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Title: Towards energy transition in Tunisia: sustainability assessment of a hybrid concentrated solar power and biomass plant

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Keywords: Triple-Bottom Line; CSP-biomass; LCA-IO; energy transition; Tunisia; BIOSOL project.

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Abstract: Electricity demand in the Middle East and North Africa (MENA) region increases at a rate of 6-8% per year. It is expected to double by 2020 and triple by 2030. Renewable electricity ensures climate protection and energy security. This work presents a sustainability assessment of CSP hybridization with biomass technology to be installed in Tunisia. Environmental impacts have been assessed by Life Cycle Analysis (LCA). For socioeconomic impacts, a Multiregional Input-Output (MRIO) analysis was used to estimate the production of goods and services, value added and employment creation. Regarding the results, the system reports 22 gCO2eq per kWh. The most important component in terms of emissions is the gasifier system, due to biomass transport. Socioeconomic results show important impacts for employment creation in Tunisia, coming essentially from the O&M phase. The multiplier effect of the direct investment for production of goods and services amounts to 2.4 (3.5 accounting induced effects). Domestic value added in investment is low, only 28.9% of the overall value added created. Thus, increasing the national content of the investment stage would bring additional local benefits. Using extended MRIO, CO2 emissions have also been calculated and differences in the CO2 emission with both methodologies are discussed.

Response to Reviewers: Reviewers/Editor comments:
Reviewer #2: All my previous comments have been satisfactorily addressed. I would just recommend a final review by the authors to improve some minor language issues.
Response to Reviewer comment No.1: Thank you for your comments regarding English. Indeed, there were some grammar mistakes that have been addressed in the final manuscript. These language issues can also be found in the revised manuscript.
Reviewer #4: The work deals with the social analysis of the integrated CSP-biomass facility in Tunisia towards a more sustainable future and within the context of energy transition. The work, although interesting, is not easy to follow in terms of how the authors compute the results and the explanation of the figures presented. Before further consideration, the authors are advised to consider the following comments

11.- It is not that the analysis has been performed for a scale up system. The problem is that form 25MW to 500 MW all scale up system the need for biomass can be such that you cannot operate the facility. That is the reason behind this comment

Response to Reviewer comment No.2: Thank you for this comment. As pointed out by the reviewer, this limitation has been addressed and included in line 470 of the final manuscript:

“However, the boundaries of scaling up the system should be considered: for much higher installed capacities, the need for biomass can be such that the facility cannot be operated.”

***Cover Letter**

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

January 22, 2020

Respected Editor,

We want to express our interest in submitting the article called “Towards energy transition in Tunisia: sustainability assessment of a hybrid concentrated solar power and biomass plant”, since we present triple-bottom line indicators that impact the total environment through Life Cycle and Input-Output analyses. We regret having missing the opportunity to submit our paper to the Special Issue of the Journal “Modalities to bio-transform waste to sustainable energy with a zero-waste approach: A step forward to meet circular economy challenges to rescue environmental insecurity”, that made our paper suitable. Nevertheless, having found interesting sustainability assessments in the line with our research, we think this article fits perfectly into Science of the Total Environment.

We attest that this article has not been published previously, nor submitted to publication in any other journal. The article was developed as part of results of the BIOSOL project, funded by JOINT CALL ON Renewable Energies, Water Resources and their connections for the Mediterranean Region, and also by the Subdirectorate General of International Projects of the Spanish Ministry of Economy and Competitiveness.

If you have any questions or concerns do not hesitate to contact us through the corresponding author in the information presented below.

Sincerely,

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Towards energy transition in Tunisia: sustainability assessment of a hybrid concentrated solar power and biomass plant

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RESPONSE TO REVIEWERS

Thank you for the comments regarding the language issues and the limitations of the presented prototype when scaling-up the power plant. We firmly think that, with your suggestions, the quality of the document has been improved.

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Reviewer #2: All my previous comments have been satisfactorily addressed. I would just recommend a final review by the authors to improve some minor language issues.

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Abstract

Electricity demand in the Middle East and North Africa (MENA) region increases at a rate of 6-8% per year. It is expected to double by 2020 and triple by 2030. Renewable electricity ensures climate protection and energy security. This work presents a sustainability assessment of CSP hybridization with biomass technology to be installed in Tunisia. Environmental impacts have been assessed by Life Cycle Analysis (LCA). For socioeconomic impacts, a Multiregional Input-Output (MRIO) analysis was used to estimate the production of goods and services, value added and employment creation. Regarding the results, the system reports 22 gCO_2eq per kWh. The most important component in terms of emissions is the gasifier system, due to biomass transport. Socioeconomic results show important impacts for employment creation in Tunisia, coming essentially from the O&M phase. The multiplier effect of the direct investment for production of goods and services amounts to 2.4 (3.5

accounting induced effects). Domestic value added in investment is low, only 28.9% of the overall value added created. Thus, increasing the national content of the investment stage would bring additional local benefits. Using extended MRIO, CO_2 emissions have also been calculated and differences in the CO_2 emission with both methodologies are discussed.

Keywords: Triple-Bottom Line; CSP-biomass; LCA-IO; energy transition; Tunisia; BIOSOL project.

1. Introduction

Tunisia is currently facing significant challenges in terms of energy supply security and climate change in the path to energy transition. Being one of the countries most exposed to climate change in the Mediterranean (Waha et al., 2017; World Energy Council, 2019), Tunisia's energy system is heavily dependent on imported natural gas and oil (Schmidt et al., 2017). Besides, the country is energy-dependent and relatively vulnerable to energy shocks. Since energy is a limiting factor to GDP growth (Belloumi, 2009), making a transition from a fossil fuel-based to a renewable energy-based economy is needed. Hence, the country has decided to forge ahead with the energy transition process addressing two pillars: energy efficiency and renewable energies (Ministry of Environment and Sustainable Development, 2015).

The country has already launched a package of strategies to strengthen national renewable energy policy and become an international hub for industrial production and an exporter of renewable energies (Ben Jebli and Ben Youssef, 2015), such as the national climate change strategy, the energy efficiency strategy, or the Tunisian Solar Plan. Altogether with the National Determined Contribution (NDC), these strategies are aimed at guaranteeing a healthy and balanced environment and contributing to the climate's integrity (Ministry of Environment and Sustainable Development, 2015). An expected installed renewable energy capacity of 3,815 MW is expected for 2030, aimed to contribute cutting down 41% of its greenhouse gases (GHG) emissions across all sectors to decrease carbon intensity compared to 2010 levels (Mahlooji et al., 2019). Tunisian official target to reach 30% renewable electricity production in its power mix by 2030 is highly conditioned by international support (concessional lines of credit, donations, direct investments, technology transfer). In this sense, the European Union becomes an important stakeholder in the development of renewable energy in the southern basin of the Mediterranean by bringing technology transfer to Middle East and North African (MENA) countries (Stoffaës, 2016).

The vast majority of installed renewable energy capacity is expected to come from wind and solar photovoltaic (PV) (Waissbein et al., 2018); only 450 MW for concentrated solar power (CSP) and 100

MW biomass are expected to be deployed in 2030, accounting for the 14.4% of renewable energy capacity by 2030 (Ministry of Environment and Sustainable Development, 2015; Tractebel, 2019). Recently the private sector has started to explore the commercial applications for solar power (Ben Jebli and Ben Youssef, 2015). In this sense, CSP becomes a promising technology in a region with unexploited solar potential (Tsikalakis et al., 2011). This research is framed within the BIOSOL project (Development and demonstration of a Hybrid CSP-biomass gasification boiler system) funded by EU ERANETMED programme ("BIOSOL - solar CSP gasification biomass boiler hybrid system," 2018) and aims to integrate a biomass gasification boiler prototype in an existing CSP plant in Tunisia. This existing system corresponds to a hybrid renewable electricity production mini-power plant (60 kW electrical output), developed in the framework of EU/FP7 REELCOOP project (Oliveira and Coelho, 2013). The hybridization of these technologies is expected to be an attractive solution in terms of dispatchability and flexibility (Peterseim et al., 2014).

Technical and economic analyses of this technology are abundant in literature: a hybrid solar-biomass that uses rice husk as a fuel for power generation in India has been tested (Srinivas and Reddy, 2014) under variable solar radiation and plant conditions in order to optimize its operation. The feasibility of hybrid solar-biomass power plants was also tested in India against technical, financial and environmental criteria (Nixon et al., 2012). It was found that hybrid plants reduce biomass and land usage by 14–29% compared to biomass-only plants, but the levelised costs of energy ~~costs~~ are increased by 1.8–5.2 ¢/kWh in comparison to biomass-only. They recommend the use of tri-generation (simultaneous production of electricity, cooling and heat) as the most feasible application for this technology. Peterseim and colleagues (Peterseim et al., 2014) evaluated the operation of a hybrid CSP-biomass power plant in Spain and found that the combination of a biomass and solar tower energy system is beneficial to maximise the cycle efficiency and reduce costs compared to solar only power plants. They also found interesting additional benefits of avoiding the burning agricultural residues in the field. (Petrollese et al., 2018) investigated the best configuration of an ORC plant for supplying power and useful heat to industrial processes, using a solar plant based on linear Fresnel

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collectors integrated with a two-tank Thermal Energy Storage (TES) system, a biomass furnace and an ORC system. They highlighted the fundamental role of the biomass contribution (about 50% of the overall thermal energy input). Vidal and co-worker (Vidal and Martín, 2015) modelled the integration of a polygeneration system based on biomass with a concentrated solar power facility evaluating different gasifiers and reformers and syngas use. They found that the optimal integration involved the use of indirect gasification, steam reforming and a Brayton cycle to produce electricity and hydrogen as a credit. ~~;~~ Amoresano et al (Amoresano et al., 2015) focused on a thermodynamic analysis of the substitution of steam bleed regeneration with water preheating by solar energy. A novel hybrid solar-biomass combined Brayton/organic Rankine-cycle plants integrated with thermal storage (TES) is also proposed by Pantaleo and co-workers (Pantaleo et al., 2018) claiming that the recovery of heat in the TES can significantly increase the investment profitability. (Pereira Soares, 2018) provided a review of different solutions for solar/biomass hybrid electricity generation systems addressing technical and economic issues.

Environmental benefits of hybridizing solar and biomass technologies have also been investigated in the literature. (Anvari et al., 2019) evaluated the CO_2 emissions effect of hybridizing these technologies and found a reduction of about 31% in CO_2 emissions. Important benefits in terms of CO_2 reduction compared to alternative configurations were also found ~~by~~ (Wang and Yang, 2016). However, complete sustainability assessment of this technology is scarce in literature. Corona and co-workers (Corona et al., 2016; Corona and San Miguel, 2015; San Miguel and Corona, 2014) analyzed the environmental performance of a hybrid CSP technology with biogas and other biomass fuels in comparison with the use of natural gas and found a significant improvement of the environmental performance due to reduced impacts in the natural land transformation, depletion of fossil resources, and climate change. However, other environmental impacts namely human toxicity, eutrophication, acidification and marine ecotoxicity worsened when using biogas and biomethane. Piemonte and co-workers (Piemonte et al., 2011) performed a Life Cycle Assessment of a molten salt concentrating solar power plant combined with a biomass Back-Up Burner and compared it with natural gas and an oil fed power plants. They found important benefits of the CSP plant in terms of fossil energy consumption and greenhouse gas emissions compared to both oil and natural gas power plants. However, natural gas power plants were preferable in terms of human toxicity, acidification and eutrophication impacts.

The effects of ~~Biomass~~ biomass ~~effects~~ on ~~employment~~ job creation ~~is~~ are among the highest in~~of~~ renewable ~~energies~~ energy (IRENA, 2017) and the expected benefits in rural and agricultural areas can help fighting against unemployment, which remains an issue in Tunisia (15.4% in 2018) ~~as~~ where economic activity has stagnated in low-productivity sectors (International Labour Organization (ILO), 2015; The World Bank Group, 2014). The socioeconomic assessment in terms of employment and economic growth implications of this technology is, to the best of our knowledge, absent in literature. The deployment of this technology also brings a solution to oil residue management for this top producing olive oil country (FAO, 2017).

To meet the Tunisian CSP and biomass goals, investments in new power plants must be made. The deployment of these power plants will unavoidably generate positive economic effects (value added and employment), as well as negative environmental impacts (i.e. CO_2 emissions) that must be accounted ~~taken into account~~ and compared with those of alternative technologies. The development of this new energy prototype could support the promotion of renewable energy technologies using environmentally-friendly solutions in emerging regions ~~such as~~like the MENA region, which ~~have~~ has large renewable energy potential such as solar or biomass (Tsikalakis et al., 2011).

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The purpose of this research is to fill the gap identified in the literature review and perform a sustainability analysis (environmental and socioeconomic) of the technology proposed in the BIOSOL project. To that end, and considering that the prototype was intended as a small-scale demonstrator of the CSP-biomass concept applicable to larger-scale centralised electricity generation, the analysis was carried out for a scaled-up and enhanced 1 MWel decentralized generation, more representative of a real-life application (Soares et al., 2018b). The assessment includes a Life Cycle Assessment (LCA) for the scaled power plant, with the new biomass gasifier system. In this sense, a biomass gasification boiler has been developed and integrated with the CSP prototype 3 of the REELCOOP project. Besides, the potential impact on local economy (value added, job creation and CO_2 emissions) due to the investment costs and operation and maintenance (O&M) expenditures are calculated. These two well-known methodologies are widely used to assess renewable energy investments (Jenniches, 2018; Stamford and Azapagic, 2014). The present study enlarges the current knowledge about CSP and biomass (Soares et al., 2018a, 2018b) by combining LCA and Input-Output approaches in order to assess this novel technology in Tunisia, from a triple-bottom line (TBL) perspective (Henriques and Richardson, 2004).

The research is structured as follows. Section 2 presents a deep description of materials and methodologies used. In Section 3, the main results from the two followed approaches (LCA and input-output) are presented and discussed, and finally, Section 4 shows the most important conclusions found.

2. Materials and methods

Two main methodological approaches have been used in this research, the Life cycle assessment (LCA) and the input output analysis (IOA). The hybridization of these two approaches has been widely undertaken (AENOR, 2006a; Leontief, 1936; Zafrilla et al., 2014), allowing the extension of results from processes to the economy at a macro-level. In the present study, the two approaches are used to present complementary results.

2.1. Life cycle assessment

Life Cycle Assessment (LCA) is a methodology that compiles all the inputs and outputs of energy and materials, in order to analyse all the potential environmental impacts of a product, process or system (Sala et al., 2016). The application of the methodology is normalized in ISO standards 14040 and 14044 (AENOR, 2006b, 2006c). According to ISO 14040, “life cycle assessment is a tool to determin~~at~~e all the environmental aspects and potential impacts associated with a product, making an inventory with the most important inputs and outputs of the system, evaluating the potential environmental impacts associated with these inputs and outputs, and interpreting the results of the different phases of the inventory and the impacts ~~In~~ in relation with the study objectives".

The life cycle of a product starts with the exploration of the raw materials and ends with the waste treatment. Between these two phases, there are other stages in the production chain such as the production process, the transportations~~s~~, recycling activities, etc. According to the ISO standards 14040 and 14044, an LCA consists of~~in~~ four phases:

- *Goal and Scope definition:* the first step in a LCA is the definition of the objective and scope of the developed study. This ~~is connected with~~relates to the definition of the system boundaries and the functional unit. The results subsequently gained in the analysis are associated to the intended and linked to the proposed scope.
- *Life Cycle Inventory Analysis (LCI):* LCI is the phase of LCA involving the compilation and quantification of inputs and outputs for the product, process or system under analysis. Results of this phase are a~~, as complete as possible,~~ list, as complete as possible, of inputs and outputs of energy and materials referred to the functional unit.
- *Life Cycle Impact Assessment:* this phase seeks to understand and evaluate the magnitude of the environmental impacts of a product based on the results obtained in the previous phase.
- *Interpretation:* to obtain conclusions of the results is necessary to identify, quantify and evaluate the results. This technique gives a systematic approach, which includes integrity or sensitivity analysis, to prepare the conclusions.

In this work we follow a special variant of this methodology proposed by the European Commission in an attempt to harmonize LCA methods applied to products that is called Product Environmental Footprint (EC, 2013).

2.1.1. Goal and scope

The concrete goal of this analysis is to calculate the Environmental Footprint of a concentrated solar power and biomass hybridization plant in Tunisia. For this study, as a Functional Unit (FU), 1 kWh of electricity output has been considered. The lifetime of the plant has been estimated in 25 years. The system boundary comprises all relevant process stages from the raw material extraction, production and manufacturing until the stage of end-of-life of the materials with the transportation included. The different processes considered have been categorized in the following main components: solar field, boiler system (that includes the provision of the residual biomass), power block, electrical installation and the balance of the system (which comprises every other essential part to the electrical, thermal or aesthetic integrity of the array). Furthermore, in order to involve the end-of-life stage in the system, a scenario of waste disposal in landfill, including the transportation of wastes, has also been considered~~., including the transportation of wastes at the end of life of the system.~~

The system that is being analyzed corresponds to a power plant concept, that uses concentrated solar energy and biomass. The development and design stage included solar collector simulation, with and without shading, and circuit thermal and hydraulic design and led to the configuration shown in Figure 1.

