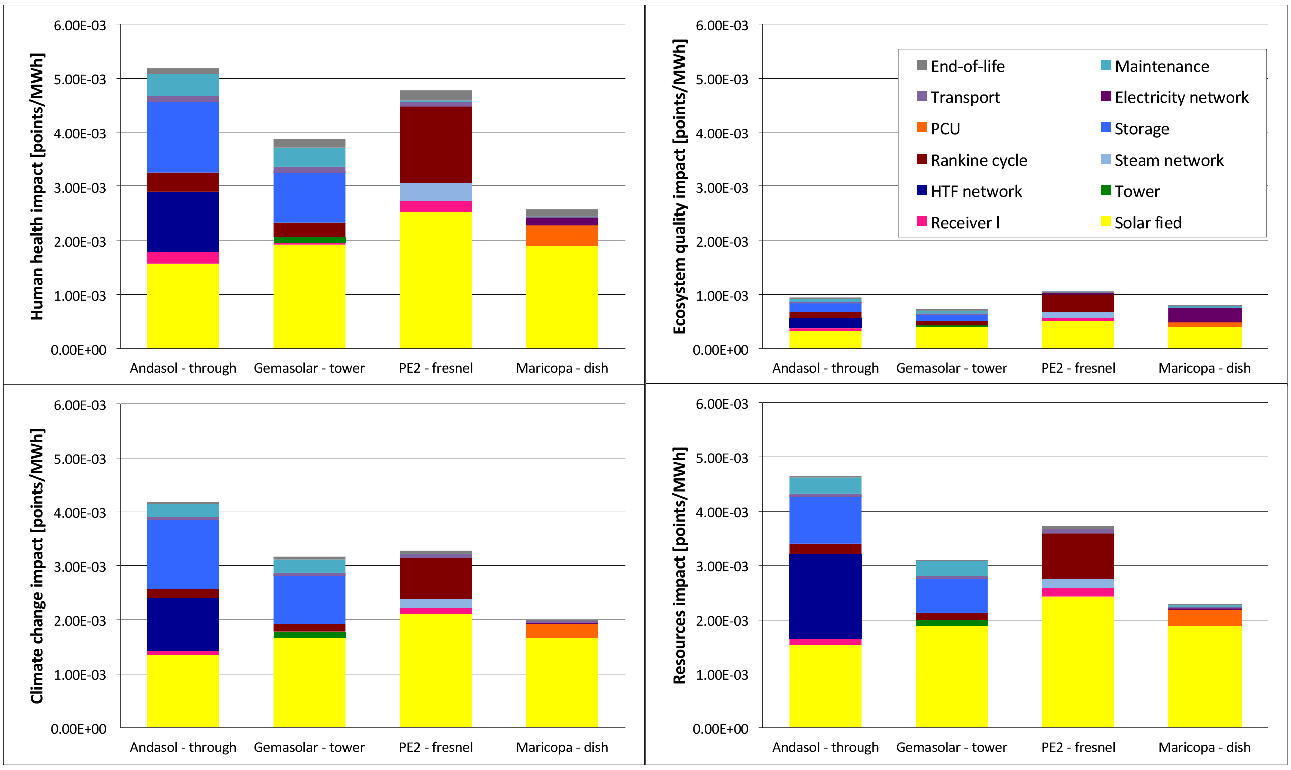

Fig. 2. Impact comparison for the different CSP technologies, for the four categories of Impact2002+

For all the categories and for all the technologies, the end-of-life has a very limited impact. For the maintenance, which relates to the operation stage, this is as well the case for PE2 (fresnel) and for Maricopa (dish). Though it is more significant for Andasol (through) and Gemasolar (tower), the construction stage and its associated materials are dominating the impact for all technologies and all categories.

For all technologies and categories, the solar field has an important share in the construction contribution, due to the steel used in the structure to support the mirrors.

The storage with two tanks and molten salt, assumed to be potassium nitrate, is also responsible for an important part of the impacts for Andasol and Gemasolar. Indeed, the synthesis of potassium nitrate emits carbon dioxide and dinitrogen monoxide, two greenhouse gases having an important impact on climate change. The materials to build the tanks, namely aluminium, stainless steel and concrete, impact the resources. Moreover, the stainless steel contains chromium, known to be toxic to human health and ecosystem quality.

In the case of Andasol, the synthetic oil for the HTF network has the highest contribution for the resources, and is as well important for the three other impact categories. This is due to its production, requiring substances like chlorine, nitric acid, phenol or sodium hydroxide, as well as an important quantity of electricity. Moreover, it has to be noted that the present LCA does not take into account the risk of spillage for the synthetic oil, which has highly toxic degradation products, such as benzene and phenol [21].

For PE2, the impact of the Rankine cycle is much more important than for Andasol and Gemasolar. This impact difference is due mainly to the air condenser, which has a large transfer area and requires therefore much more steel for the heat exchange, than the water condensers of the two other power plants, though it uses less water. The steel involved in the turbine production has as well an important contribution.

The impact of the PCU for Maricopa, which has no storage, Rankine cycle or HTF network, is much less important, and is mostly due to the steel, iron, copper and chromium steel of the Stirling engines.