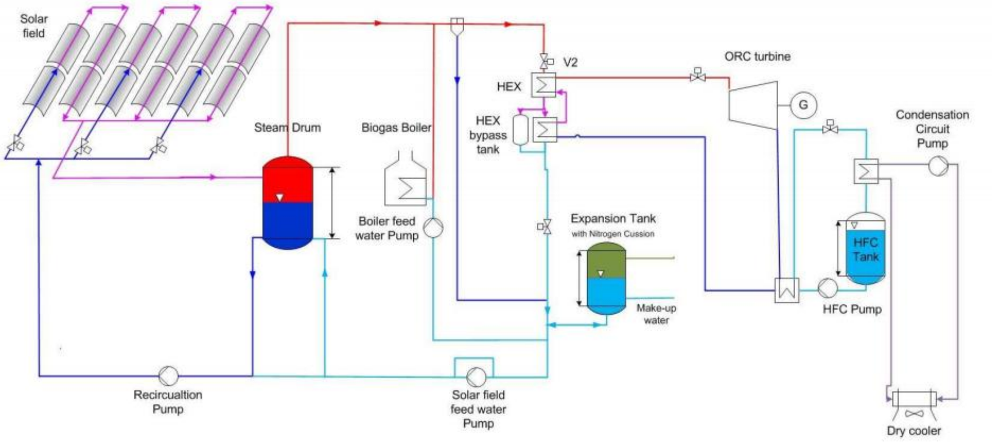

Figure 1. Schematic representation of the original CSP-biomass prototype system. Source: (Oliveira, 2018)

For this study, the analysis for a scaled-up prototype to demonstrate the hybrid concept has been developed. Therefore, a 1 MWel power plant was considered, with the same basic characteristics of prototype 3 of REELCOOP project. Nevertheless, in contrast to the original prototype with specific collectors, generic parabolic trough collectors with a larger aperture width of 4.6m and a vacuum receiver were considered, in order to reach outlet temperatures of 350°C with high efficiencies, with a solar field (SF) area of 10,000 m^2. For the boiler system (BS) definition, the same biogas boiler with a nominal output of 5 MWth was used. For this case, the biogas is produced from gasification by pyrolysis of olive pomace, with a lower heating value of 20.64 MJ/m^3. Additionally, the power block (PB) was based on the SST-110 model from Siemens. The PB steam inlet conditions were defined as 40 bar and 350°C. Figure 2 below shows schematically the new design conditions for the solar field and power block, as well as the power cycle nominal conditions.

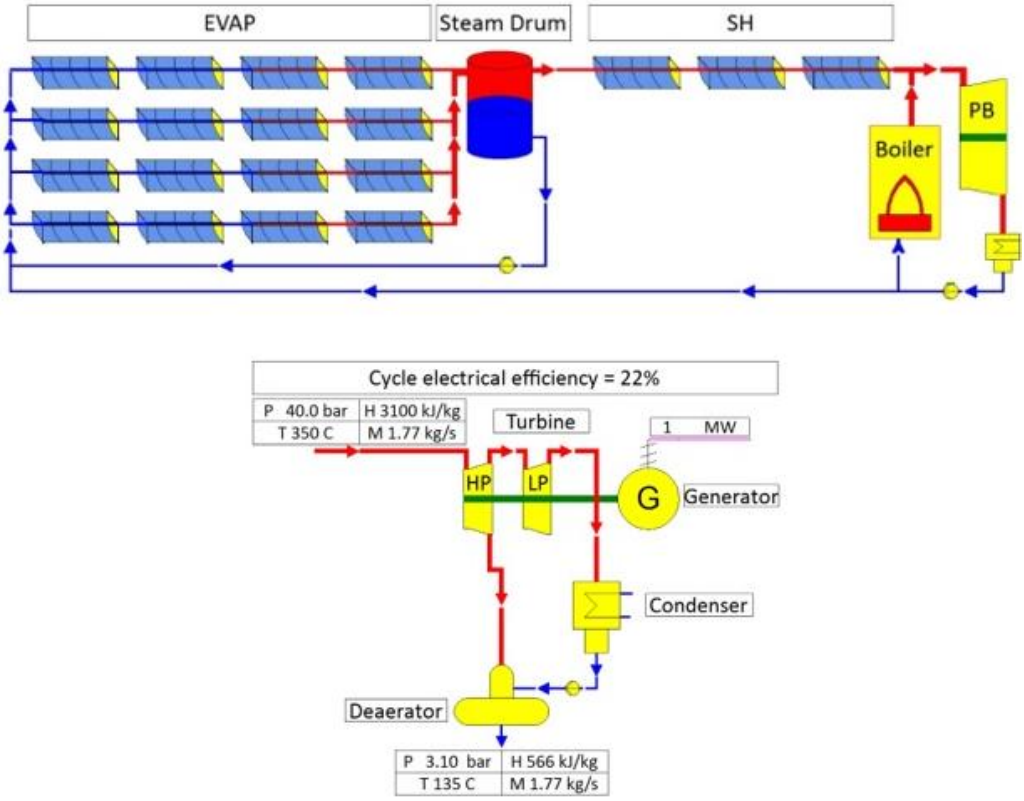

Figure 2. Schematic representation of the modified CSP-biomass system. Source: (Oliveira, 2018)

The plant is using a direct steam generation (as in Prototype from REELCOOP project) and a steam turbine, with an output power of 1 MWel, operating from 6:00 to 22:00 every day.

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Under these conditions, the simulation for Tunis indicated an average solar field efficiency of 40%, an average biogas consumption of 1,564 m^3/day, a solar share of 27.5%, and an electrical energy generation of 2,052 MWh/year, with average power block efficiency of 20.81%. Table 1 summarizes the main data of the conditions of the studied system.

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Table 1. Solar field, boiler system and power block data.

	Value	Unit
DNI	1,922	kWh/(m^2 year)
Annual heat generated - solar field	7,750	MWhth
Specific thermal field output	771	kWhth/m^2
Mean annual solar field efficiency	40.1	%
Solar share	27.5	%
Solar field dumped heat	232	MWhth
Annual heat generated - boiler	2,112	MWhth
Mean annual boiler efficiency	85	%
Annual biogas consumption	0.57	hm^3
Average biogas consumption	1,564	m^3/day
Annual useful heat from solar field and boiler	9,862	MWhth
Annual power generated	2,052	MWhel
Mean annual power block efficiency	20.81	%

Source: own elaboration by data from REELCOOP project (Oliveira, 2018; Soares et al., 2018b).

2.1.2. Life Cycle Inventory

The different stages considered have been categorized in the processes of manufacturing of the components: solar field, boiler system, power block, electrical installation and the balance of the system (BoS) of the components, which comprise every component essential to the electrical, thermal or aesthetic integrity of the array, forming part of the overarching power generation. Finally, an end-of-life scenario of waste disposal in landfill has been also considered, including the transportation stage.

All the considerations and assumptions, such as the energy coefficients and the service periods assigned for the system and the operation stages, before compiling inventory data, are detailed below. From a LCA perspective, the system is formed by four subsystems (see Figure 3): Solar field, boiler system, power block and balance of the system.

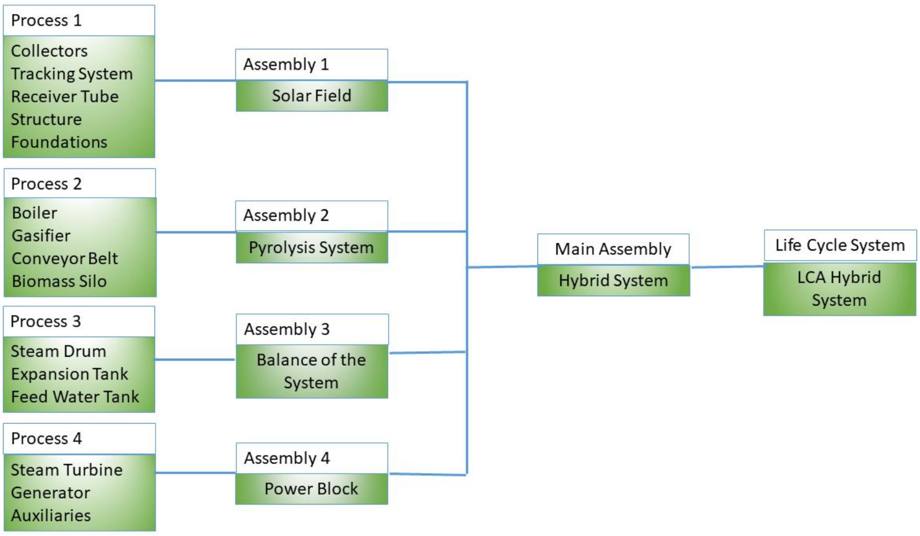

Figure 2~~3~~. General scheme of the system and components.

2.1.2.1. Solar field

The solar field (SF) consists of several components such as mirrors, vacuum and torque tubes, fittings, motors pylons, mirror arms and electrical panels. For this inventory, and according to definition the system is constituted by four loops of four collectors in the EVAP section, and one loop of three collectors in the SH section, with a total effective solar aperture area of about 10,000 m^2. The goal is to get temperatures of 350ºC in the power block, with high efficiencies. The optical efficiency of the collectors is estimated at 77%. Additionally, there is a steam drum in the solar field which is not included in this group. The water which cannot be evaporated in the evaporator is recirculated to the evaporator again, and the steam goes to the superheater in order to get the ideal temperatures. The recirculation pump has the aim of recirculating all the water of the steam drum to the evaporator. The annual direct normal irradiance is 1,922 kWh/m^2. Hence, with this irradiance that falls upon the solar panel, the annual heat that the solar field generates is 7,750 MWhth (Soares et al., 2018b).

2.1.2.2. Boiler system (BS)

The boiler system is formed by gasification by means of pyrolysis and the steam boiler. The pyrolysis system consists of the production of synthesis gas from biomass gasification. This system is assessed in the frame of the following sequences:~~-~~ biomass silo, conveyor belt and the gasifier. The first step, after biomass transport to the plant, is the storage in a galvanized steel silo. From the silo, and by means of a conveyor belt, the biomass will be led to the gasifier, where through~~,~~ drying, oxidation, pyrolysis and reduction processes, the biomass is converted into synthesis gas or biogas to be feed to the boiler. The gasifier consists of a downdraft gasifier, ~~due to~~ attractive for biomass gasification because of ~~and also to~~ its easy fabrication and operation, and also because of the low tar content in ~~producer~~ the resulting biogas. The pyrolysis system can supply about 1,120 annual tons of biogas to the boiler.

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Additionally, the steam boiler ~~is able to~~can supply 960 MJ/hour of heat at 150ºC and 40 ~~bar~~bar. The boiler includes a modular and hybrid burner. These specifications permit the operation of the boiler at partial load, which is desirable for hybrid systems, as well as the operation either with biogas or natural gas. The annual boiler efficiency is about 85% and the biogas consumption is 570 dam^3. The olive pomace is one of the olive mill solid residues. The solid residues generated from olive oil production processes are usually referred to as olive mill solid waste, olive husk or olive pomace (Ducom et al., 2020).

2.1.2.3. *Power Block system (PB)*

~~-~~In the power block system, the steam turbine set is based on the SST-110 model~~s~~ from the Siemens manufacturer. This specific model is a dual-casing turbine on one gearbox, with the possibility of being used as backpressure or condensing units, with or without extraction. Other relevant characteristics are quick~~-~~-start without preheating and commercial use in cogeneration plants. A 60% design isentropic efficiency was defined for the steam turbine (Soares et al., 2018b). The annual efficiency of the power block is about 20.81%, and the annual power generated 2,052 MWhel (Soares et al., 2018b).

2.1.2.4. *Balance of the system*

The balance of system (BoS) encompasses all components of the hybrid system other than SF, BS and PB. This includes the steam drum, the feed water tank and the expansion tank. The drum water tank has the function of separating the water and the steam coming from the solar field. The expansion tank is used to avoid corrosion in the system. Its main function is to prevent the entry of air into the system with nitrogen gaseous which is at a pressure higher than the atmospheric pressure. Additionally, wiring, switches, a mounting system, anemometer, or task-specific accessories designed to meet specialized requirements for the system.

2.1.2.5. End of life

The last phase of the system is the end of life scenario. In that stage, all the parts of the system will be transported to Jber Borj Chakir, a landfill located at 15 km of distance from the location of the system.

2.1.2.6. Additional considerations for the Life Cycle Inventory

In order to carry out the LCA, a series of considerations and assumptions have been taken into account. These considerations are detailed below:

- No water losses.
- Biomass transport (475 t/year for 25 years, by lorry). The transportation ~~is~~ takes place between the collection points and the installation, and the biomass is transported 250 km as average distance.
- The transportation of some ~~of the parts of~~ imported materials has been considered ~~to be~~in 1,000 km.

Finally, Life Cycle Inventory data of the whole parts and processes ~~are~~ is detailed in Annex 1, from Table A1 to A5.

2.1.3. Environmental Impact Assessment

Life cycle impact assessment step is a quantitative process to characterize and evaluate the environmental effects by inventory data. In this process, there are three mandatory steps: a selection of impact categories, the definition of category indicators and selection of characterization models. In this work, the allocation of inventory results to the selected environmental categories and the characterization or calculation of the results by means of factors have been developed ~~by means of~~based on the software Simapro ^{TM} (Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, 2016).

The environmental footprint method has been selected for the environmental impact assessment step. The environmental footprint method is being developed under the auspices of the European Commission (EC) who has developed a reference method for the calculation of the environmental footprint for products (PEF) and organizations (OEF) in support of improving the sustainability of production and consumption (Fazio et al., 2018; Pelletier et al., 2014). This method consists of an analysis of sixteen impact categories. The impact categories are all those environmental consequences generated by a system or a product, and that depending on the impacts can have a harmful effect on human health, natural environment or natural resources (Sala et al., 2016). The impact categories proposed in this method are shown in Table 2.

Table 2.
Impact categories for Environmental Footprint Method

Impact category	Category indicator
Climate change	kg CO_2 eq
Ozone depletion	kg CFC11 eq
Ionising radiation, HH	kBq U-235 eq
Photochemical ozone formation, HH	kg NMVOC eq
Respiratory inorganics	disease incidence
Non-cancer human health effects	CTUh
Cancer human health effects	CTUh
Acidification terrestrial and freshwater	mol H+ eq
Eutrophication freshwater	kg P eq
Eutrophication marine	kg N eq
Eutrophication terrestrial	mol N eq
Ecotoxicity freshwater	CTUe
Land use	Pt
Water scarcity	m^3 depriv.
Resource use, energy carriers	MJ
Resource use, mineral and metals	kg Sb eq

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Climate change – fossil	kg CO$_2$ eq
Climate change – biogenic	kg CO$_2$ eq
Climate change - land use and transform.	kg CO$_2$ eq

Source: own elaboration based on (Fazio et al., 2018).

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2.2. Input-Output Analysis

The a~~A~~ssessment of the socioeconomic impacts of BIOSOL prototype has been performed using the Input-Output methodology (Leontief, 1936). The Input-Output (IO) methodology considers the trade relationships existing within economic sectors ~~through the use of~~using Input-Output Tables (IOTs). IOTs describe, in columns, the monetary value of products that a sector needs from the rest of the sectors to obtain its total production (inputs); whereas rows show the distribution, in monetary values, of the production of a sector over the rest of the sectors (outputs). When considering various regions or countries, it is possible to estimate the economic stimulation produced in other regions due to a change in the demand of goods and services (G&S) of one region, ~~by the use of~~by using Multiregional Input-Output Tables (MRIOTs) (Wiedmann, 2009) (see Annex II, Figure A1). The monetary value of products that one sector needs from the other sectors to obtain one monetary unit of production is represented by technical coefficients, which are gathered within the technical coefficient matrix or A matrix (Miller and Blair, 2009; ten Raa, 2006). The total G&S produced by a specific demand can be estimated as shown in Eq. (1).

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

Where x is the total production of goods and services (total effects) matrix of dimension (m×n)×m (being m the regions and n the sectors), A is the (m×n)×(m×n) technical coefficient matrix, $(I - A)^{-1}$ is the inverse of Leontief which represents direct and indirect effects and y is the (m×n)×m final demand. This methodology can be extended to a hybrid model LCA-IO (Crawford et al., 2018) by combining input-output data with BIOSOL prototype investment and O&M cost data, in order to allow the estimation of the total economic stimulation produced by an increase in the demand of goods and services needed to build and operate the prototype. Direct effects are related to the components and services required for the project (see Table 3) and indirect effects are those inputs necessary to satisfy the direct demand provided by intermediate suppliers.

$$x_I = (I - A)^{-1}\hat{y}_I \quad (2)$$

Where x_I is the total, direct, and indirect impact matrix (m×n)×(m×n) of BIOSOL investments on the production, and $\hat{y}_I$ is the BIOSOL investments expressed as a final demand diagonalized vector (m×n)×(m×n). The IO analysis allows estimating other impacts (e.g. employment, CO_2 emissions), by extending the methodology with vectors describing specific impacts per monetary unit produced in each economic sector. These impacts can be calculated as expressed in Eq. (3).

$$F = \hat{f}(I - A)^{-1}\hat{y}_I \quad (3)$$

Where F is the total (direct and indirect) socioeconomic/environmental effect (m×n)×(m×n) matrix, $\hat{f}$ is the (m×n)×(m×n) socioeconomic/environmental diagonalized vector (value added, employment and CO_2 emissions in this sense) and $\hat{y}_I$ is the BIOSOL prototype investments expressed as a final demand diagonalized vector of (m×n)×(m×n) dimensions (see Annex II, Equation A1). Induced impacts on employment can also be calculated following the Miyazawa's approach (Miyazawa, 1968). The matrix A is expanded to include the private expenditure by households as a new column and the wages of employees' row vector as a new row (see Eq. 4).