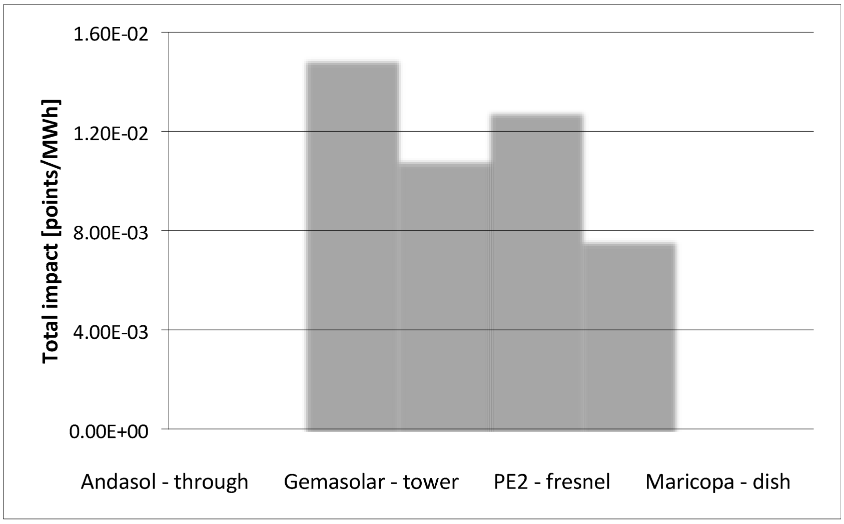

Fig. 3. Total impact comparison for the different CSP technologies

When comparing the four technologies in terms of total impacts by adding the categories to each other, it appears that Maricopa has the best environmental performance of all. It has a 29%, 40% and 49% impact reduction when compared with Gemasolar, PE2 and Andasol, respectively. These results are explained by the high total efficiency of Maricopa power plant and its lower requirement in construction materials. However, for the ecosystem quality category, Gemasolar engenders 10% less impact than Maricopa. This is due to the higher contribution of the electricity network, which has a high impact on ecosystem quality due to the copper in the electricity lines, as it can be seen from Fig. 2. Indeed, the electricity network distance is similar for all power plants. Since Maricopa has no storage and produces thus less electricity, the impact per MWh_e is inevitably more harmful to the ecosystem quality. To reduce the impact contribution of the electricity network for Maricopa, the electricity produced has to be increased and therefore the number of dishes.

Regarding the worst power plant, Andasol results in more impact for all categories, except for ecosystem quality. The biggest drawback of Andasol is the use of synthetic oil, which increases considerably the total impact. The drawback of PE2, which is the second worst option, is its low efficiency. For the ecosystem quality, PE2 impact is 12% higher than Andasol. Indeed, the solar field and steam cycle of PE2 results in higher impacts on ecosystems, mostly due to the metal of the turbine and to the steel structure. Although the steel weight of PE2 has been minimized per m^2 of mirror, the weight per MWh_e of electricity (6.22 kg/MWh_e) is 1.5 times bigger than Andasol (3.93 kg/MWh_e).

2.3.2. Comparison with fossil competitors

For the comparison with the fossil competitors, namely coal, natural gas and nuclear power plants, the through power plant (Andasol), which has the worst environmental performance of the four CSP for all impact categories, is taken.

Ecoinvent© is as well used for assessing the impacts of the fossil power plants. The coal power plant is assumed to be an average of the different European coal power plants, with 2.78 kWh_{th} of coal resulting in 1 kWh_e of electricity. The natural gas power plant is as well a European average, with 2.63 kWh_{th} of natural gas resulting in 1 kWh_e of electricity. The nuclear power plant is as well a European mix, with 90% Pressure Water Reactor (PWR), and 10% Boiling Water Reactor (BWR).

The results of this comparison are displayed in Fig. 4.

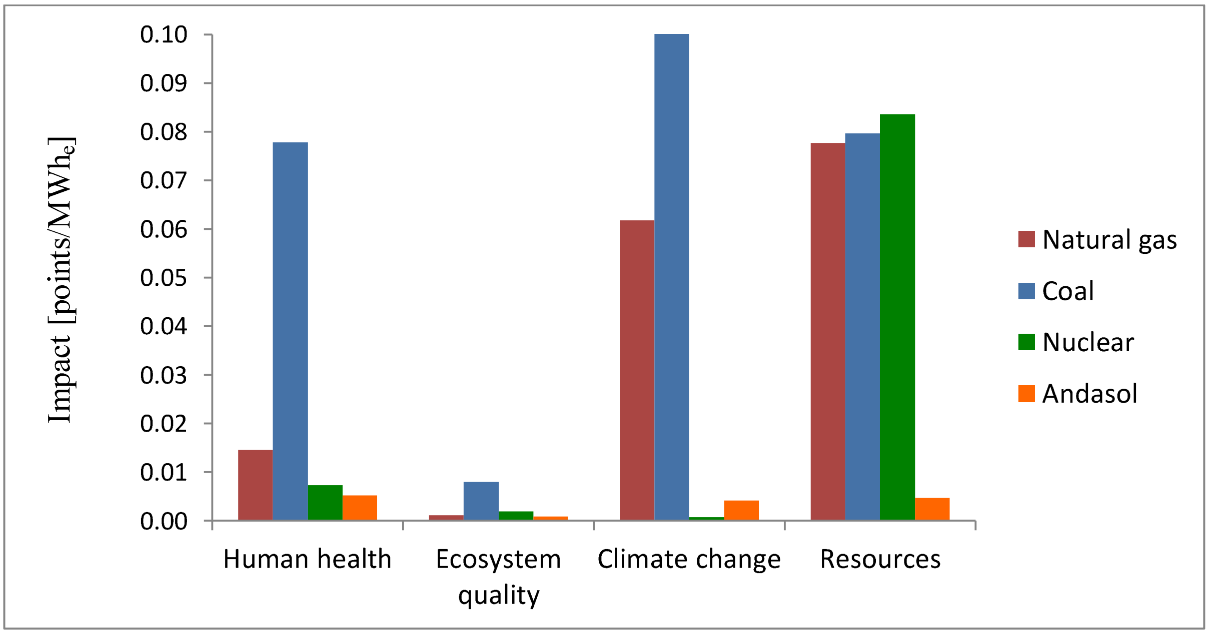

Fig. 4. Impact comparison for other types of power plants using fossil energy

The CSP performs clearly better than all fossil power plants for the impact on the resources, since it uses renewable solar power and not fossil non-renewable resources. It has as well a clear advantage over coal power plants for all other categories, and over natural gas power plants for the impacts on climate change and on human health. Regarding nuclear power plants, CSP is environmentally more beneficial for the impacts on human health, and slightly more beneficial for ecosystem quality. However, for climate change, CSP has a higher impact than nuclear power. Indeed, these two technologies do not emit fossil carbon dioxide during operation phase, and the impact is therefore mainly due to the construction, which is higher for CSP since it requires more material per produced MWh_e. It is important to note that the long-lived radioactive waste disposal and the risk of nuclear accident are not considered with the impact assessment method used in the present LCA study. However, these aspects should be accounted for when choosing between CSP and nuclear.

3. Influence of the location

The location of the power plant has a significant influence on the LCA results. Indeed, some significant elements depend on the location: the cooling system, the grid connection and the DNI (direct normal irradiation $kWh/m^2/yr$). Obviously, the power output is directly correlated to the irradiation of the location which varies with the local climate and the latitude.

Concerning the cooling system, the condenser at the turbine outlet can be fed with water or air depending on the available water resources. For example, the PE2 Fresnel plant is the only one that features dry cooling: it uses an air condenser rather than a water condenser. This way no cooling water is necessary. However, the condenser area is larger because of the lower heat transfer coefficient, and the steam cycle efficiency is slightly lower due to the higher air temperature compared to the water temperature. Therefore, according to the LCA of the PE2 Fresnel plant, the impact of the condenser becomes significant. This raises the interest of a comparison between the impacts of wet and dry cooling.

The length of the grid connection and its type depend on the distance from the existing power grid. For a few kilometres, medium voltage power lines are used, whereas high voltage power lines have a better efficiency for a longer distance. These power lines are usually working with alternating current (AC). However, for a very long distance (more than 700 km) with high voltage, the HVDC system (high-voltage direct current) is less expensive and has lower electrical losses [22]. Moreover, it requires less material (only 2 conductors instead of 3) and thus has a lower environmental impact. This system has been selected in the Desertec project to bring a share of the power generated in North Africa to Europe. Two types of lines have to be used: overhead lines on land and submarine cables to cross the Mediterranean Sea. On the one hand, the overhead lines are composed of aluminum and steel for the conductors that are suspended by ceramic isolators, and of steel and concrete for the pylons. On the other hand, the submarine cables are made of multiple layers of copper and isolation material surrounded by a lead jacket, a steel armour and a polypropylene protection. The amount of each material used to perform the LCA is presented in Table 9 (see Appendix A). The overhead line is built to transmit 1 GW_e and the submarine cable 1.25 GW_e with a voltage of 800 kV. The rectifier stations and transformers are not taken into account as their impact is not significant in comparison with the length of the line.

Table 1. Characteristics of the scenarios

Scenarios	condenser type	power line distance
1	air	1 km (MVAC)
2	air	10 km (HVAC)
3	air	2018 km (HVDC), 2 km (MVAC)
4	water	1 km (MVAC)
5	water	10 km (HVAC)
6	water	2018 km (HVDC), 2 km (MVAC)

To analyze the influence of these three elements, a LCA sensitivity on the PE2 Fresnel power plant is carried out with 6 different scenarios (listed in Table 1). The DNI is varied for each scenario from 800 to 2500 $kWh/m^2/yr$. The lower boundary corresponds to the irradiation in northern Europe above 50° of latitude whereas the upper boundary corresponds to the irradiation in the deserts of North Africa below 30° of latitude.

Regarding the power lines, three scenarios are proposed. The first power line is 1 km long with medium voltage and alternating current (MVAC). The second line is longer and with high voltage (HVAC). For both of them, the length is the distance to join the nearest existing power grid. For the last power line scenario, 2 km of MVAC is needed to connect to the power grid, and the HVDC connection has to be built. Therefore, 2000 km of overhead HVDC and 18 km of submarine HVDC are added to cross the Strait of Gibraltar. Obviously, several power plants will use the same line and the amounts of material for this LCA are divided by the share of the line effectively used by the PE2 Fresnel plant.

To switch from dry to wet cooling, the water cooling is added to the inventory depending mainly on the water temperature and the condenser heat output, which is assumed the same for both systems. The fan consumption and its quantity of material are adjusted to the mass flux. Finally, the condenser area is calculated as a function of the overall heat transfer coefficient ($U = 50\ W/m^2/K$ for air condenser and $U = 1000\ W/m^2/K$ for water condenser) and the minimum approach temperature ($\Delta T_{lm} = 37.4$ K for air condenser and $\Delta T_{lm} = 47.6$ K for water condenser.