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$$F' = \hat{f}'(I - A')^{-1}\hat{y}_I' \quad (4)$$

Where F' expresses the total (direct, indirect and induced) socioeconomic/environmental impacts on the output, the new inverse of Leontief $(I - A')^{-1}$ incorporates the household consumption and the wages of employees, and $\hat{y}'$ also includes the personnel costs related to the O&M phase. Induced effects capture the effect in the consumption of goods and services derived from changes in the economic compensation of employees. As a resulting increase of final demand, households are paid for their work force. Received payments are used for consumption and saving purposes. Consumption will further stimulate final demand and production. In the present research, we assume that propensity to consume is 1.

MRIO analysis in this work uses the OECD Inter-Country Input-Output (ICIO) tables (Yamano and Ahmad, 2006) that provide a time series of data (1995 – 2015) for 36-sector symmetric industry-by industry MRIOT and 69 regions with matching employment and CO_2 emissions satellite accounts (Wiebe and Yamano, 2016). In particular, data used for Tunisia (year 2015) corresponds to the last edition (OECD, 2018) based on the United Nations' International Standard Industrial Classification of All Economic Activities (ISIC Rev 4) (United Nations, 2008), maintaining the number of sectors (n=36) and aggregating to six regions (m=6, Tunisia, Italy, France, rest of Europe, China and the rest of the world) to facilitate the management and interpretation of the results without losing relevant information (see Annex II, Table A1). Due to data limitations regarding the Tunisian employment data coming from the ICIO-OECD tables, ILOSTAT data has been considered IO assessment (International Labour Organization (ILO), 2015). This data is compatible with the ICIO table since both rely on the ISIC Rev.4. Thus, 9 out of 36 economic sectors have been directly allocated. For the remaining sectors, aggregated data from ILOSTAT has been reallocated using the ICIO-OECD Israeli employment coefficients, calculated by dividing the "people engaged" of each economic sector by the total output obtained by each economic sector.

2.2.1. Cost data

Cost data considered for both the investment and the O&M phases is provided by BIOSOL project (see Table 3). We assume that the investment phase takes place in the first year. Annual O&M costs are brought to the net present value. Assuming a plant life expectancy of 25 years and a discount rate of 6% for Tunisia (Soares et al., 2018b), the total O&M costs along the life cycle amount to 1,417,360.8$. Personnel costs are not considered here. Data provided under BIOSOL project gives a cost of biomass (oil-cake) of 0.1 $/kg, in the range of green and agricultural waste (Bouaoun, 2014).

Transport costs per kilogram are in the same range. The gasifier is assumed to require about 475 tons per year.

Table 3.
BIOSOL investment cost disaggregation and manufacturing country.

Cost data	Cost breakdown	Country	2015 US$
Investment	Solar Field (SF)	ITA	4,505,027.4
	Boiler System (BS)	FRA	233,084.8
	Pyrolysis burner	*FRA*	*8,964.8*
	Gasifier	*FRA*	*224,120.0*
	Power Block (PB)	ITA (89%), TUN (11%)	896,332.6
	Contingencies and other costs	TUN	1,380,607.2
	Total		**7,015,052.0**
O&M (annual costs)	Resources and energy costs (transport & biomass)		95,000.0
	Personnel costs		301,634.2
	O&M and replacement of Anaerobic Digestor		8,858.5
	O&M and replacement of Solar Field		3,825.9
	O&M and replacement of Boiler		31.8
	O&M and replacement of Power Block		3,159.2
	Total		**412,509.7**

Source: data provided by EU ERANETMED consortium.
Note: Italy (ITA), France (FRA), Tunisia (TUN).

Investment costs provided here (7.0 k.US$/kW or 6.3 k.EUR/kW, year 2015) are comparable with the existing hybrid CSP-biomass power plants in the literature. Most recent studies point out that investment stage costs are in the range of 5.7 (Pedrazzi et al., 2019) to 6.3 (Oyekale et al., 2018) k.EUR/kW (2018 as a reference year). Pantaleo and colleagues (Pantaleo et al., 2017) provide results for five case studies with different configurations. Based on interviews and data collection from manufacturers of the selected technologies (Camporeale et al., 2015), investment costs vary from 3.5 to 4.5 k.EUR/kW (year 2017). Although values are lower, the O&M costs are ranged from 0.7 to 1.1 k.EUR-year/kW, presenting higher values when compared to the present research (0.4 k.EUR-year/kW) and Oyekale's (0.3 k.EUR-year/kW).

2.2.2. Final demand vector

Once all costs have been accounted for, demand of goods and services considered in Table 3 for investment and O&M are assigned to the corresponding economic sectors and countries on the input-output table (see Annex II, Table A2), according to the United Nations Statistics classification (United Nations, 2008) and the sector disaggregation of a solar thermal power plant provided by Rodriguez-Serrano and colleagues (Rodríguez-Serrano et al., 2017). This allows constructing the demand vectors ($\hat{y}_I$ and $\hat{y}'$ see Eq. 2 and 4), which correspond to the direct effects, which will be ~~later~~ used later to calculate the indirect and induced effects. Table 4 shows the final demand vector, which is the total investment and operational costs assigned to the corresponding economic sectors of each country. Costs related to biomass supply are included in sector Food products, beverages and tobacco, since oil-cake residues are classified in class 1040 according to ISIC Rev.4. This vector excludes personnel costs.

Table 4.
BIOSOL Final demand vector for ICIO-OECD database ($2015).

Country	Sector allocation	Investment costs	O&M costs	Total costs
ITA	Electrical equipment	1,988,794		1,988,794
ITA	Other non-metallic mineral products	976,234		976,234
ITA	Fabricated metal products	852,396		852,396
ITA	Basic metals	806,643		806,643
ITA	Machinery and equipment, nec	512,633		512,633
ITA	Computer, electronic and optical products	167,417		167,417
FRA	Machinery and equipment, nec	231,964		231,964
FRA	Other business sector services	1,121		1,121
TUN	Construction	97,243	4,381	101,625
TUN	Transportation and storage	509,763	607,209	1,116,972
TUN	Financial and insurance activities	475,006		475,006
TUN	Other business sector services	395,838		395,838
TUN	Food products, beverages and tobacco		607,209	607,209
TUN	Other non-metallic mineral products		10,599	10,599
TUN	Basic metals		8,757	8,757
TUN	Fabricated metal products		10,819	10,819
TUN	Computer, electronic and optical products		1,818	1,818
TUN	Electrical equipment		29,823	29,823
TUN	Machinery and equipment, nec		23,097	23,097
TUN	Other manufacturing; repair and installation of machinery and equipment		113,648	113,648
Total costs		**7,015,052**	**1,417,361**	**8,432,413**

Source: own elaboration on the basis of (Rodríguez-Serrano et al., 2017).

3. Results and discussion

3.1. Environmental assessment results

Results of the Life cycle inventory (LCI) are shown in Annex I from Table A1 to A5. Environmental Impacts are the result of the life cycle impact assessment (LCIA) phase in the LCA. These impacts have been assessed as described in the method and materials section. Additionally, the hot spots stages in each system part have been identified. The summary of the environmental impact assessment for hybrid power plant analyzed in this study is presented in Table 5 and Figure 3.

Table 5. Environmental impact results

Impact category		Amount	Unit Per MWh
Climate change	CC	21.74	kg CO_2 eq
Ozone depletion	ODP	3.29E-06	kg CFC11 eq
Ionising radiation, HH	IR	2.91E+00	kBq U-235 eq
Photochemical ozone formation, HH	POF	1.79E-01	kg NMVOC eq
Respiratory inorganics	RI	9.37E-06	disease inc.
Non-cancer human health effects	NC-HHE	6.43E-06	CTUh
Cancer human health effects	C-HHE	7.01E-07	CTUh
Acidification terrestrial and freshwater	AT-FW	1.50E+00	mol H+ eq
Eutrophication freshwater	EFW	1.77E-02	kg P eq
Eutrophication marine	EM	2.79E-02	kg N eq
Eutrophication terrestrial	ET	3.15E-01	mol N eq
Ecotoxicity freshwater	ECFW	2.23E+01	CTUe
Land use	LU	9.60E+01	Pt
Water scarcity	WS	2.00E+03	m^3 depriv.
Resource use, energy carriers	RU-E	2.98E+02	MJ
Resource use, mineral and metals	RS-M	4.14E-04	kg Sb eq
Climate change – fossil	CC-F	21.70	kg CO_2 eq
Climate change – biogenic	CC-B	4.03E-02	kg CO_2 eq
Climate change - land use and transform.	CC-LUT	2.25E-03	kg CO_2 eq

Source: own elaboration.

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Global warming emissions per MWh of electricity generated in this plant are quantified in around 22 kg of CO_2 eq. This value is lower than the values published in the literature. San Miguel and co-workers (San Miguel and Corona, 2014) found values ranging from 34 to 64 kg CO_2 eq/MWh for different biomass fuels (wheat straw, wood pellets and biomethane). (Piemonte et al., 2011) found global warming emissions of 190 kg CO_2 eq/MWh. Reasons for these discrepancies can be found in the residual nature of the biomass used in this prototype (olive oil cake) that does not entail any embodied environmental impact other than those of transporting it to the power plant. Another reason could be the fact that the pyrolysis process used to produce the syngas avoids the release of digestion emissions considered in their study. Corona and coworker (Corona and San Miguel, 2015) found values ranging from 68 to 96 kg CO_2 eq/MWh for the hybrid operation of a CSP plant with biomethane from different substrates (grass, sewage, biowaste and mixed manure), with the highest impacts corresponding to grass (energy crop) due to the impacts originated in the cultivation phase. And also Corona (Corona et al., 2016) found values ranging from 29 to 46 kg CO_2 eq/MWh for a CSP hybrid power plant using biomethane, with different values depending on the location of the power plant and their respective DNI.

Graphically, Figure 4 shows the contributions made to the different impacts, by the different parts of the system.

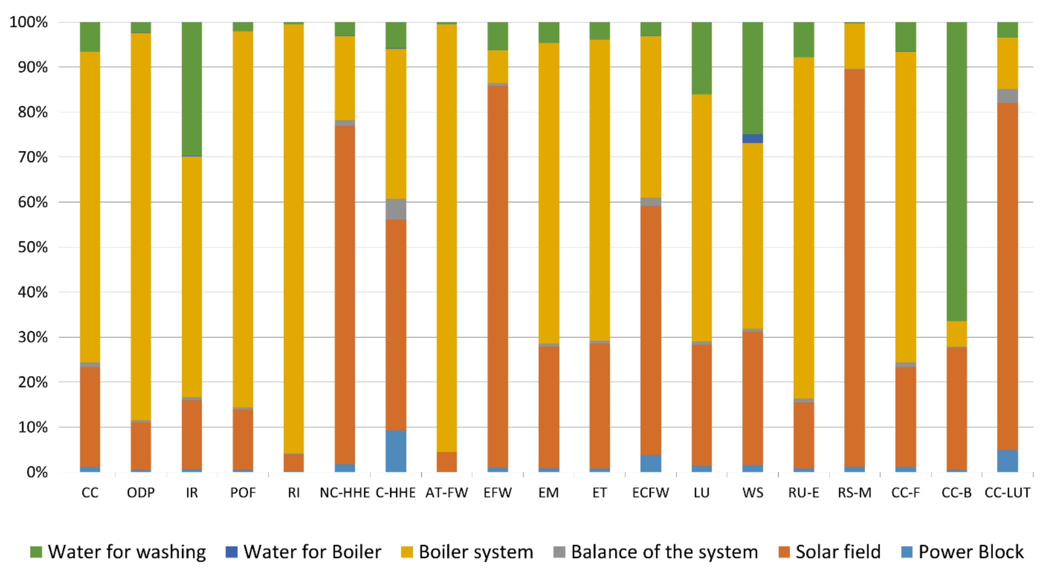

Figure 4. Distribution of the contributions by the different parts of the system.

Both the solar field and the boiler system account for most of the impacts in all the impact categories. The solar field dominates the impacts related to non-cancer human health effects (NC-HHE), freshwater eutrophication impacts (EFW), freshwater ecotoxicity (ECFW), mineral and metals resource use (RS-M) and land use change GHG emissions (CC-LUT). The boiler system ~~dominates~~ highlights in the rest of the impact categories with the notable exception of the CC-B where the provision of water for washing dominates.

In terms of energy, fossil energy demand has been quantified in 298 MJ/MWh, a value substantially lower than other published studies ranging from 757 MJ/MWh (Corona et al., 2016) and 1,400 MJ/MWh (Piemonte et al., 2011) up to 3,026 (Corona and San Miguel, 2015) but in the range of the values found by San Miguel in (San Miguel and Corona, 2014).

Figures 4 to 6 show ~~on~~ in a graphic form the main contributions to the different impact categories of each component: power block, solar field and the boiler system, and its percentage participation.

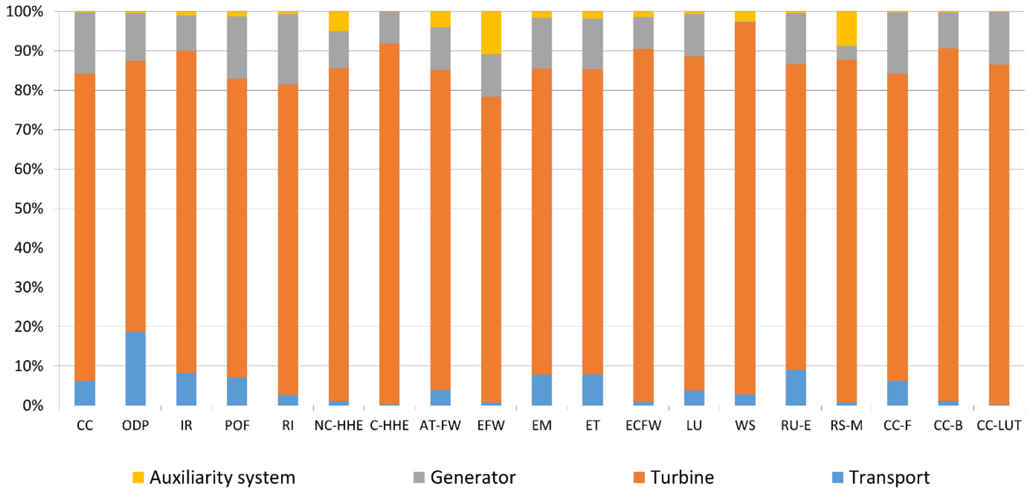

Figure 34. Distribution of the contributions by the different parts of the power block system.

In the power block, the steam turbine is the cause of most of the impacts. In this case, the influence of the steam turbine is due to the production of the steel used for its manufacture. In terms of human toxicity, it is the extraction of copper from the turbine fabrication which generates most of the impacts.

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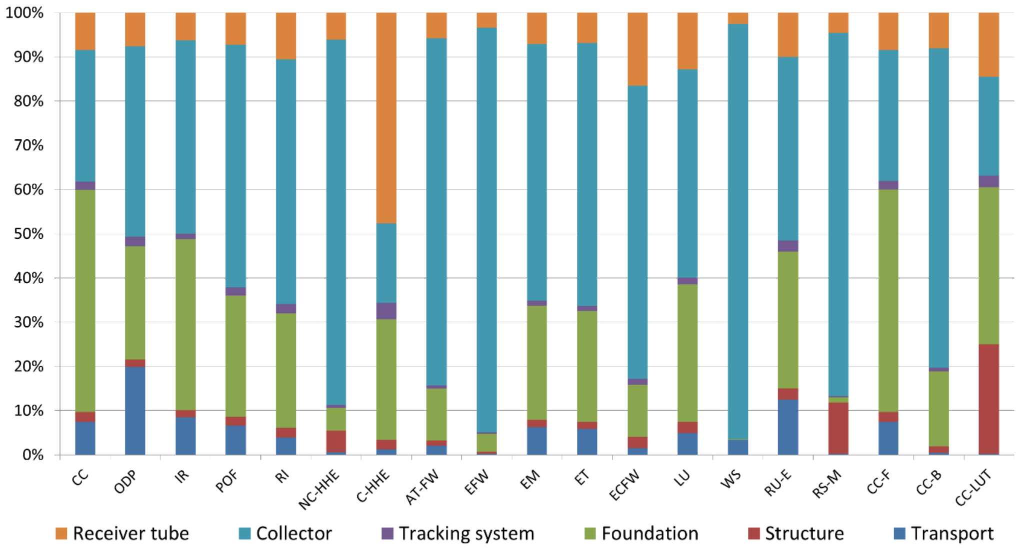


Figure 4~~5~~. Distribution of the contributions by the different parts of the solar field system.

Regarding the solar field, the foundations and the collectors are the major contributors. There is an important contribution of the solar collectors and the structure to the impact resource use minerals and metals. Similar results have also been found by others (Corona et al., 2016; Lechón et al., 2008). The collectors and the foundations contribute to climatic change due to the production of glass and the production of concrete, respectively. In the rest of the environmental impacts, the collectors are the major contributor due to the extraction of copper.