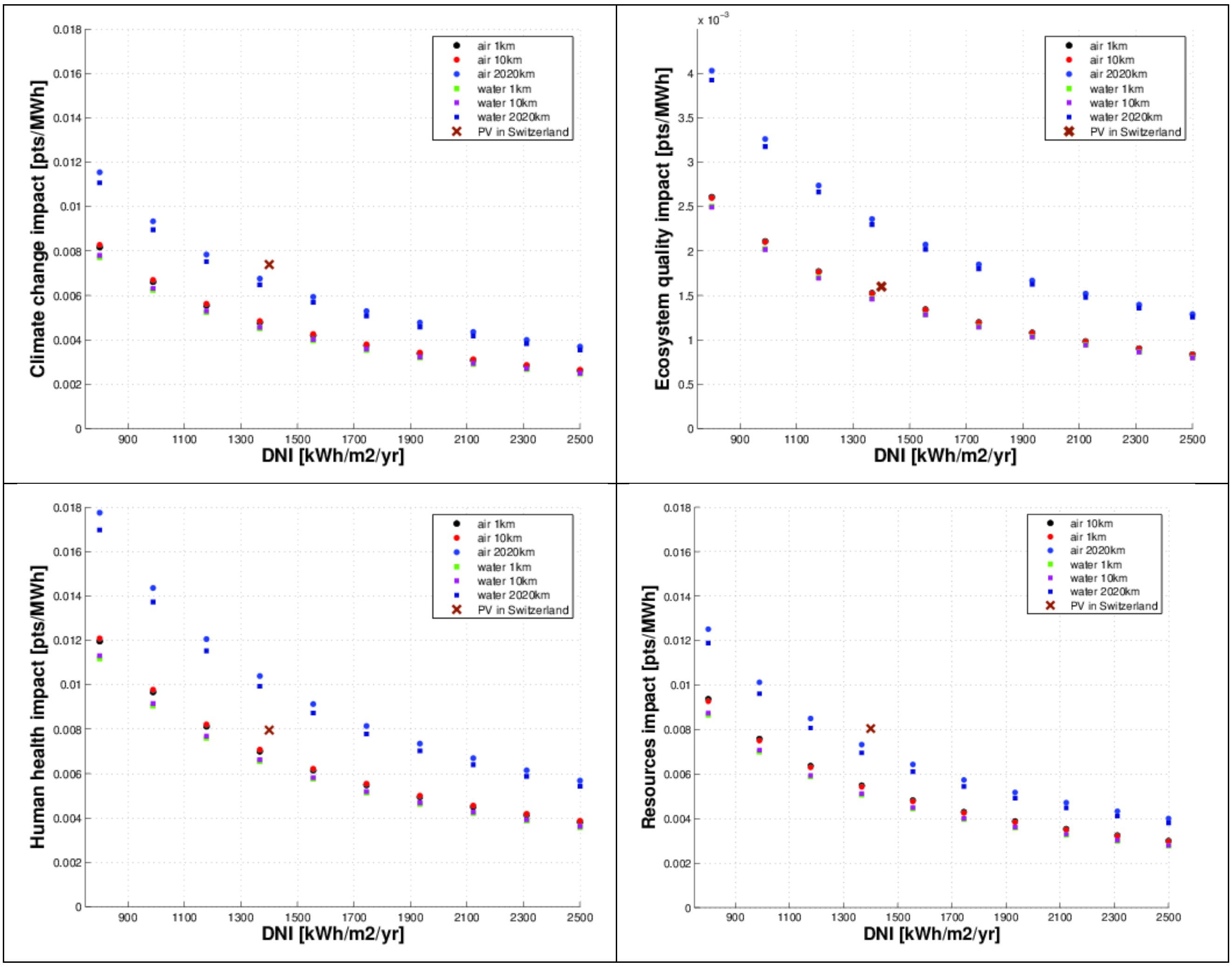

Fig. 5. Impact comparison for other types of power plants using fossil energy

The results of the sensitivity analysis are presented in Fig. 5. First, the impact in North Africa turns out to be three times lower than in northern Europe, thanks to a greater electricity output. Second, wet cooling shows a slightly lower impact than dry cooling. However, the difference between the impacts of the two options reaches only 1% to 6% of the total impact at 2000 kWh/m^2/yr and decreases with the increase in DNI: it becomes insignificant for plants in North Africa. Therefore, the selection of the cooling system depends mainly on the availability of water.

The curves between 1 km and 10 km of power lines are very close and the impact difference reaches a few percent only. Obviously, the shorter the distance is, the lower the impact will be.

Although the HVDC impact calculation comes from a rough estimate without taking into consideration the material transport and maintenance, the impact with 2020 km is between 1.2 to 1.5 times grater depending on the impact category and the DNI. The greatest difference is observed on the human health curves and is due to the manufacturing of overhead lines, which includes the production of aluminum and steel. Furthermore, a plant in North Africa with a HVDC power line shows lower impacts than a plant at a location where the DNI is lower than 1700-1800 kWh/m^2/yr depending on the impact categories. However, a Spanish plant that is connected to the existing power grid would have a lower impact than the Desertec project.

Therefore, it is interesting to compare local photovoltaics (PV) with foreign CSP. In Fig. 5, the PV impacts have been added from the ecoinvent© database. However, they are installed in Valais in Switzerland where the solar energy is maximal (DNI = 1400 kWh/m^2/yr).

In parallel, the comparison with PV in Switzerland (Valais, 1400 kWh/m^2/yr) shows that a local PV plant has larger impacts than the plants in South France, in Spain or in the Desertec project in all categories.

4. Environomic multi-objective optimization

4.1. Optimization problem

In order to find the plant configurations that achieve both the best economic performance and the lowest impacts, the use of a multi-objective optimiser (MOO) based on an evolutionary algorithm (EA) is proposed [23]. Hence some key parameters of a CSP plant have to be defined as decision variables, with a lower and upper limit of variation. In this way, the optimiser is able to randomly pick a value for each variable within the specified boundaries, and calculate the two objectives (e.g. levelised cost of electricity in c/kWh$_e$ and impacts in pts/MWh$_e$) for this very first set of values. The MOO then repeats this operation until it reaches a given initial population of plants (e.g. 100 individuals). Subsequently, only the best individuals are kept: every individual that is worse than another in both objectives is eliminated. In other words, a plant set-up is left aside if any other plant set-up has both a lower levelized cost of electricity (LEC) and a lower impact. Based on this population of selected set-ups, some operations of crossover and mutation allow the creation of new individuals, and the operation of selection can be performed on the whole population once again. The entire process is repeated until the desired number of individual evaluations is reached (e.g. 5000 evaluations).

Table 2.Decision variables for each CSP technology

Decision variables	*Tower*	*Parabolic*	*Fresnel*	*Dish*
Number of modules	1000-20000	50-1000	2-200	1-1000
Solar multiple	1.05-2.8	1.05-2.8	-	-
Hybridization ratio	0-0.9	0-0.9	0-0.9	-

The decision variables are selected among the key design parameters (see Table 2): the number of collector modules, the solar multiple of the plant, and the hybridization ratio. The number of collector modules is the number of heliostats for a tower plant (2650 x 120 m^2 at Gemasolar), of parabolic trough collectors for a trough plant (156 x 3207 m^2 for Andasol), of linear Fresnel collectors for a Fresnel plant (43 x 7046 m^2 for PE2), and of parabolic dish mirrors for a dish plant (60 x 87.7 m^2 at Maricopa). The solar multiple is the ratio of the maximal receiver output to the cycle nominal input, which depends on the storage capacity: the solar multiple is 1 without storage and about 2.8 with a storage capacity that allows overnight operation in the summer. In this study, only the tower and parabolic plants are assumed to feature a storage system. Then the hybridization ratio ranges from 0% for pure solar configurations, up to 90% for highly hybridized configurations and is not available for dish plants.

The objectives have to be contradictory, otherwise if they are correlated the population of plant set-ups degenerates into the single trivial solution of a mono-objective problem. As stated previously, the economic and the environmental performances are expected to be contradictory: a cheap plant turns out to be have more impact, and vice versa, an expensive plant has a lower impact. This way the objectives taken here are the LEC and the impact, and both of them are to be minimized.

4.2. Optimal configurations

The environomic optimal configurations are represented graphically as a set of trade-off set-ups between cost and impact along a Pareto front curve for each impact category (see Fig. 6). As a result, the fact that the impacts decrease when the LEC increases is confirmed: the best plants at the environmental level are the most expensive ones. For the impacts on the climate change, the resources and the ecosystem quality, the Pareto curves show the same trend. The linear curve section corresponds to the configuration with hybridization: the impact decreases as the rate of hybridization decreases from 70% to 20%. 70% is the highest possible ratio since it allows 8760 hours operation per year without storage. As the hybridization ratio of the optimal configurations progressively decreases, the storage capacity and the corresponding solar multiple increase, keeping the annual operation time at 8760 hours. Below 20%, the hybridization is not recommended since the boiler investment gets too high in comparison with the gain in energy output: at this stage, the LEC is lower without than with hybridization. For instance in the case of trough plants, above 13 c/kWh$_e$ only the storage capacity and the number of modules affect the impact and the LEC. At even higher LEC, the storage capacity and the operating time decrease with the LEC, which further decreases the impact. At the same time, the number of collector modules drops significantly. In the end, the impact is lower without hybridization but obviously the electricity is more expensive.