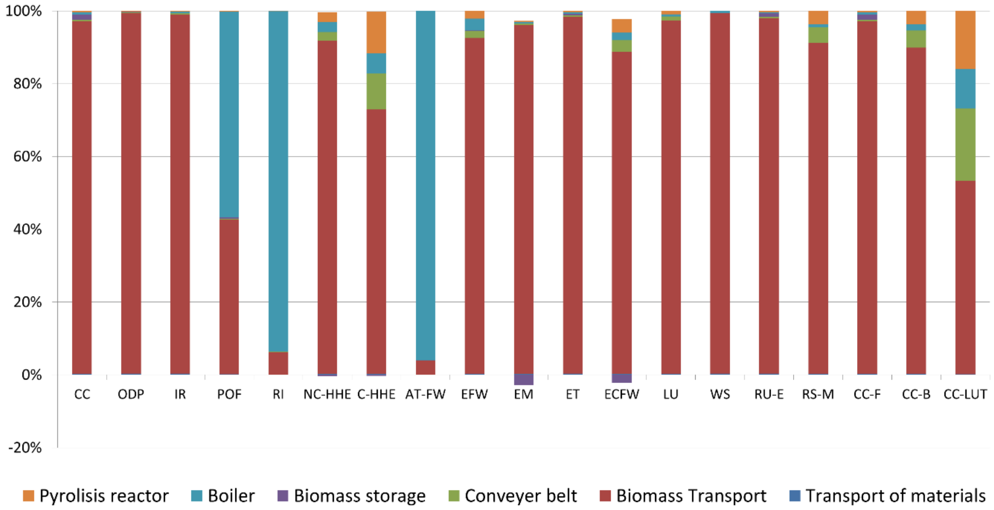


Figure 5~~6~~. Distribution of the contributions by the different parts of the boiler system.

Environmental impacts of the boiler system are dominated by the impacts due to biomass transport activities with the exception of photochemical ozone formation (POF), respiratory inorganics (RI) and terrestrial and freshwater acidification (AT-FW) that are mainly caused by the manufacturing of the boiler.

According to the results presented in this paper, the assessed CSP and biomass hybrid power plant is an attractive option. In a country where olive production is so relevant, using the residual olive pomace (a second generation biofuel) (Naik et al., 2010) as a fuel for producing electricity may reduce the main biomass disadvantages coming from water and land footprint (Mahlooji et al., 2019). However, the boundaries of scaling up the system should be considered: for much higher installed capacities, the need for biomass can be such that the facility cannot be operated. Nevertheless ~~Besides~~, this technology could be used for sustainable energy provision in the agricultural sector (Mekhilef et al., 2013). For example, exploring activities such as supplying energy to the irrigation systems in the olive production (Todde et al., 2019) or thermal energy for the olive industry or the residential sector (Masghouni and Hassairi, 2000) could bring additional benefits to this exporting sector.

3.2. Socioeconomic assessment results

According to our results, BIOSOL project plant requirements create an estimated global economic stimulation 2.4 times larger than the initial investment. This multiplier effect gives information about the total stimulation produced from direct effects (Caldés et al., 2009). Nonetheless, the largest impact in terms of production and value added is generated outside Tunisia. Despite the higher initial investment participation (34.3%), total effects in production and ~~value added~~value-added creation are only 22.6 and 28.9%, respectively (see Table 6). Each indicator corresponds to the overall (direct and indirect) socioeconomic/environmental effect (sum of *F* matrix, see Eq. 2).

Table 6. BIOSOL effects on production, value added, employment and CO_2 emissions

Phase/Indicator	**Production ($2015)**	**Value added ($2015)**	**Employment (FTE)**	**Emissions (Gg CO_2)**
Investment	17,084,857	6,603,827	179	3.01
O&M	3,132,611	1,381,701	111	0.93
Fuel costs (biomass)	*2,668,209*	*1,185,157*	*97*	*0.73*
Total effects	20,217,468	7,985,528	290	3.94
Tunisian share	*22.6%*	*28.9%*	*63.3%*	*33.9%*
Jobs in power plant			227	

Source: own elaboration.

Table 7 shows how the value added is generated along the value chain. ~~In terms of value added,~~ Tunisian value added in imports from Italy, France and the rest of the world account for only 0.07% of the total value added creation, pointing out the low insertion of this country in forward linkages (Sammoud and Dhaoui, 2019). This high dependency of imported components could be undermining the GDP and employment growth potentialities in Tunisia. In this sense, policy actions developed towards either foreign direct investments (FDI) attraction or the promotion of a domestic business and technological network of energy-related components become an interesting option for the Tunisian economy in order maximize the economic growth in the country, the creation of jobs and the access to other markets such as the MENA region.

Table 7. Value added creation along the BIOSOL project value chain

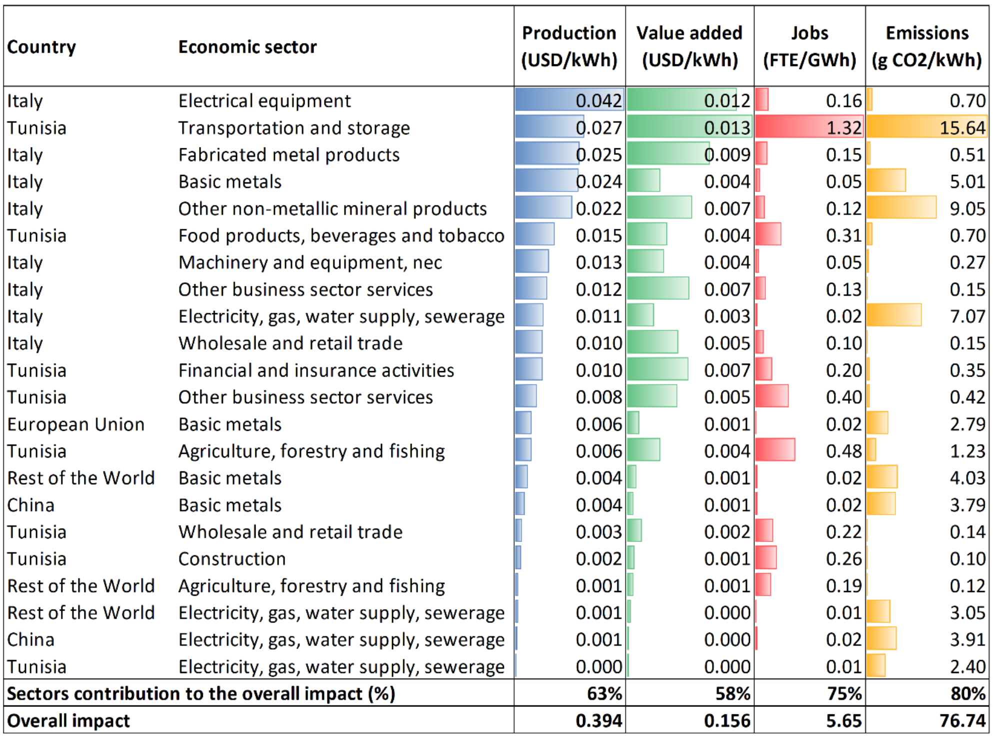
Value chain	**Country-origin**	**Participation**
Domestic value added	Tunisia	28.9%
In Tunisian direct and indirect requirements		28.83%
In imports		0.07%

Foreign value added		71.1%
In intermediates		6.60%
	Italy	*8.7%*
	France	*17.2%*
	Rest of Europe	*23.2%*
	China	*4.4%*
	Rest of the World	*46.5%*
In final goods and services		64.50%
	Italy	*67.7%*
	France	*5.2%*
	Rest of Europe	*11.8%*
	China	*2.8%*
	Rest of the World	*12.5%*

Source: own elaboration.

Even though Tunisia has not a relevant role in the investment phase, the O&M phase is remarkable for the country as a host of the power plant, benefiting local long-term employment. Total employment created is estimated in 11.6 FTE jobs/year (290 FTE during the lifetime of the power plant). From that amount, Tunisia is creating 7.4 FTE (63.3%). The O&M phase would create 4.4 FTE jobs/year for 25 years (111 FTE). Fuel costs (olive pomace) are the main reason as an estimated 3.8 FTE jobs/year (97 FTE) would be created in Tunisia as a consequence of the the management and transportation of olive oil residues needed to feed the biomass boiler. The rest is expected to come from the replacement of the components (boiler, power block, solar field and contingencies). Direct employment (personnel costs related to the operation phase) can be estimated ~~on the basis of~~based on engaged people and compensation of employees provided by OECD, ILOSTAT and the direct personnel costs provided in Table 3. Engaged people in the electricity sector Tunisia was almost 20.7 thousand ~~people~~ workers in 2015. Compensation of employees in this sector was 293.2 million dollars. Thus, an average employee in the Tunisian electricity sector ~~in Tunisia~~ was paid 14,160 dollars that year. An amount of 3,219,877.6 dollars of personnel costs (2015 prices) is assumed to take place in Tunisia during the lifespan of the power plant. This would result in 227.4 additional FTE in the Electricity sector during the 25 years of the hybrid power plant lifespan. Hence, the annual job direct requirements would be 9.1 employees. Altogether with the investment (3) and the O&M phase (4.4), the overall annual employment in Tunisia would be 16.5 direct and indirect jobs per year.

Figure 7 below shows the sectors and countries that contribute the most to the socioeconomic impacts. Neither induced effects nor direct jobs in the power plant are accounted for. The *Transport and storage* sector in Tunisia is the most important sector in terms of production, value added, employment creation and CO_2 emissions when measured altogether. The Solar Field and the Power Block coming from Italy are reflected in sectors such as *Electrical equipment*, *Basic metals* and *Fabricated metals*, as well as *Other non-metallic mineral products*. Since these components account for the largest investments, effects in production and value added are high (33.1% and 23.7%, respectively). Services (*Other business sector services*; *Financial and insurance activities*; *Wholesale and retail trade*) are considered essentials in the process of manufacturing – a phenomena called *servicification* of manufacturing (Lanz and Maurer, 2015) – contributing to value added creation not only in developed but also in developing countries (Banacloche, 2017). Finally, in terms of employment, apart from the *Transportation and storage* sector, the main indirect sectors benefited correspond to *Agriculture, forestry and fishing*, *Wholesale and retail trade*, related to the biomass process.



Country	Economic sector	Production (USD/kWh)	Value added (USD/kWh)	Jobs (FTE/GWh)	Emissions (g CO2/kWh)
Italy	Electrical equipment	0.042	0.012	0.16	0.70
Tunisia	Transportation and storage	0.027	0.013	1.32	15.64
Italy	Fabricated metal products	0.025	0.009	0.15	0.51
Italy	Basic metals	0.024	0.004	0.05	5.01
Italy	Other non-metallic mineral products	0.022	0.007	0.12	9.05
Tunisia	Food products, beverages and tobacco	0.015	0.004	0.31	0.70
Italy	Machinery and equipment, nec	0.013	0.004	0.05	0.27
Italy	Other business sector services	0.012	0.007	0.13	0.15
Italy	Electricity, gas, water supply, sewerage	0.011	0.003	0.02	7.07
Italy	Wholesale and retail trade	0.010	0.005	0.10	0.15
Tunisia	Financial and insurance activities	0.010	0.007	0.20	0.35
Tunisia	Other business sector services	0.008	0.005	0.40	0.42
European Union	Basic metals	0.006	0.001	0.02	2.79
Tunisia	Agriculture, forestry and fishing	0.006	0.004	0.48	1.23
Rest of the World	Basic metals	0.004	0.001	0.02	4.03
China	Basic metals	0.004	0.001	0.02	3.79
Tunisia	Wholesale and retail trade	0.003	0.002	0.22	0.14
Tunisia	Construction	0.002	0.001	0.26	0.10
Rest of the World	Agriculture, forestry and fishing	0.001	0.001	0.19	0.12
Rest of the World	Electricity, gas, water supply, sewerage	0.001	0.000	0.01	3.05
China	Electricity, gas, water supply, sewerage	0.001	0.000	0.02	3.91
Tunisia	Electricity, gas, water supply, sewerage	0.000	0.000	0.01	2.40
Sectors contribution to the overall impact (%)		**63%**	**58%**	**75%**	**80%**
Overall impact		**0.394**	**0.156**	**5.65**	**76.74**

Figure 6~~7~~. Main economic sectors in terms of socioeconomic effects.
Source: own elaboration.

Assessing the BIOSOL project carbon footprint, the most important impacts in terms of CO_2 emissions are originated by the Tunisian transportation of both, olive oil waste and components, accounting for 0.8 Gg CO_2 (15.6 g CO_2/kWh produced) out of 3.94 Gg (76.7 g CO_2/kWh)~~-~~. Since Italy is the main provider of components (Solar Field and Power Block), the country produces 33.2% of the overall emissions, mainly from sectors such as *Other non-metallic mineral products*; and the *Electricity, gas and water supply* sectors (see Figure 7). The latter sector has been usually identified as one of the most important in terms of CO_2 emissions. Global value chains phenomena determines the role of regions such as China and the Rest of the World as intermediates providers. Although no direct investments are made (see Table 3), intermediates are needed (i.e. basic metals and electricity) to produce the final components. Developing countries are identified to have a more carbon intensive electricity mix. Hence, emissions embodied in these intermediates have a notable impact in the installation of the BIOSOL power plant. Transport efficiency and a renewable energy sources (RES) intensive electricity mix of the countries involved in the BIOSOL project value chain would reduce CO_2 emissions substantially.

Induced effects capture the effect in the consumption of goods and services derived from changes in the economic compensation of employees. As a resulting increase of final demand, households are paid for their work force. Received payments are used for consumption and saving purposes. Consumption will further stimulate final demand and production. Assuming that every income is spent (propensity to consume equal to 1) the multiplier effect becomes 3.5 instead of 2.4. Salaries earned by the payment of labour services needed to satisfy the project demand have an additional and very important stimulus in the global economy. When induced effects are included, the installation of 11,652,290 dollars BIOSOL project in Tunisia, along with the personnel costs required during the lifespan of the installation, would have an estimated impact in production of 40,624,268 dollars. Direct and indirect income-generation per unit of income originated can also be assessed. In this project, since only Tunisia is hiring personnel directly, the initial 3,219,878 dollars income earned by personnel gives an indirect rise of 4,477,803 dollars income in the region itself, plus 3,342,813 incomes in Italy, 892,912 in France, 1,758,498 in the rest of Europe, 399,144 in China and 2,352,358 in the rest of the world.

Figure 8 represents the total effects of BIOSOL investment, when induced impacts are considered. The income generated as a consequence of the labour payments during the investments and later spent in the economy has a larger boost when compared to the direct and indirect effects in the production of goods and services, value-added creation and employment generation. In terms of CO_2 induced emissions are a 45% of the total figure. These induced emissions are largely disregarded in the literature and could be, as demonstrated in this work, very important.

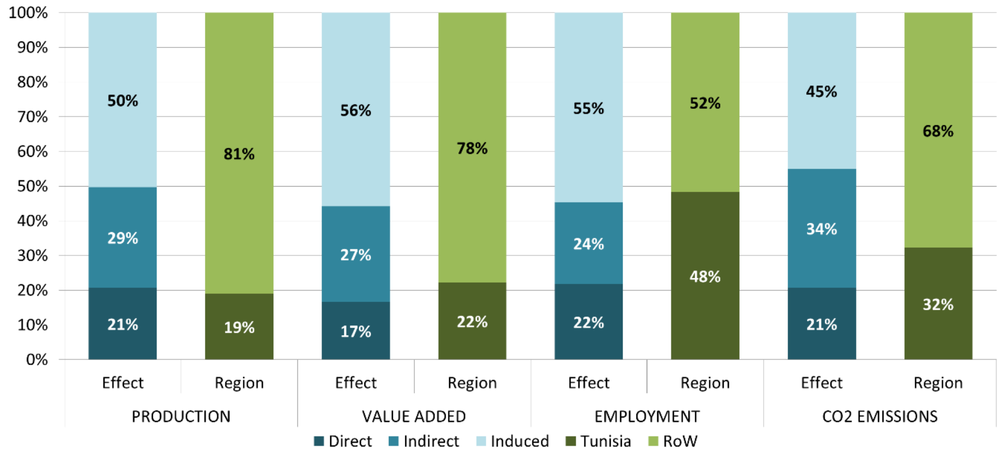


Figure 7~~8~~. Total effects on production, value added, employment and CO_2 emissions (induced effects included)
Source: own elaboration.

In order to deploy RES investments, foster local employment and reduce carbon emissions, Tunisia must face an initial increase in CO_2 emissions. However, the main origin of emissions comes from outside the country due to the import dependency. Future green investments, compatible with the national package of RES deployment and the Paris Agreement, can be targeted to promote domestic value added. When looking at these results, it is worth ~~to consider~~considering the limitations of this analysis that has assumed that every dollar received by the personnel is reinvested in the economy and that nothing is saved.

3.3. Comparison of CO_2 emissions calculated by both methodologies

In terms of CO_2 emissions, the 77 gCO_2 eq/kWh calculated by the IOA contrast with the 22 gCO_2 eq/kWh that result from the LCA. Although results are consistent with the literature and in the range of published results, differences between the LCA and the IOA come from the assumptions made by each methodology and have been extensively discussed in the literature (Crawford et al., 2018; Lenzen, 2000; Rowley et al., 2009; Suh et al., 2004). In principle, it is expected that IOA gives higher results than LCA since IOA avoids the specification of limits to the system. However, there could be other reasons for the high discrepancies observed. First, LCA here analyses the production processes for imported components as if they were produced in Europe, disregarding the country-origin of the intermediate products needed for these components. Hence, CO_2 emissions are calculated with the characteristics of the European technological and energy supply systems. By contrast, IOA considers the country-~~ of ~~origin of the components and captures all the successive rounds of production and the trade relations between countries and sectors. Carbon-intensive economies such as China and other developing countries have an important role under the IOA, due to global value chains and the importance of intermediates in the fragmentation of production. Thus, CO_2 emissions will have a larger impact under this approach. Second, LCA can capture the technological details of all the processes involved in the value chain of the technology, while IOA only provides sector averaged results. This sector aggregation could distort the correct calculation of emissions by IOA and could be overestimating them. And third, the sources of the emission data in both methodologies are completely different. LCA relies on technology specific calculation of emissions while IOA uses national inventories of emissions per sector.

4. Conclusions

The development of this system contributes to bringing to the market energy-efficient, renewable electricity generation systems. The environmental sustainability and economics of the prototype systems have been assessed, and the results obtained should be disseminated to industry and research, as a proof-of-concept of renewable electricity generation solutions.

The hybrid system shows a result of GHG emissions close to 22 gCO_2eq/kWh. By component, the boiler system is the major contributor to this impact due mainly to the biomass transport. After an analysis of the whole system, it is observed that, in general, the boiler system and the solar field are the parts of the installation that most influence have in the calculated environmental impacts. On one hand, the boiler system has an influence on all the impacts that are related mainly to the emissions caused by the transport of biomass, which could be reduced by the definition of shorter biomass transport distances~~.~~. On the other hand, the solar field has a lot of influence in human toxicity, freshwater ecotoxicity and resource use minerals and metals. The major contribution of the solar field to these impacts is due to the manufacturing process of the solar collectors and the extraction of the copper needed in the manufacturing process. From an energy point of view, the system shows very low demand for fossil energy.

From the socioeconomic analysis performed, the investment assessed creates a stimulation of production of goods and services of 2.4 (3.5 when induced effects are accounted for). Employment and emissions become the most important impacts for Tunisia. In terms of CO_2 emissions, the 77 gCO_2 eq/kWh contrast with the results of the environmental analysis. Differences have been discussed and are related to the different assumptions made by each methodology.

The O&M phase becomes an important stage in the generation of domestic long-term employment mainly due to the biomass supply activities. In ~~all of~~all the socioeconomic impacts, the imported content is high, highlighting the Tunisian dependency in installing a hybrid CSP-biomass power plant. Europe offers a strong technology base, being home of some of the world's leading multinational energy and systems integration companies, as well as many smaller research institutions and specialized companies. In order to maximize the positive socioeconomic effects, the national content of the investments has to be maximized (e.g. producing the main components and attracting FDI).

Results remain highly explorative, as the technology has not been deployed. Limitations of data, both at a macro and project specific level must be stressed. Besides, calculated effects are gross estimations. Net effects would result if the economic and employment effects of alternative ways of generating electricity and heat were also analyzed and subtracted. Despite these uncertainties, this paper points out the role of CSP in Tunisia as part of the solution to energy demand and Climate Change.

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Annex I. Life Cycle Inventory results (LCI)

Tables below show data and results of the LCI of the studied system. All these data are referred to one year of operation of the plant.

Table A1. Solar field inventory

Item	Value	Unit
Collector		
Flat glass coated	3,485	kg
Copper, at regional storage	1,100.48	kg
Synthetic rubber, at plant	43.90	kg
Collectors	19	p
Receiver tube		
Steel, chromium steel 18/8, hot rolled production	291.20	kg
Flat glass, uncoated production	221	kg
Aluminium oxide, at plant	3	kg
Copper, at regional storage	30	kg
Receiver tube	19	p
Structure		
Reinforcing steel production	61.12	kg
Aluminium oxide, treatment of aluminium scrap	414.88	kg
Structure	19	p
Foundation		
Concrete	73,728	kg
Reinforcing steel	1,103.36	kg
foundation	19	p
Tracking system		
Reinforcing steel	138.4	kg
Nickel, 99.5% nickel mine operation, sulfidic ore	0.074	kg
Lubricating oil production	13.335	kg
Chromium production	0.074	kg
Polyethylene, high density, granulate production	10.08	kg
Wire drawing, copper processing	8.32	kg
Pump, 40W production	2	p
Tracking system	19	p

Source: own elaboration.

Table A2. Life cycle inventory of the power block.

Item	Value	Unit
Turbine system		
Reinforcing steel	1,248.63	kg
Copper, at regional storage	57.63	kg
Ceramic tile {CH}|production	29.2	kg
Steel, chromium steel 18/8, hot rolled	1,128.25	kg
Aluminium, production mix, at plant	145.99	kg

Turbine	1	p
Generator		
Reinforcing steel	832.63	kg
Ceramic tile{CH}	19.47	kg
Generator	1	p
Generator auxiliaries		
Copper, at regional storage	19.47	kg
Generator auxiliaries	1	p

Source: own elaboration.

Table A3. Balance of the system inventory

Item	**Value**	**Unit**
Steam drum		
Sanitary ceramics, at regional storage	17.58	kg
Cast iron /	135.64	kg
reinforcing steel production	818.25	kg
Aluminium,	17.58	kg
Transport, lorry 7.5-16 t, EURO5	979.63	tkm
Expansion tank		
Sanitary ceramics, at regional storage	44.81	kg
Cast iron, at plant/	345.65	kg
Reinforcing steel	2,085.08	kg
Aluminium, production mix, at plant	20.8	kg
Transport, lorry 7.5-16 t, EURO5	2496.33	tkm
Feed water tank		
Sanitary ceramics, at regional storage	17.58	kg
Cast iron, at plant	135.64	kg
Reinforcing steel {RER}| production	818.25	kg
Aluminium, production mix, at plant/ RER U	17.58	kg
Transport, lorry 7.5-16 t, EURO5	979.63	tkm

Source: own elaboration.

Table A4. Life cycle inventory of the boiler system.

Item	**Value**	**Unit**
Digester		
Concrete, normal	1.75	m^3
Reinforcing steel, at plant	476.91	kg
Chromium steel 18/8, at plant	52.29	kg
Copper, at regional storage	6.12	kg
Polyethylene, high density, granulate production	4.52	kg
Polyvinyl chloride, at regional storage	0.59	kg
Synthetic rubber, at plant	1.56	kg
Transport, lorry 7.5-16 t, EURO5	542.76	tkm
Boiler		
Sanitary ceramics, at regional storage	46.37	kg
Cast iron, at plant	357.71	kg
Reinforcing steel	2157	kg

Aluminium, production mix, at plant	21.53	kg
Transport, lorry 7.5-16 t, EURO5	2,583.43	tkm
Electricity, medium voltage,	872,960	kWh
Methane biogenic emission	113.78	kg
Nitrogen monoxide	44.7	kg
Carbon dioxide	97,9	t
Waste food	127.75	ton/year
Gas natural	1,574.74	kg/year
Decanter		
Polyvinyl chloride	70	kg
Transport, lorry 7.5-16 t, EURO5	70	tkm
Mixing tank		
Reinforcing steel	215	kg
Transport, lorry 7.5-16 t, EURO5	215	tkm

Source: own elaboration.

Table A5. End of life scenario

Item	Value	Unit
Landfill	15	km
Solar field	80.48	ton
Power block	3.48	ton
Biogas system	4.74	ton
Balance of the system	4.47	ton

Source: own elaboration.

Annex II. Input-output analysis supplementary material

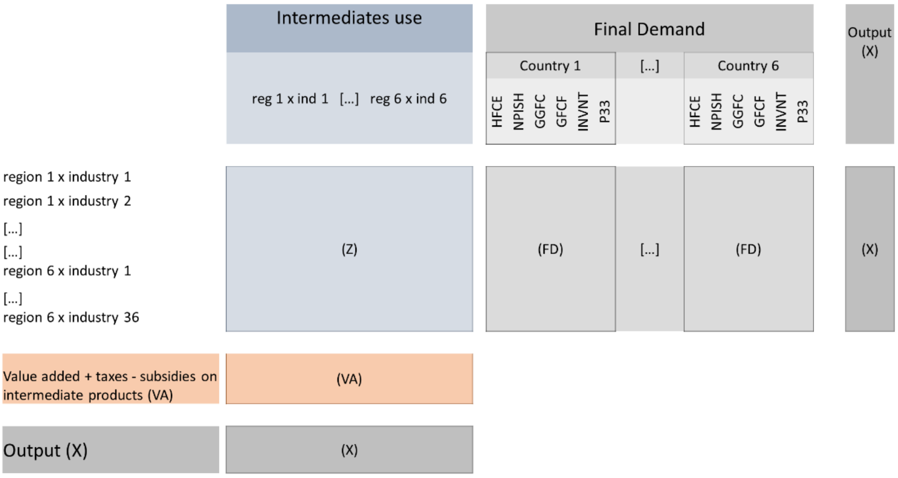
Equation A1. Socioeconomic/environmental impacts

We assume two regions (m=r,s) and two sectors (n=1,2) identified in the superscripts and subscripts, respectively. The first position corresponds to the region/sector origin. The second position to the destination. Taking in example $L = (I - A)^{-1}$, the Leontief inverse matrix, $L_{2,1}^{rs}$ is interpreted as the total requirements originated in sector 2 from country *r* and destinated to satisfy sector 1 in country *s*. Direct requirements (goods and services needed for the deployment) provided by both regions, *r* and *s*, are captured in matrix $\hat{y}_I$. Assuming that the project installation takes place in country *r*, the second position of country-origin will always be *r*, that is, the country that demands the goods and services.

$$F = \begin{bmatrix} \hat{f}_1^r & 0 & 0 & 0 \\ 0 & \hat{f}_2^r & 0 & 0 \\ 0 & 0 & \hat{f}_1^s & 0 \\ 0 & 0 & 0 & \hat{f}_2^s \end{bmatrix} \begin{bmatrix} L_{1,1}^{rr} & L_{1,2}^{rr} & L_{1,1}^{rs} & L_{1,2}^{rs} \\ L_{2,1}^{rr} & L_{2,2}^{rr} & L_{2,1}^{rs} & L_{2,2}^{rs} \\ L_{1,1}^{sr} & L_{1,2}^{sr} & L_{1,1}^{ss} & L_{1,2}^{ss} \\ L_{2,1}^{sr} & L_{2,2}^{sr} & L_{2,1}^{ss} & L_{2,2}^{ss} \end{bmatrix} \begin{bmatrix} \hat{y}_1^{rr} & 0 & 0 & 0 \\ 0 & \hat{y}_2^{rr} & 0 & 0 \\ 0 & 0 & \hat{y}_1^{sr} & 0 \\ 0 & 0 & 0 & \hat{y}_2^{sr} \end{bmatrix}$$

$$= \begin{bmatrix} \hat{f}_1^r L_{1,1}^{rr} \hat{y}_1^{rr} & \hat{f}_1^r L_{1,2}^{rr} \hat{y}_2^{rr} & \hat{f}_1^r L_{1,1}^{rs} \hat{y}_1^{sr} & \hat{f}_1^r L_{1,2}^{rs} \hat{y}_2^{sr} \\ \hat{f}_2^r L_{2,1}^{rr} \hat{y}_1^{rr} & \hat{f}_2^r L_{2,2}^{rr} \hat{y}_2^{rr} & \hat{f}_2^r L_{2,1}^{rs} \hat{y}_1^{sr} & \hat{f}_2^r L_{2,2}^{rs} \hat{y}_2^{sr} \\ \hat{f}_1^s L_{1,1}^{sr} \hat{y}_1^{rr} & \hat{f}_1^s L_{1,2}^{sr} \hat{y}_2^{rr} & \hat{f}_1^s L_{1,1}^{ss} \hat{y}_1^{sr} & \hat{f}_1^s L_{1,2}^{ss} \hat{y}_2^{sr} \\ \hat{f}_2^s L_{2,1}^{sr} \hat{y}_1^{rr} & \hat{f}_2^s L_{2,2}^{sr} \hat{y}_2^{rr} & \hat{f}_2^s L_{2,1}^{ss} \hat{y}_1^{sr} & \hat{f}_2^s L_{2,2}^{ss} \hat{y}_2^{sr} \end{bmatrix}$$

Figure A1. ICIO-OECD table scheme



Source: OECD

Table A1. ICIO-OECD region and sector classification

Region (69)				Sector (36)	ICIO Code	ISIC Rev.4
AUS	Australia	ARG	Argentina	Agriculture, forestry and fishing	D01T03	01, 02, 03
AUT	Austria	BRA	Brazil	Mining and extraction of energy producing products	D05T06	05, 06
BEL	Belgium	BRN	Brunei Darussalam	Mining and quarrying of non-energy producing products	D07T08	07, 08
CAN	Canada	BGR	Bulgaria	Mining support service activities	D09	09
CHL	Chile	KHM	Cambodia	Food products, beverages and tobacco	D10T12	10, 11, 12
CZE	Czech Republic	CHN	China (People's Republic of)	Textiles, wearing apparel, leather and related products	D13T15	13, 14, 15
DNK	Denmark	COL	Colombia	Wood and products of wood and cork	D16	16
EST	Estonia	CRI	Costa Rica	Paper products and printing	D17T18	17, 18
FIN	Finland	HRV	Croatia	Coke and refined petroleum products	D19	19
FRA	France	CYP	Cyprus	Chemicals and pharmaceutical products	D20T21	20, 21
DEU	Germany	IND	India	Rubber and plastic products	D22	22
GRC	Greece	IDN	Indonesia	Other non-metallic mineral products	D23	23
HUN	Hungary	HKG	Hong Kong, China	Basic metals	D24	24
ISL	Iceland	KAZ	Kazakhstan	Fabricated metal products	D25	25
IRL	Ireland	MYS	Malaysia	Computer, electronic and optical products	D26	26
ISR	Israel	MLT	Malta	Electrical equipment	D27	27
ITA	Italy	MAR	Morocco	Machinery and equipment, nec	D28	28
JPN	Japan	PER	Peru	Motor vehicles, trailers and semi-trailers	D29	29
KOR	Korea	PHL	Philippines	Other transport equipment	D30	30
LVA	Latvia	ROU	Romania	Other manufacturing; repair and installation of machinery and equipment	D31T33	31, 32, 33
LTU	Lithuania	RUS	Russian Federation	Electricity, gas, water supply, sewerage, waste and remediation services	D35T39	35 – 39
LUX	Luxembourg	SAU	Saudi Arabia	Construction	D41T43	41, 42, 43
MEX	Mexico	SGP	Singapore	Wholesale and retail trade; repair of motor vehicles	D45T47	45, 46, 47
NLD	Netherlands	ZAF	South Africa	Transportation and storage	D49T53	49 – 53
NZL	New Zealand	TWN	Chinese Taipei	Accommodation and food services	D55T56	55, 56
NOR	Norway	THA	Thailand	Publishing, audio-visual and broadcasting activities	D58T60	58, 59, 60
POL	Poland	TUN	Tunisia	Telecommunications	D61	61
PRT	Portugal	VNM	Viet Nam	IT and other information services	D62T63	62, 63
SVK	Slovak Republic	ROW	Rest of the World	Financial and insurance activities	D64T66	64, 65, 66
SVN	Slovenia	MX1	Mexico Non-Global Manufacturing	Real estate activities	D68	68
ESP	Spain	MX2	Mexico Global Manufacturing	Other business sector services	D69T82	69 – 82
SWE	Sweden	CN1	China Domestic sales only	Public admin. and defence; compulsory social security	D84	84
CHE	Switzerland	CN2	China Processing goods exporters	Education	D85	85
TUR	Turkey			Human health and social work	D86T88	86, 87, 88
GBR	United Kingdom			Arts, entertainment, recreation and other service activities	D90T96	90 – 96
USA	United States			Private households with employed persons	D97T98	97, 98

Source: OECD

Table A2. BIOSOL project cost breakdown

Cost breakdown	Country-origin	Costs ($)	Sector allocation	Cost distribution
Investment costs		**7,015,052.0**		
A. Total solar field: electrical components installation and commissioning; solar collectors (including metal structures, mirrors and receiver tubes); Instrumentation sensors (radiation, wind speed, GPS); solar field terrain drainage; others.	Italy	4,505,027	Other non-metallic mineral products	22%
			Electrical equipment	39%
			Basic metals	18%
			Fabricated metal products	18%
			Computer, electronic and optical products	4%
B. Power block: turbine, generator, heat exchangers, expander	Italy	896,333	Machinery and equipment, nec	57%
	Tunisia		Construction	11%
	Italy		Fabricated metal products	5%
	Italy		Electrical equipment	27%
C. Total pyrolysis system: burner design, burner construction	France	8,964.8	Other business sector services	13%
			Machinery and equipment, nec	87%
D. Total gasifier system costs	France	224,120	Machinery and equipment, nec	100%
E. Components transportation	Tunisia	509,763	Transportation and storage	100%
F. Other costs: project design and implementation	Tunisia	870,845	Financial and insurance activities	55%
			Other business sector services	45%
O&M costs (annual)		**412,509.7**		
A. Labour costs	Tunisia	301,634.2	Included in induced impacts only	
B. Resources and energy costs: transportation, olive-oil waste	Tunisia	95,000	Transportation and storage	50%

			Food products, beverages and tobacco	50%
C.	**Anaerobic Digestor**	Tunisia	8,858.5	Other manufacturing; repair and installation of machinery and equipment	100%
D.	**Solar Field**	Tunisia	3,825.9	Other non-metallic mineral products	22%
				Electrical equipment	39%
				Basic metals	18%
				Fabricated metal products	18%
				Computer, electronic and optical products	4%
E.	**Boiler**	Tunisia	31.8	Other manufacturing; repair and installation of machinery and equipment	100%
F.	**Power Block**	Tunisia	3,159.2	Machinery and equipment, nec	57%
				Construction	11%
				Fabricated metal products	5%
				Electrical equipment	27%