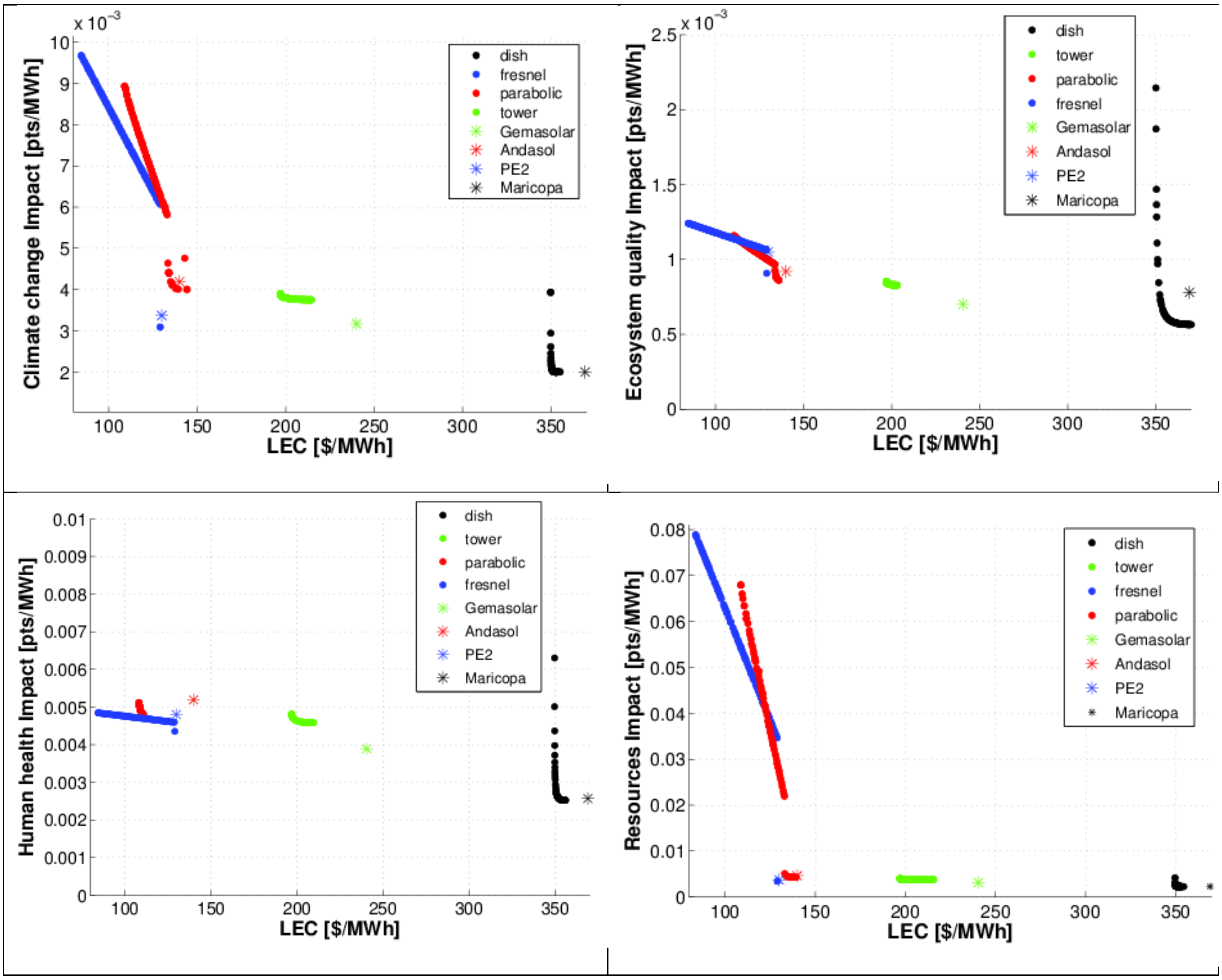

Fig. 6. Pareto fronts of environomic optimal configurations

Unlike the other categories, the impact on human health shows a rather flat trend. As a matter of fact, the hybridization ratio has a lower impact on human health than the storage system, and remains constant at its maximum (70%, no storage). Therefore, the trend of the Pareto curve is mainly due to the decreasing number of modules which leads to smaller turbines depending on the LEC (e.g. from 500 MW$_e$ to 100 MW$_e$ for trough plants). The size of the plant clearly affects the LEC.

Besides, the number of collector modules differs according to the impact category. With hybridization, the minimum impact on climate change occurs at around 650 trough modules, whereas that on the ecosystem quality occurs at 400. Moreover, once again unlike the other categories, the minimum impact on human health occurs at a the maximum hybridization ratio of

70%. For that reason, one impact category might be selected as the objective to minimize before building a new power plant.

4.3. Minimal CO_2 tax for break-even

The four CSP technologies clearly show lower impacts on the environment than fossil-based technologies. However, the LEC of CSP remains much more expensive than that of fossil-based plant (see Fig. 7). Two fossil power plants in Germany have been taken from [24] and compared with tower and parabolic technologies. The coal power plant is a PCC (pulverised coal combustion) type of 800 MW_e and has an efficiency of 46%. The natural gas power plant is a CCGT (Combined cycle gas turbine) type with a power of 800 MW_e and an efficiency of 60%.

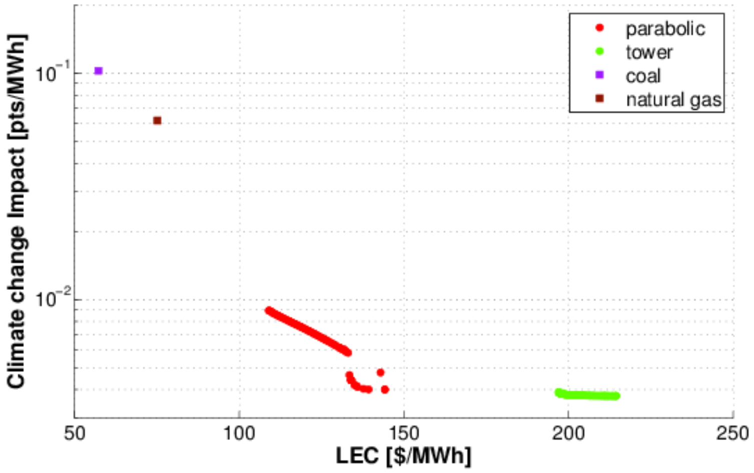

Fig. 7. Pareto fronts of environomic optimal configurations

As the relative investment for a new CSP plant remains significantly higher than for a fossil plant, the tax on the CO_2 emissions should make CSP economically more attractive.

Dish and Fresnel power plants are not considered here because of their higher LCOE. The results are presented in Table 3: a tax of around 60 $/ton of CO_2-eq is already sufficient to make tower technology more attractive than natural gas power plants. Moreover, tower technology needs a lower tax than parabolic with and without hybridization.

Table 3.Decision variables for each CSP technology

Power plants variables	*Minimal CO2 tax [$/ton of CO_2-eq]*
Coal/Tower	54.0
Natural gas/Tower	60.8
Coal/Parabolic (without hybrid.)	120.3
Natural gas/Parabolic (without hybrid.)	59.1
Coal/Parabolic (with 70% hybrid.)	90.2
Natural gas/Parabolic (with 70% hybrid.)	125.8

5. Conclusions

The Life Cycle Assessment (LCA) presented in the first part of this study allowed for identifying the environmental hot spots of four different Concentrating Solar Power (CSP) technologies: parabolic through (Andasol), tower (Gemasolar), Fresnel (PE2) and dishes (Maricopa). The results demonstrate first that for all technologies and considered impact categories, the construction is responsible for the majority of the impacts (between 86% and 99%). These impacts are mainly due to the solar field, the storage or the HTF parts, depending on the technologies. The LCA indicates that Maricopa, the dish power plants, has the best environmental performance, due to its high efficiency and reduced quantities of construction materials. Andasol, the parabolic through power plant, has on the other hand the worst environmental performance, due to the synthetic oil in the HTF network and to the molten salt storage system. The environmental performances of these technologies could be enhanced by working on the design of the structure for the mirrors, in order to minimize the steel consumption. The impacts could be further reduced by developing alternatives to the type of molten salt used for the technologies using storage (i.e. parabolic through and tower) and the synthetic oil in parabolic through. However, when compared with fossil competitors, any CSP technology has a clear advantage over coal and natural gas, as well as nuclear power.

Then, the environomic multi-objective optimization has confirmed that a plant with a low LEC has more impact than another one with a higher LEC. It also showed that the impact decreases as a function of the hybridization rate, and gets lower without hybridization, but which obviously increases the LEC. Regarding the CO_2 tax for break-even, a tax of around 60 \$/ton of CO_2-eq is already sufficient to make the tower technology more attractive than natural gas power plants.