Source: own elaboration on the basis of BIOSOL project

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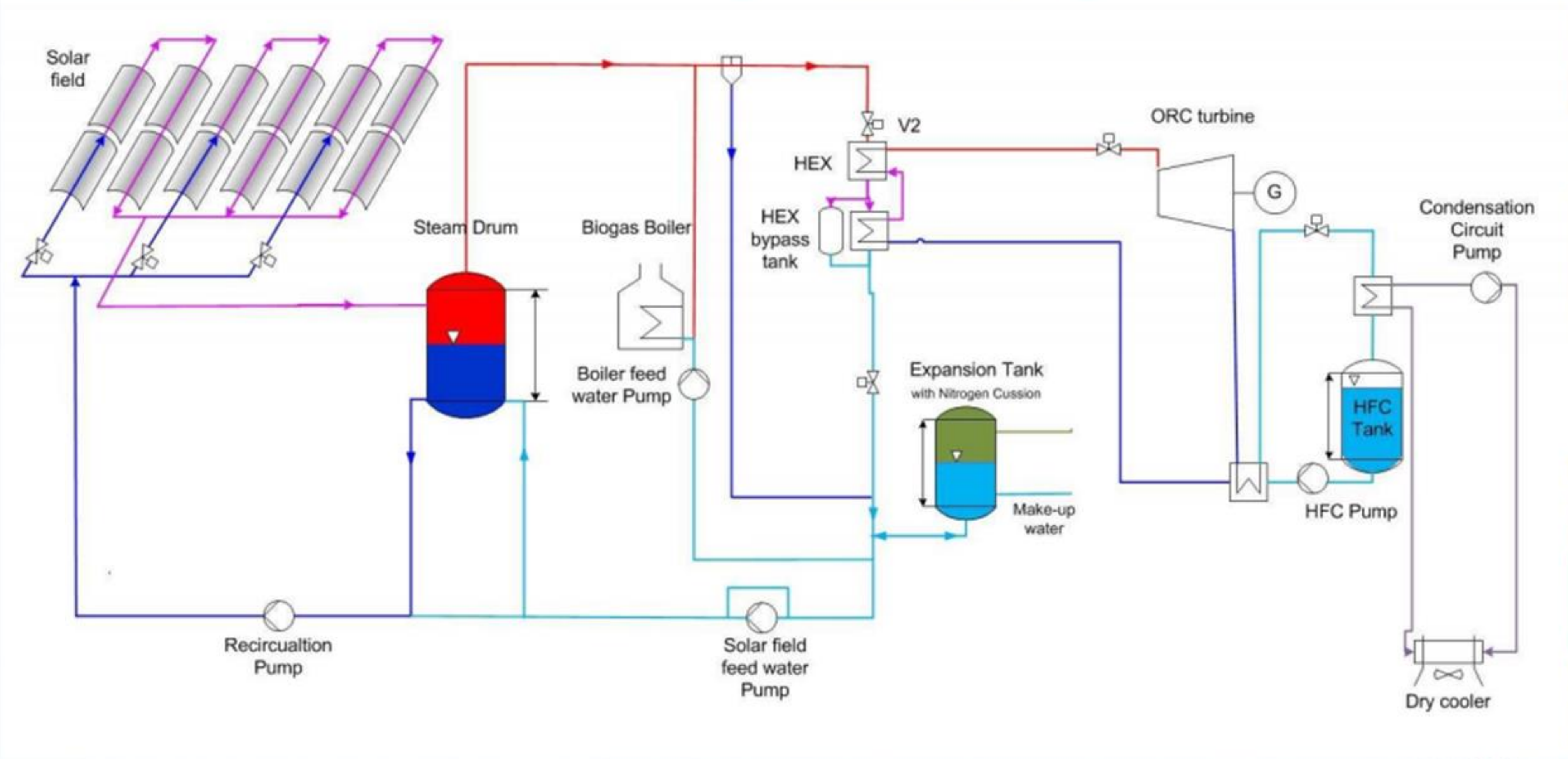
*Graphical Abstract



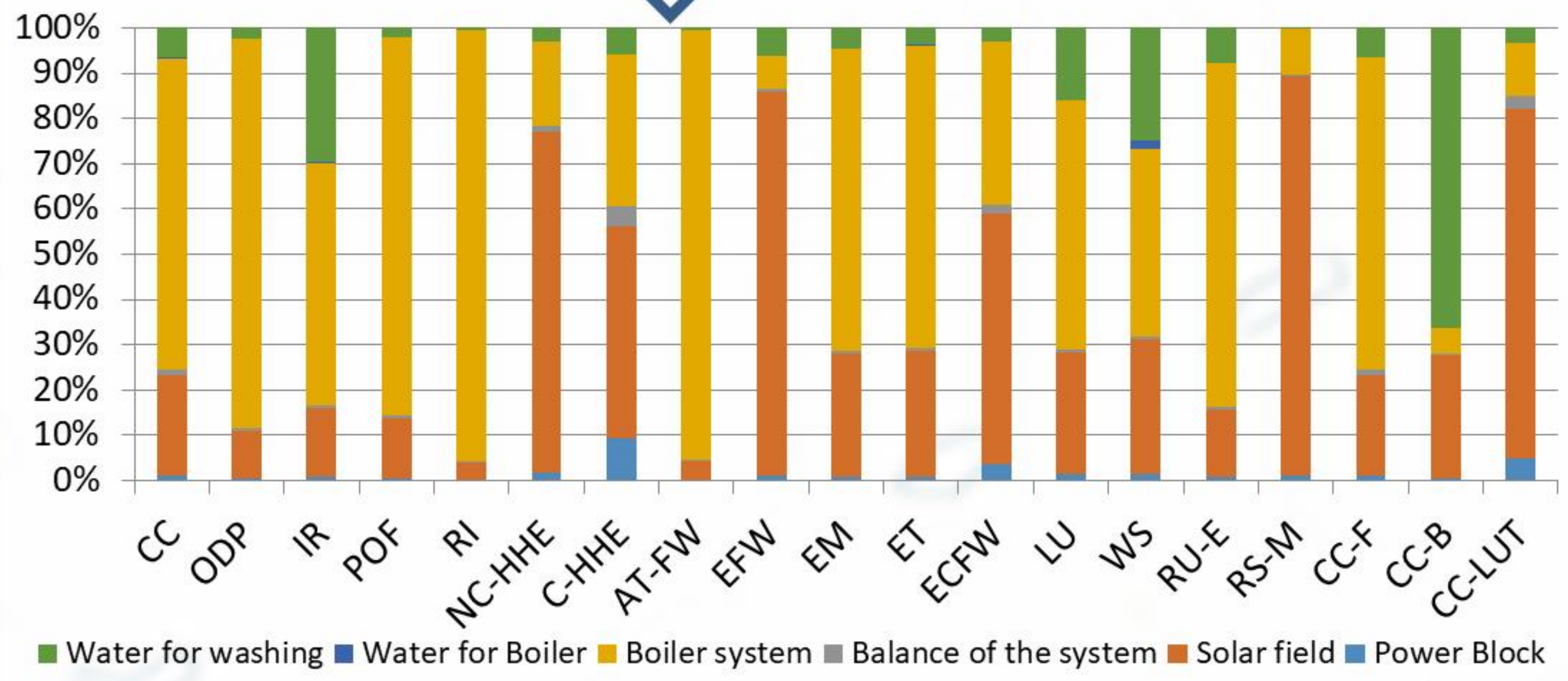
MATERIALS AND METHODS

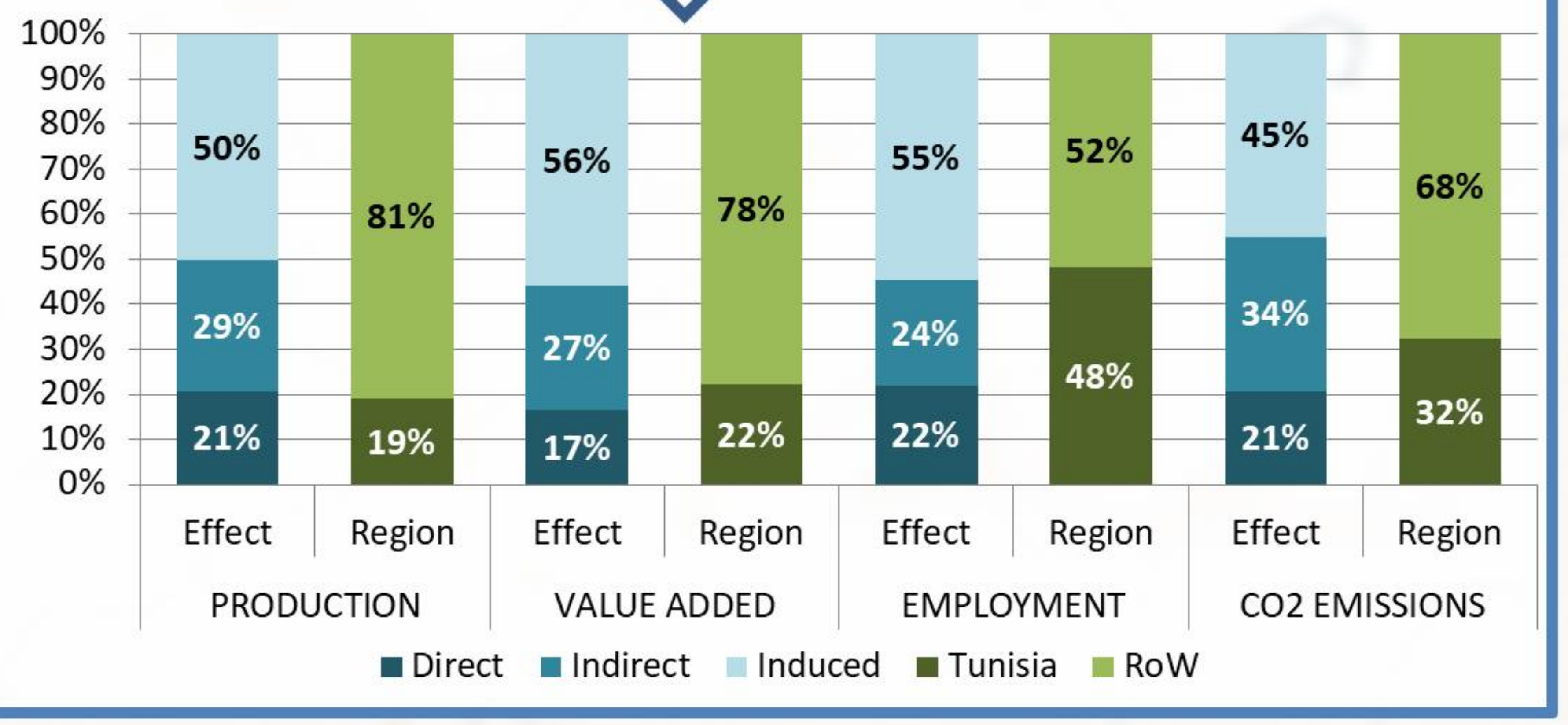
Life Cycle Assessment

Input-Output Analysis

	Intermediate Consumption				Final Demand					
	Country A	Country B	Country C	RoW	Country A	Country B	Country C	RoW	Preliminary adjustments	Total output
Country A	$Z^{A,A}$	$Z^{A,B}$	$Z^{A,C}$	$Z^{A,RoW}$	$Y^{A,A}$	$Y^{A,B}$	$Y^{A,C}$	$Y^{A,RoW}$	Pr^{A}	$Output^{A}$
Country B	$Z^{B,A}$	$Z^{B,B}$	$Z^{B,C}$	$Z^{B,RoW}$	$Y^{B,A}$	$Y^{B,B}$	$Y^{B,C}$	$Y^{B,RoW}$	Pr^{B}	$Output^{B}$
Country C	$Z^{C,A}$	$Z^{C,B}$	$Z^{C,C}$	$Z^{C,RoW}$	$Y^{C,A}$	$Y^{C,B}$	$Y^{C,C}$	$Y^{C,RoW}$	Pr^{C}	$Output^{C}$
Rest of the World (RoW)	$Z^{RoW,A}$	$Z^{RoW,B}$	$Z^{RoW,C}$	$Z^{RoW,RoW}$	$Y^{RoW,A}$	$Y^{RoW,B}$	$Y^{RoW,C}$	$Y^{RoW,RoW}$	Pr^{RoW}	$Output^{RoW}$
Freight and insurance	FI^{A}	FI^{B}	FI^{C}	FI^{RoW}						
Total intermediate	TI^{A}	TI^{B}	TI^{C}	TI^{RoW}						
Value added (basic prices)	VA^{A}	VA^{B}	VA^{C}	VA^{RoW}						
Total output	$Output^{A}$	$Output^{B}$	$Output^{C}$	$Output^{RoW}$						

OECD





***Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

- A solar/biomass hybrid power plant renewable electricity system has been analysed.
- LCA and IO have been applied to assess environmental and socioeconomic impacts.
- CSP in Tunisia could be part of the solution to energy demand and Climate Change.
- Calculated total GHG emissions range from 22 (LCA) to 77 gCO_2eq/kWh (IO).
- Low domestic content of the components hinders Tunisian employment and GDP growth.

Towards energy transition in Tunisia: sustainability assessment of a hybrid concentrated solar power and biomass plant

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Abstract

Electricity demand in the Middle East and North Africa (MENA) region increases at a rate of 6-8% per year. It is expected to double by 2020 and triple by 2030. Renewable electricity ensures climate protection and energy security. This work presents a sustainability assessment of CSP hybridization with biomass technology to be installed in Tunisia. Environmental impacts have been assessed by Life Cycle Analysis (LCA). For socioeconomic impacts, a Multiregional Input-Output (MRIO) analysis was used to estimate the production of goods and services, value added and employment creation. Regarding the results, the system reports 22 gCO_2eq per kWh. The most important component in terms of emissions is the gasifier system, due to biomass transport. Socioeconomic results show important impacts for employment creation in Tunisia, coming essentially from the O&M phase. The multiplier effect of the direct investment for production of goods and services amounts to 2.4 (3.5

accounting induced effects). Domestic value added in investment is low, only 28.9% of the overall value added created. Thus, increasing the national content of the investment stage would bring additional local benefits. Using extended MRIO, CO_2 emissions have also been calculated and differences in the CO_2 emission with both methodologies are discussed.

Keywords: Triple-Bottom Line; CSP-biomass; LCA-IO; energy transition; Tunisia; BIOSOL project.

1. Introduction

Tunisia is currently facing significant challenges in terms of energy supply security and climate change in the path to energy transition. Being one of the countries most exposed to climate change in the Mediterranean (Waha et al., 2017; World Energy Council, 2019), Tunisia’s energy system is heavily dependent on imported natural gas and oil (Schmidt et al., 2017). Besides, the country is energy-dependent and relatively vulnerable to energy shocks. Since energy is a limiting factor to GDP growth (Belloumi, 2009), making a transition from a fossil fuel-based to a renewable energy-based economy is needed. Hence, the country has decided to forge ahead with the energy transition process addressing two pillars: energy efficiency and renewable energies (Ministry of Environment and Sustainable Development, 2015).

The country has already launched a package of strategies to strengthen national renewable energy policy and become an international hub for industrial production and an exporter of renewable energies (Ben Jebli and Ben Youssef, 2015), such as the national climate change strategy, the energy efficiency strategy, or the Tunisian Solar Plan. Altogether with the National Determined Contribution (NDC), these strategies are aimed at guaranteeing a healthy and balanced environment and contributing to the climate’s integrity (Ministry of Environment and Sustainable Development, 2015). An expected installed renewable energy capacity of 3,815 MW is expected for 2030, aimed to contribute cutting down 41% of its greenhouse gases (GHG) emissions across all sectors to decrease carbon intensity compared to 2010 levels (Mahlooji et al., 2019). Tunisian official target to reach 30% renewable electricity production in its power mix by 2030 is highly conditioned by international support (concessional lines of credit, donations, direct investments, technology transfer). In this sense, the European Union becomes an important stakeholder in the development of renewable energy in the southern basin of the Mediterranean by bringing technology transfer to Middle East and North African (MENA) countries (Stoffaës, 2016).

The vast majority of installed renewable energy capacity is expected to come from wind and solar photovoltaic (PV) (Waissbein et al., 2018); only 450 MW for concentrated solar power (CSP) and 100

MW biomass are expected to be deployed in 2030, accounting for the 14.4% of renewable energy capacity by 2030 (Ministry of Environment and Sustainable Development, 2015; Tractebel, 2019). Recently the private sector has started to explore the commercial applications for solar power (Ben Jebli and Ben Youssef, 2015). In this sense, CSP becomes a promising technology in a region with unexploited solar potential (Tsikalakis et al., 2011). This research is framed within the BIOSOL project (Development and demonstration of a Hybrid CSP-biomass gasification boiler system) funded by EU ERANETMED programme ("BIOSOL - solar CSP gasification biomass boiler hybrid system," 2018) and aims to integrate a biomass gasification boiler prototype in an existing CSP plant in Tunisia. This existing system corresponds to a hybrid renewable electricity production mini-power plant (60 kW electrical output), developed in the framework of EU/FP7 REELCOOP project (Oliveira and Coelho, 2013). The hybridization of these technologies is expected to be an attractive solution in terms of dispatchability and flexibility (Peterseim et al., 2014).

Technical and economic analyses of this technology are abundant in literature: a hybrid solar-biomass that uses rice husk as a fuel for power generation in India has been tested (Srinivas and Reddy, 2014) under variable solar radiation and plant conditions in order to optimize its operation. The feasibility of hybrid solar-biomass power plants was also tested in India against technical, financial and environmental criteria (Nixon et al., 2012). It was found that hybrid plants reduce biomass and land usage by 14–29% compared to biomass-only plants, but the levelised costs of energy are increased by 1.8–5.2 ¢/kWh in comparison to biomass-only. They recommend the use of tri-generation (simultaneous production of electricity, cooling and heat) as the most feasible application for this technology. Peterseim and colleagues (Peterseim et al., 2014) evaluated the operation of a hybrid CSP-biomass power plant in Spain and found that the combination of a biomass and solar tower energy system is beneficial to maximise the cycle efficiency and reduce costs compared to solar only power plants. They also found interesting additional benefits of avoiding the burning agricultural residues in the field. (Petrollese et al., 2018) investigated the best configuration of an ORC plant for supplying power and useful heat to industrial processes, using a solar plant based on linear Fresnel collectors integrated with a two-tank Thermal Energy Storage (TES) system, a biomass furnace and an ORC system. They highlighted the fundamental role of the biomass contribution (about 50% of the overall thermal energy input). Vidal and co-worker (Vidal and Martín, 2015) modelled the integration of a polygeneration system based on biomass with a concentrated solar power facility evaluating different gasifiers and reformers and syngas use. They found that the optimal integration involved the use of indirect gasification, steam reforming and a Brayton cycle to produce electricity and hydrogen as a credit. Amoresano et al (Amoresano et al., 2015) focused on a thermodynamic analysis of the substitution of steam bleed regeneration with water preheating by solar energy. A novel hybrid solar-biomass combined Brayton/organic Rankine-cycle plants integrated with thermal storage (TES) is also proposed by Pantaleo and co-workers (Pantaleo et al., 2018) claiming that the recovery of heat in the TES can significantly increase the investment profitability. (Pereira Soares, 2018) provided a review of different solutions for solar/biomass hybrid electricity generation systems addressing technical and economic issues.

Environmental benefits of hybridizing solar and biomass technologies have also been investigated in the literature. (Anvari et al., 2019) evaluated the CO_2 emissions effect of hybridizing these technologies and found a reduction of about 31% in CO_2 emissions. Important benefits in terms of CO_2 reduction compared to alternative configurations were also found (Wang and Yang, 2016). However, complete sustainability assessment of this technology is scarce in literature. Corona and co-workers (Corona et al., 2016; Corona and San Miguel, 2015; San Miguel and Corona, 2014) analyzed the environmental performance of a hybrid CSP technology with biogas and other biomass fuels in comparison with the use of natural gas and found a significant improvement of the environmental performance due to reduced impacts in the natural land transformation, depletion of fossil resources, and climate change. However, other environmental impacts namely human toxicity, eutrophication, acidification and marine ecotoxicity worsened when using biogas and biomethane. Piemonte and co-workers (Piemonte et al., 2011) performed a Life Cycle Assessment of a molten salt concentrating solar power plant combined with a biomass Back-Up Burner and compared it with natural gas and an oil fed power plants. They found important benefits of the CSP plant in terms of fossil energy consumption and greenhouse gas emissions compared to both oil and natural gas power plants.

However, natural gas power plants were preferable in terms of human toxicity, acidification and eutrophication impacts.

The effects of biomass on job creation are among the highest in renewable energy (IRENA, 2017) and the expected benefits in rural and agricultural areas can help fighting against unemployment, which remains an issue in Tunisia (15.4% in 2018) where economic activity has stagnated in low-productivity sectors (International Labour Organization (ILO), 2015; The World Bank Group, 2014). The socioeconomic assessment in terms of employment and economic growth implications of this technology is, to the best of our knowledge, absent in literature. The deployment of this technology also brings a solution to oil residue management for this top producing olive oil country (FAO, 2017).

To meet the Tunisian CSP and biomass goals, investments in new power plants must be made. The deployment of these power plants will unavoidably generate positive economic effects (value added and employment), as well as negative environmental impacts (i.e. CO_2 emissions) that must be accounted and compared with those of alternative technologies. The development of this new energy prototype could support the promotion of renewable energy technologies using environmentally-friendly solutions in emerging regions like the MENA region, which has large renewable energy potential such as solar or biomass (Tsikalakis et al., 2011).

The purpose of this research is to fill the gap identified in the literature review and perform a sustainability analysis (environmental and socioeconomic) of the technology proposed in the BIOSOL project. To that end, and considering that the prototype was intended as a small-scale demonstrator of the CSP-biomass concept applicable to larger-scale centralised electricity generation, the analysis was carried out for a scaled-up and enhanced 1 MWel decentralized generation, more representative of a real-life application (Soares et al., 2018b). The assessment includes a Life Cycle Assessment (LCA) for the scaled power plant, with the new biomass gasifier system. In this sense, a biomass gasification boiler has been developed and integrated with the CSP prototype 3 of the REELCOOP project. Besides, the potential impact on local economy (value added, job creation and CO_2 emissions) due to the investment costs and operation and maintenance (O&M) expenditures are calculated. These two well-known methodologies are widely used to assess renewable energy investments (Jenniches, 2018; Stamford and Azapagic, 2014). The present study enlarges the current knowledge about CSP and biomass (Soares et al., 2018a, 2018b) by combining LCA and Input-Output approaches in order to assess this novel technology in Tunisia, from a triple-bottom line (TBL) perspective (Henriques and Richardson, 2004).

The research is structured as follows. Section 2 presents a deep description of materials and methodologies used. In Section 3, the main results from the two followed approaches (LCA and input-output) are presented and discussed, and finally, Section 4 shows the most important conclusions found.

2. Materials and methods

Two main methodological approaches have been used in this research, the Life cycle assessment (LCA) and the input output analysis (IOA). The hybridization of these two approaches has been widely undertaken (AENOR, 2006a; Leontief, 1936; Zafrilla et al., 2014), allowing the extension of results from processes to the economy at a macro-level. In the present study, the two approaches are used to present complementary results.

2.1. Life cycle assessment

Life Cycle Assessment (LCA) is a methodology that compiles all the inputs and outputs of energy and materials, in order to analyse all the potential environmental impacts of a product, process or system (Sala et al., 2016). The application of the methodology is normalized in ISO standards 14040 and 14044 (AENOR, 2006b, 2006c). According to ISO 14040, “life cycle assessment is a tool to determine all the environmental aspects and potential impacts associated with a product, making an inventory with the most important inputs and outputs of the system, evaluating the potential environmental impacts associated with these inputs and outputs, and interpreting the results of the different phases of the inventory and the impacts in relation with the study objectives”.

The life cycle of a product starts with the exploration of the raw materials and ends with the waste treatment. Between these two phases, there are other stages in the production chain such as the production process, the transportation, recycling activities, etc. According to the ISO standards 14040 and 14044, an LCA consists of four phases:

- *Goal and Scope definition:* the first step in a LCA is the definition of the objective and scope of the developed study. This relates to the definition of the system boundaries and the functional unit. The results subsequently gained in the analysis are associated to the intended and linked to the proposed scope.
- *Life Cycle Inventory Analysis (LCI):* LCI is the phase of LCA involving the compilation and quantification of inputs and outputs for the product, process or system under analysis. Results of this phase are a list, as complete as possible, of inputs and outputs of energy and materials referred to the functional unit.
- *Life Cycle Impact Assessment:* this phase seeks to understand and evaluate the magnitude of the environmental impacts of a product based on the results obtained in the previous phase.
- *Interpretation:* to obtain conclusions of the results is necessary to identify, quantify and evaluate the results. This technique gives a systematic approach, which includes integrity or sensitivity analysis, to prepare the conclusions.

In this work we follow a special variant of this methodology proposed by the European Commission in an attempt to harmonize LCA methods applied to products that is called Product Environmental Footprint (EC, 2013).

2.1.1. Goal and scope

The concrete goal of this analysis is to calculate the Environmental Footprint of a concentrated solar power and biomass hybridization plant in Tunisia. For this study, as a Functional Unit (FU), 1 kWh of electricity output has been considered. The lifetime of the plant has been estimated in 25 years. The system boundary comprises all relevant process stages from the raw material extraction, production and manufacturing until the stage of end-of-life of the materials with the transportation included. The different processes considered have been categorized in the following main components: solar field, boiler system (that includes the provision of the residual biomass), power block, electrical installation and the balance of the system (which comprises every other essential part to the electrical, thermal or aesthetic integrity of the array). Furthermore, in order to involve the end-of-life stage in the system, a scenario of waste disposal in landfill, including the transportation of wastes, has also been considered. The system that is being analyzed corresponds to a power plant concept, that uses concentrated solar energy and biomass. The development and design stage included solar collector simulation, with and without shading, and circuit thermal and hydraulic design and led to the configuration shown in Figure 1.

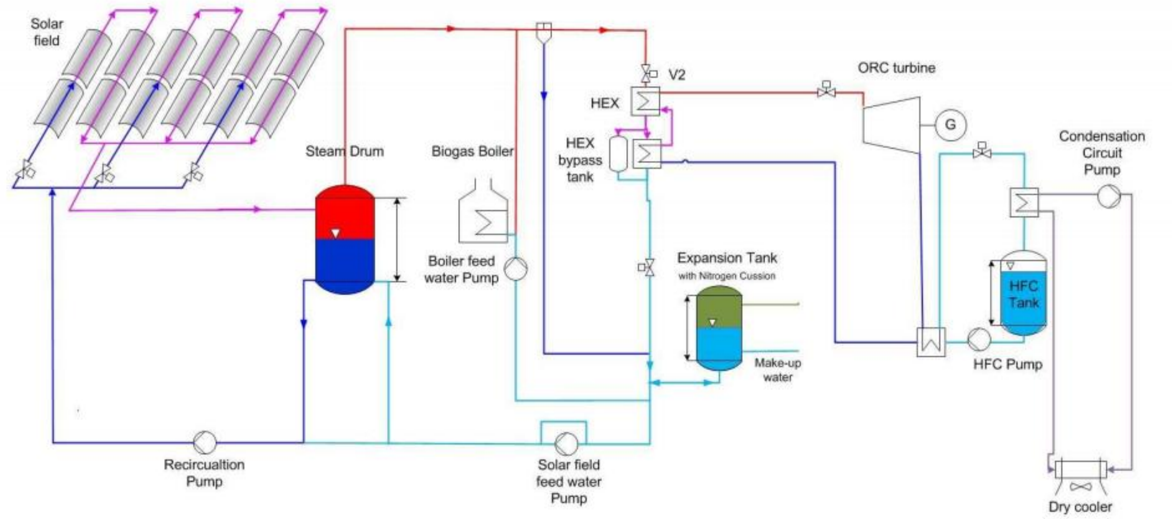


Figure 1. Schematic representation of the original CSP-biomass prototype system. Source: (Oliveira, 2018)

For this study, the analysis for a scaled-up prototype to demonstrate the hybrid concept has been developed. Therefore, a 1 MWel power plant was considered, with the same basic characteristics of prototype 3 of REELCOOP project. Nevertheless, in contrast to the original prototype with specific collectors, generic parabolic trough collectors with a larger aperture width of 4.6m and a vacuum receiver were considered, in order to reach outlet temperatures of 350°C with high efficiencies, with a solar field (SF) area of 10,000 m^2. For the boiler system (BS) definition, the same biogas boiler with a nominal output of 5 MWth was used. For this case, the biogas is produced from gasification by pyrolysis of olive pomace, with a lower heating value of 20.64 MJ/m^3. Additionally, the power block (PB) was based on the SST-110 model from Siemens. The PB steam inlet conditions were defined as 40 bar and 350°C. Figure 2 below shows schematically the new design conditions for the solar field and power block, as well as the power cycle nominal conditions.

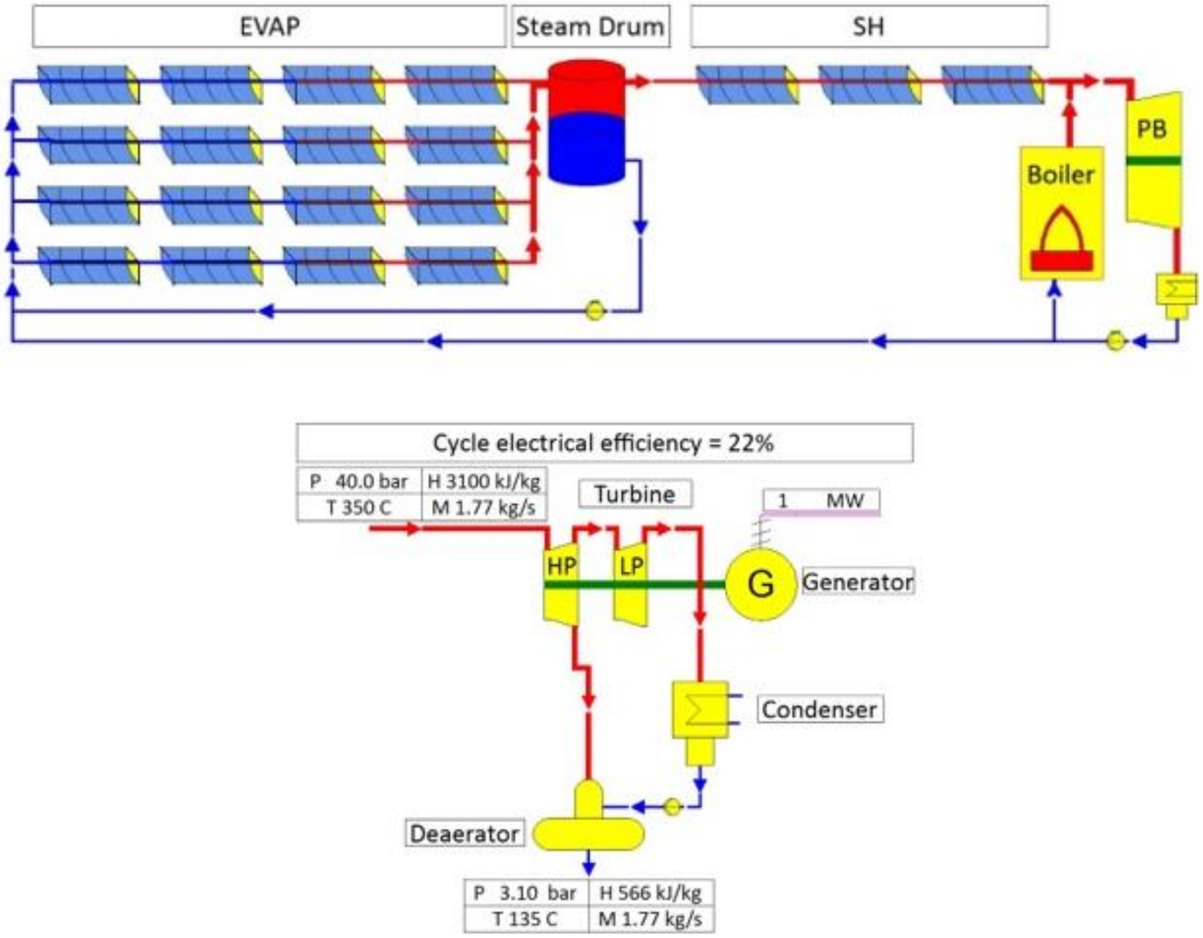


Figure 2. Schematic representation of the modified CSP-biomass system. Source: (Oliveira, 2018)

The plant is using a direct steam generation (as in Prototype from REELCOOP project) and a steam turbine, with an output power of 1 MWel, operating from 6:00 to 22:00 every day. Under these conditions, the simulation for Tunis indicated an average solar field efficiency of 40%, an average biogas consumption of 1,564 m^3/day, a solar share of 27.5%, and an electrical energy generation of

2,052 MWh/year, with average power block efficiency of 20.81%. Table 1 summarizes the main data of the conditions of the studied system.

Table 1. Solar field, boiler system and power block data.

	Value	**Unit**
DNI	1,922	kWh/(m^2 year)
Annual heat generated - solar field	7,750	MWhth
Specific thermal field output	771	kWhth/m^2
Mean annual solar field efficiency	40.1	%
Solar share	27.5	%
Solar field dumped heat	232	MWhth
Annual heat generated - boiler	2,112	MWhth
Mean annual boiler efficiency	85	%
Annual biogas consumption	0.57	hm^3
Average biogas consumption	1,564	m^3/day
Annual useful heat from solar field and boiler	9,862	MWhth
Annual power generated	2,052	MWhel
Mean annual power block efficiency	20.81	%

Source: own elaboration by data from REELCOOP project (Oliveira, 2018; Soares et al., 2018b).

2.1.2. Life Cycle Inventory

The different stages considered have been categorized in the processes of manufacturing of the components: solar field, boiler system, power block, electrical installation and the balance of the system (BoS) of the components, which comprise every component essential to the electrical, thermal or aesthetic integrity of the array, forming part of the overarching power generation. Finally, an end-of-life scenario of waste disposal in landfill has been also considered, including the transportation stage.

All the considerations and assumptions, such as the energy coefficients and the service periods assigned for the system and the operation stages, before compiling inventory data, are detailed below. From a LCA perspective, the system is formed by four subsystems (see Figure 3): Solar field, boiler system, power block and balance of the system.