Appendix A

Table 4: Life Cycle Inventory of Andasol - through power plant

Element	*Ecoinvent equivalence*	*Quantity*	*Unit*
Solar field			
Mirrors	Flat glass coated, RER	5.81e+06	kg
Steel structure	Reinforcing steel, RER	1.58e+07	kg
Steel structure manufact.	Steel product manufacturing, RER	1.58e+07	kg
Foundation concrete	Concrete, sole plate and foundation, CH	1.46e+03	m^3
Foundation excavation	Excavation, hydraulic digger, RER	1.46e+03	m^3
Receiver			
Steel receiver	Chromium steel 18/8, RER	3.81e+05	kg
Steel receiver manufact.	Chromium steel product manufact., RER	3.81e+05	kg
Borosillicate glass	Glass tube, borosilicate, DE	3.04e+05	kg
Anti-reflex coating	Anti-reflex coating, solar glass, DK	3.53e+03	m^2
Pump (900kW, 40 bar)	[19]	1	unit
Cold pipes	Reinforcing steel, RER	2.59e+05	kg
Cold pipes manufact.	Steel product manufact., RER	2.59e+05	kg
Hot pipes	Chromium steel 18/8, RER	2.84e+05	kg
Hot pipes manufact.	Chromium steel product manufact., RER	2.84e+05	kg
Concrete	Concrete, sole plate and foundation, CH	235	m^3
Aluminium pipes	Aluminium, production mix, RER	5.77e+04	kg
Aluminium pipes manufact.	Aluminium production manufact, RER	5.77e+04	kg
Synthetic oil	Diphenylether-compounds, RER	1.99e+06	kg
Storage and Molten salt			
Hot tank	[19]	1	unit
Cold tank	[19]	1	unit
Pump (315W, 10 bar)	[19]	1	unit
Heat exch. (715 m^2, 30 bar)	[19]	6	unit
Molten salt	Potassium nitrate, as N, RER	3.95e+06	kg
Propane	Propane/butane, RER	4.64e+03	kg
NO_2 emissions	Nitrogen oxides, air	7.65e+04	kg
Rankine cycle			
Turbine (50 MW)	[19]	1	unit
Preheater (279 m^2, 100 bar)	[19]	1	unit
Evaporator (964 m^2, 100 bar)	[19]	1	unit
Superheater (497 m^2, 100 bar)	[19]	1	unit
Reheater (367 m^2, 20 bar)	[19]	1	unit
Pump (534 kW, 100 bar)	[19]	1	unit

Condenser (5131m^2, 0.06 bar)	[19]	1	unit
Cooling tower concrete	Concrete, normal, CH	8.43e+01	kg
Cooling tower steel	Reinforcing steel, RER	2.98e+04	kg
Cooling tower steel manuf.	Steel product manufacturing, RER	2.98e+04	kg
Transport			
Rail transport	Transport, freight, rail, RER	2.66e+07	tkm
Road transport	Transport, lorry>16t, fleet average, RER	7.09e+06	tkm
Sea transport	Transport, transoceanic freight ship, OCE	6.3e+07	tkm
Electricity network	Transmission network, medium voltage, CH	1	km
Maintenance			
Water to clean mirrors	Water, deionised, CH	3.19e+08	kg
Water transport	Transport, lorry 3.5-16t, average, RER	2.87e+07	tkm
Cooling water	Water, decarbonised, RER	1.90e+10	kg

Table 5: Life Cycle Inventory of Gemasolar. tower power plant

Element	*Ecoinvent equivalence*	*Quantity*	*Unit*
Solar field			
Mirrors	Flat glass coated, RER	3.18e+06	kg
Steel structure	Reinforcing steel, RER	1.12e+07	kg
Steel structure manufact.	Steel product manufacturing, RER	1.12e+07	kg
Foundation concrete	Concrete, sole plate and foundation, CH	8.15e+03	m^3
Foundation excavation	Excavation, hydraulic digger, RER	8.15e+03	m^3
Receiver			
Steel receiver	Chromium steel 18/8, RER	5.99e+03	kg
Steel receiver manufact.	Chromium steel product manufact., RER	5.99e+03	kg
Pump (900kW, 40 bar)	[19]	1	unit
Cold pipes	Reinforcing steel, RER	3.76e+03	kg
Cold pipes manufact.	Steel product manufact., RER	3.76e+03	kg
Hot pipes	Chromium steel 18/8, RER	3.86e+03	kg
Hot pipes manufact.	Chromium steel product manufact., RER	3.86e+03	kg
Tower concrete	Concrete, sole plate and foundation, CH	5.07e+03	m^3
Tower excavation	Excavation, hydraulic digger, RER	2e+02	kg
Tower steel	Reinforcing steel, RER	5.07e+05	kg
Storage and Molten salt			
Hot tank	[19]	1	unit
Cold tank	[19]	1	unit
Pump (55kW, 10 bar)	[19]	1	unit
Molten salt	Potassium nitrate, as N, RER	1.49e+06	kg
Propane	Propane/butane, RER	1.78e+03	kg
NO_2 emissions	Nitrogen oxides, air	2.94e+04	kg
Rankine cycle			
Turbine (19 MW)	[19]	1	unit
Preheater (58 m^2, 100 bar)	[19]	1	unit
Evaporator (99 m^2, 100 bar)	[19]	1	unit
Superheater (125 m^2, 100 bar)	[19]	1	unit
Reheater (593 m^2, 20 bar)	[19]	1	unit
Pump (304 kW, 100 bar)	[19]	1	unit
Condenser (1858m^2, 0.08 bar)	[19]	1	unit
Cooling tower concrete	Concrete, normal, CH	8.43e+01	kg
Cooling tower steel	Reinforcing steel, RER	2.97e+04	kg
Cooling tower steel manuf.	Steel product manufacturing, RER	2.97e+04	kg
Transport			

Rail transport	Transport, freight, rail, RER	1.40e+07	tkm
Road transport	Transport, lorry>16t, fleet average, RER	3.46e+06	tkm
Sea transport	Transport, transoceanic freight ship, OCE	2.38e+07	tkm
Electricity network	Transmission network, medium voltage, CH	1	km
Maintenance			
Water to clean mirrors	Water, deionised, CH	1.75e+08	kg
Water transport	Transport, lorry 3.5-16t, average, RER	1.26e+07	tkm
Cooling water	Water, decarbonised, RER	2.49e+11	kg

Table 6: Life Cycle Inventory of PE2, fresnel power plant

Element	***Ecoinvent equivalence***	***Quantity***	***Unit***
Solar field			
Mirrors	Flat glass coated, RER	2.27e+06	kg
Steel structure	Reinforcing steel, RER	6.68e+06	kg
Steel structure manufact.	Steel product manufacturing, RER	6.68e+06	kg
Receiver			
Steel receiver	Chromium steel 18/8, RER	5.99e+03	kg
Steel receiver manufact.	Chromium steel product manufact., RER	5.99e+03	kg
Pump (702kW, 55 bar)	[19]	1	unit
Cold pipes	Reinforcing steel, RER	5.88e+04	kg
Cold pipes manufact.	Steel product manufact., RER	5.88e+04	kg
Hot pipes	Chromium steel 18/8, RER	1.65e+05	kg
Hot pipes manufact.	Chromium steel product manufact., RER	1.65e+05	kg
Borosillicate glass	Glass tube, borosilicate, DE	1.84e+05	kg
Anti-reflex coating	Anti-reflex coating, solar glass, DK	1.00e+04	m^2
Fiberglass wool	Glass wool mat, CH	3.18e+04	kg
Concrete	Concrete, sole plate and foundation, CH	139	m^3
Aluminium pipes	Aluminium, production mix, RER	1.81e+04	kg
Aluminium pipes manufact.	Aluminium production manufact, RER	1.81e+04	kg
Steam cycle			
Turbine (30 MW)	[19]	1	unit
Pump (216 kW, 55 bar)	[19]	1	unit
HTF: Water	Water, ultrapure, GLO	4.77e+05	kg
Steam storage	Chromium steel 18/8, RER	4.58e+04	kg
Steam storage manufact.	Chromium steel product manufact., RER	4.58e+04	kg
Steam separator	Chromium steel 18/8, RER	4.58e+04	kg
Steam separator manufact.	Chromium steel product manufact., RER	4.58e+04	kg
Deaerator	Chromium steel 18/8, RER	4.58e+04	kg
Deaerator manufact.	Chromium steel product manufact., RER	4.58e+04	kg
Condenser (52896m^2, 0.3 bar)	[19]	1	unit
Fan	Reinforcing steel, RER	4.8e+04	kg
Fan manufact.	Steel product manufact., RER	4.8e+04	kg
Transport			
Rail transport	Transport, freight, rail, RER	1.11e+07	tkm
Road transport	Transport, lorry>16t, fleet average, RER	2.77e+06	tkm
Electricity network	Transmission network, medium voltage, CH	1	km
Maintenance			
Water to clean mirrors	Water, deionised, CH	1.51e+07	kg
Cleaner robot	Diesel, burned in diesel-electric generating set	2.41e+05	MJ

Table 7: Life Cycle Inventory of Maricopa, dishes power plant

Element	*Ecoinvent equivalence*	*Quantity*	*Unit*
Solar field			
Mirrors	Flat glass coated, RER	5.46e+04	kg
Steel structure	Reinforcing steel, RER	3.22e+05	kg
Steel structure manufact.	Steel product manufacturing, RER	3.22e+05	kg
Foundation concrete	Concrete, sole plate and foundation, CH	60	m^3
Foundation excavation	Excavation, hydraulic digger, RER	60	m^3
PCU			
Stirling engine	Stirling cogen unit 3 kWe, wood pellets, CH	167.4	unit
Transport			
Rail transport	Transport, freight, rail, RER	3.18e+05	tkm
Road transport	Transport, lorry>16t, fleet average, RER	6.19e+04	tkm
Electricity network	Transmission network, medium voltage, CH	1	km
Maintenance			
Water to clean mirrors	Water, deionised, CH	3.00e+06	kg
Water transport	Transport, lorry 3.5-16t, average, RER	3.47e+03	tkm

Table 8: Recycling fractions for calculating end-of-life impact

Material	*Ecoinvent equivalence*	*Fraction*
Reinforced steel	Disposal, reinforcement steel, to recycling, CH	90%
	Disposal, reinforcement steel, to final disposal, CH	10%
Concrete	Disposal, concrete, not reinforced, to recycling, CH	95%
	Disposal, concrete, not reinforced, to final disposal, CH	5%
Glass	Disposal, glass, to municipal incineration, CH	100%
Chromium steel	Disposal, steel, to municipal incineration, CH	10%
	Disposal, reinforcement steel, to recycling, CH	90%

Table 9: Material for the construction of overhead and submarine power line [22]

Overhead line	*quantity*	*unit*
Aluminium	3480	kg/km
Chromium steel	1280	kg/km
Low-alloyed steel	15000	kg/km
Concrete	16.8	m^3/km
Ceramics	400	kg/km
Submarine line	*quantity*	*unit*
Chromium steel	24000	kg/km
Copper	19000	kg/km
Lead	17000	kg/km
Polypropylene	6	kg/km

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