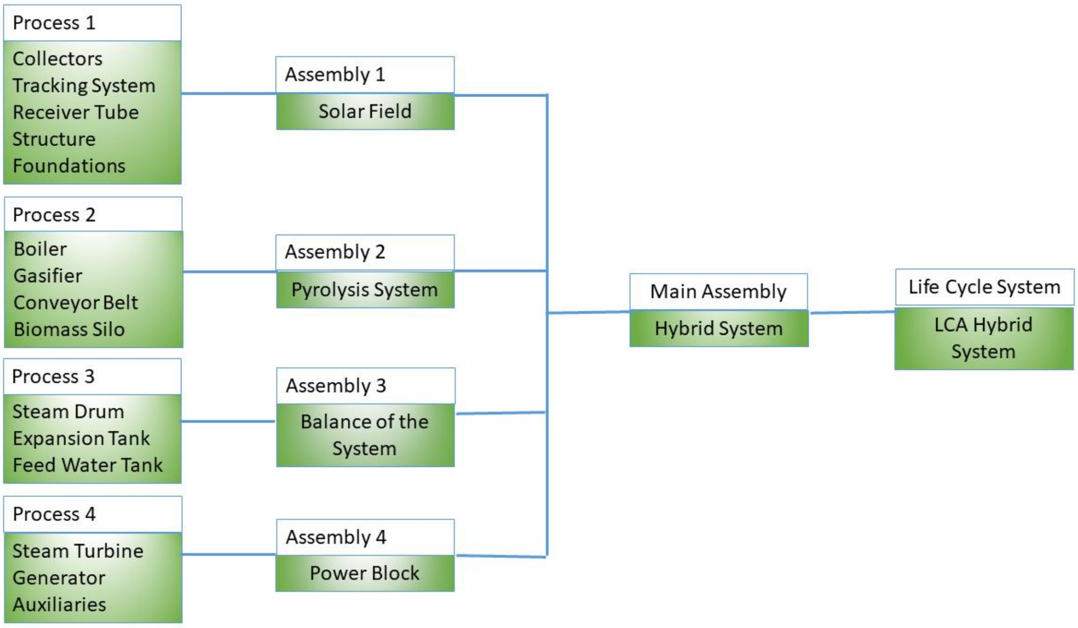


Figure 2. General scheme of the system and components.

2.1.2.1. Solar field

The solar field (SF) consists of several components such as mirrors, vacuum and torque tubes, fittings, motors pylons, mirror arms and electrical panels. For this inventory, and according to definition the system is constituted by four loops of four collectors in the EVAP section, and one loop of three collectors in the SH section, with a total effective solar aperture area of about 10,000 m^2. The goal is to get temperatures of 350ºC in the power block, with high efficiencies. The optical efficiency of the collectors is estimated at 77%. Additionally, there is a steam drum in the solar field which is not included in this group. The water which cannot be evaporated in the evaporator is recirculated to the evaporator again, and the steam goes to the superheater in order to get the ideal temperatures. The recirculation pump has the aim of recirculating all the water of the steam drum to the evaporator. The annual direct normal irradiance is 1,922 kWh/m^2. Hence, with this irradiance that falls upon the solar panel, the annual heat that the solar field generates is 7,750 MWhth (Soares et al., 2018b).

2.1.2.2. Boiler system (BS)

The boiler system is formed by gasification by means of pyrolysis and the steam boiler. The pyrolysis system consists of the production of synthesis gas from biomass gasification. This system is assessed in the frame of the following sequences: biomass silo, conveyor belt and the gasifier. The first step, after biomass transport to the plant, is the storage in a galvanized steel silo. From the silo, and by means of a conveyor belt, the biomass will be led to the gasifier, where through drying, oxidation, pyrolysis and reduction processes, the biomass is converted into synthesis gas or biogas to be feed to the boiler. The gasifier consists of a downdraft gasifier, attractive for biomass gasification because of its easy fabrication and operation, and also because of the low tar content in the resulting biogas. The pyrolysis system can supply about 1,120 annual tons of biogas to the boiler.

Additionally, the steam boiler can supply 960 MJ/hour of heat at 150ºC and 40 bar. The boiler includes a modular and hybrid burner. These specifications permit the operation of the boiler at partial load, which is desirable for hybrid systems, as well as the operation either with biogas or natural gas. The annual boiler efficiency is about 85% and the biogas consumption is 570 dam^3. The olive pomace is one of the olive mill solid residues. The solid residues generated from olive oil production processes are usually referred to as olive mill solid waste, olive husk or olive pomace (Ducom et al., 2020).

2.1.2.3. Power Block system (PB)

In the power block system, the steam turbine set is based on the SST-110 model from the Siemens manufacturer. This specific model is a dual-casing turbine on one gearbox, with the possibility of being used as backpressure or condensing units, with or without extraction. Other relevant characteristics are quick-start without preheating and commercial use in cogeneration plants. A 60% design isentropic efficiency was defined for the steam turbine (Soares et al., 2018b). The annual efficiency of the power block is about 20.81%, and the annual power generated 2,052 MWhel (Soares et al., 2018b).

2.1.2.4. Balance of the system

The balance of system (BoS) encompasses all components of the hybrid system other than SF, BS and PB. This includes the steam drum, the feed water tank and the expansion tank. The drum water tank has the function of separating the water and the steam coming from the solar field. The expansion tank is used to avoid corrosion in the system. Its main function is to prevent the entry of air into the system with nitrogen gaseous which is at a pressure higher than the atmospheric pressure. Additionally, wiring, switches, a mounting system, anemometer, or task-specific accessories designed to meet specialized requirements for the system.

2.1.2.5. End of life

The last phase of the system is the end of life scenario. In that stage, all the parts of the system will be transported to Jber Borj Chakir, a landfill located at 15 km of distance from the location of the system.

2.1.2.6. Additional considerations for the Life Cycle Inventory

In order to carry out the LCA, a series of considerations and assumptions have been taken into account. These considerations are detailed below:

- No water losses.
- Biomass transport (475 t/year for 25 years, by lorry). The transportation takes place between the collection points and the installation, and the biomass is transported 250 km as average distance.
- The transportation of some imported materials has been considered in 1,000 km.

Finally, Life Cycle Inventory data of the whole parts and processes is detailed in Annex 1, from Table A1 to A5.

2.1.3. Environmental Impact Assessment

Life cycle impact assessment step is a quantitative process to characterize and evaluate the environmental effects by inventory data. In this process, there are three mandatory steps: a selection of impact categories, the definition of category indicators and selection of characterization models. In this work, the allocation of inventory results to the selected environmental categories and the characterization or calculation of the results by means of factors have been developed based on the software Simapro ^{TM} (Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, 2016).

The environmental footprint method has been selected for the environmental impact assessment step. The environmental footprint method is being developed under the auspices of the European Commission (EC) who has developed a reference method for the calculation of the environmental footprint for products (PEF) and organizations (OEF) in support of improving the sustainability of production and consumption (Fazio et al., 2018; Pelletier et al., 2014). This method consists of an analysis of sixteen impact categories. The impact categories are all those environmental consequences generated by a system or a product, and that depending on the impacts can have a harmful effect on human health, natural environment or natural resources (Sala et al., 2016). The impact categories proposed in this method are shown in Table 2.

Table 2.
Impact categories for Environmental Footprint Method

Impact category	Category indicator
Climate change	kg CO_2 eq
Ozone depletion	kg CFC11 eq
Ionising radiation, HH	kBq U-235 eq
Photochemical ozone formation, HH	kg NMVOC eq
Respiratory inorganics	disease incidence
Non-cancer human health effects	CTUh
Cancer human health effects	CTUh
Acidification terrestrial and freshwater	mol H+ eq
Eutrophication freshwater	kg P eq
Eutrophication marine	kg N eq
Eutrophication terrestrial	mol N eq
Ecotoxicity freshwater	CTUe
Land use	Pt
Water scarcity	m^3 depriv.
Resource use, energy carriers	MJ
Resource use, mineral and metals	kg Sb eq
Climate change – fossil	kg CO_2 eq
Climate change – biogenic	kg CO_2 eq
Climate change - land use and transform.	kg CO_2 eq

Source: own elaboration based on (Fazio et al., 2018).

2.2. Input-Output Analysis

The assessment of the socioeconomic impacts of BIOSOL prototype has been performed using the Input-Output methodology (Leontief, 1936). The Input-Output (IO) methodology considers the trade relationships existing within economic sectors using Input-Output Tables (IOTs). IOTs describe, in columns, the monetary value of products that a sector needs from the rest of the sectors to obtain its total production (inputs); whereas rows show the distribution, in monetary values, of the production of a sector over the rest of the sectors (outputs). When considering various regions or countries, it is possible to estimate the economic stimulation produced in other regions due to a change in the demand of goods and services (G&S) of one region, by using Multiregional Input-Output Tables (MRIOTs) (Wiedmann, 2009) (see Annex II, Figure A1). The monetary value of products that one sector needs from the other sectors to obtain one monetary unit of production is represented by technical coefficients, which are gathered within the technical coefficient matrix or *A* matrix (Miller and Blair, 2009; ten Raa, 2006). The total G&S produced by a specific demand can be estimated as shown in Eq. (1).

$$x = (I - A)^{-1} y \tag{1}$$

Where x is the total production of goods and services (total effects) matrix of dimension (m×n)×m (being m the regions and n the sectors), A is the (m×n)×(m×n) technical coefficient matrix, $(I - A)^{-1}$ is the inverse of Leontief which represents direct and indirect effects and y is the (m×n)×m final demand. This methodology can be extended to a hybrid model LCA-IO (Crawford et al., 2018) by combining input-output data with BIOSOL prototype investment and O&M cost data, in order to allow the estimation of the total economic stimulation produced by an increase in the demand of goods and services needed to build and operate the prototype. Direct effects are related to the components and services required for the project (see Table 3) and indirect effects are those inputs necessary to satisfy the direct demand provided by intermediate suppliers.

$$x_I = (I - A)^{-1}\hat{y}_I \quad (2)$$

Where x_I is the total, direct, and indirect impact matrix (m×n)×(m×n) of BIOSOL investments on the production, and $\hat{y}_I$ is the BIOSOL investments expressed as a final demand diagonalized vector (m×n)×(m×n). The IO analysis allows estimating other impacts (e.g. employment, CO_2 emissions), by extending the methodology with vectors describing specific impacts per monetary unit produced in each economic sector. These impacts can be calculated as expressed in Eq. (3).

$$F = \hat{f}(I - A)^{-1}\hat{y}_I \quad (3)$$

Where F is the total (direct and indirect) socioeconomic/environmental effect (m×n)×(m×n) matrix, $\hat{f}$ is the (m×n)×(m×n) socioeconomic/environmental diagonalized vector (value added, employment and CO_2 emissions in this sense) and $\hat{y}_I$ is the BIOSOL prototype investments expressed as a final demand diagonalized vector of (m×n)×(m×n) dimensions (see Annex II, Equation A1). Induced impacts on employment can also be calculated following the Miyazawa’s approach (Miyazawa, 1968). The matrix *A* is expanded to include the private expenditure by households as a new column and the wages of employees’ row vector as a new row (see Eq. 4).

$$F' = \hat{f}'(I - A')^{-1}\hat{y}_I' \quad (4)$$

Where F' expresses the total (direct, indirect and induced) socioeconomic/environmental impacts on the output, the new inverse of Leontief $(I - A')^{-1}$ incorporates the household consumption and the wages of employees, and $\hat{y}'$ also includes the personnel costs related to the O&M phase. Induced effects capture the effect in the consumption of goods and services derived from changes in the economic compensation of employees. As a resulting increase of final demand, households are paid for their work force. Received payments are used for consumption and saving purposes. Consumption will further stimulate final demand and production. In the present research, we assume that propensity to consume is 1.

MRIO analysis in this work uses the OECD Inter-Country Input-Output (ICIO) tables (Yamano and Ahmad, 2006) that provide a time series of data (1995 – 2015) for 36-sector symmetric industry-by industry MRIOT and 69 regions with matching employment and CO_2 emissions satellite accounts (Wiebe and Yamano, 2016). In particular, data used for Tunisia (year 2015) corresponds to the last edition (OECD, 2018) based on the United Nations' International Standard Industrial Classification of All Economic Activities (ISIC Rev 4) (United Nations, 2008), maintaining the number of sectors (n=36) and aggregating to six regions (m=6, Tunisia, Italy, France, rest of Europe, China and the rest of the world) to facilitate the management and interpretation of the results without losing relevant information (see Annex II, Table A1). Due to data limitations regarding the Tunisian employment data coming from the ICIO-OECD tables, ILOSTAT data has been considered IO assessment (International Labour Organization (ILO), 2015). This data is compatible with the ICIO table since both rely on the ISIC Rev.4. Thus, 9 out of 36 economic sectors have been directly allocated. For the remaining sectors, aggregated data from ILOSTAT has been reallocated using the ICIO-OECD Israeli employment coefficients, calculated by dividing the "people engaged" of each economic sector by the total output obtained by each economic sector.

2.2.1. Cost data

Cost data considered for both the investment and the O&M phases is provided by BIOSOL project (see Table 3). We assume that the investment phase takes place in the first year. Annual O&M costs are brought to the net present value. Assuming a plant life expectancy of 25 years and a discount rate of 6% for Tunisia (Soares et al., 2018b), the total O&M costs along the life cycle amount to 1,417,360.8$. Personnel costs are not considered here. Data provided under BIOSOL project gives a cost of biomass (oil-cake) of 0.1 $/kg, in the range of green and agricultural waste (Bouaoun, 2014). Transport costs per kilogram are in the same range. The gasifier is assumed to require about 475 tons per year.

Table 3.
BIOSOL investment cost disaggregation and manufacturing country.

Cost data	Cost breakdown	Country	2015 US$

Investment	Solar Field (SF)	ITA	4,505,027.4
	Boiler System (BS)	FRA	233,084.8
	Pyrolysis burner	*FRA*	*8,964.8*
	Gasifier	*FRA*	*224,120.0*
	Power Block (PB)	ITA (89%), TUN (11%)	896,332.6
	Contingencies and other costs	TUN	1,380,607.2
	Total		**7,015,052.0**
O&M (annual costs)	Resources and energy costs (transport & biomass)		95,000.0
	Personnel costs		301,634.2
	O&M and replacement of Anaerobic Digestor		8,858.5
	O&M and replacement of Solar Field		3,825.9
	O&M and replacement of Boiler		31.8
	O&M and replacement of Power Block		3,159.2
	Total		**412,509.7**

Source: data provided by EU ERANETMED consortium.
Note: Italy (ITA), France (FRA), Tunisia (TUN).

Investment costs provided here (7.0 k.US$/kW or 6.3 k.EUR/kW, year 2015) are comparable with the existing hybrid CSP-biomass power plants in the literature. Most recent studies point out that investment stage costs are in the range of 5.7 (Pedrazzi et al., 2019) to 6.3 (Oyekale et al., 2018) k.EUR/kW (2018 as a reference year). Pantaleo and colleagues (Pantaleo et al., 2017) provide results for five case studies with different configurations. Based on interviews and data collection from manufacturers of the selected technologies (Camporeale et al., 2015), investment costs vary from 3.5 to 4.5 k.EUR/kW (year 2017). Although values are lower, the O&M costs are ranged from 0.7 to 1.1 k.EUR-year/kW, presenting higher values when compared to the present research (0.4 k.EUR-year/kW) and Oyekale's (0.3 k.EUR-year/kW).

2.2.2. *Final demand vector*

Once all costs have been accounted for, demand of goods and services considered in Table 3 for investment and O&M are assigned to the corresponding economic sectors and countries on the input-output table (see Annex II, Table A2), according to the United Nations Statistics classification (United Nations, 2008) and the sector disaggregation of a solar thermal power plant provided by Rodriguez-Serrano and colleagues (Rodríguez-Serrano et al., 2017). This allows constructing the demand vectors ($\hat{y}_I$ and $\hat{y}'$ see Eq. 2 and 4), which correspond to the direct effects, which will be used later to calculate the indirect and induced effects. Table 4 shows the final demand vector, which is the total investment and operational costs assigned to the corresponding economic sectors of each country. Costs related to biomass supply are included in sector Food products, beverages and tobacco, since oil-cake residues are classified in class 1040 according to ISIC Rev.4. This vector excludes personnel costs.

Table 4.
BIOSOL Final demand vector for ICIO-OECD database ($2015).

Country	Sector allocation	Investment costs	O&M costs	Total costs
ITA	Electrical equipment	1,988,794		1,988,794
ITA	Other non-metallic mineral products	976,234		976,234
ITA	Fabricated metal products	852,396		852,396
ITA	Basic metals	806,643		806,643
ITA	Machinery and equipment, nec	512,633		512,633
ITA	Computer, electronic and optical products	167,417		167,417
FRA	Machinery and equipment, nec	231,964		231,964
FRA	Other business sector services	1,121		1,121
TUN	Construction	97,243	4,381	101,625
TUN	Transportation and storage	509,763	607,209	1,116,972
TUN	Financial and insurance activities	475,006		475,006
TUN	Other business sector services	395,838		395,838
TUN	Food products, beverages and tobacco		607,209	607,209
TUN	Other non-metallic mineral products		10,599	10,599
TUN	Basic metals		8,757	8,757
TUN	Fabricated metal products		10,819	10,819
TUN	Computer, electronic and optical products		1,818	1,818
TUN	Electrical equipment		29,823	29,823
TUN	Machinery and equipment, nec		23,097	23,097
TUN	Other manufacturing; repair and installation of machinery and equipment		113,648	113,648
Total costs		**7,015,052**	**1,417,361**	**8,432,413**

Source: own elaboration on the basis of (Rodríguez-Serrano et al., 2017).

3. Results and discussion

3.1. Environmental assessment results

Results of the Life cycle inventory (LCI) are shown in Annex I from Table A1 to A5. Environmental Impacts are the result of the life cycle impact assessment (LCIA) phase in the LCA. These impacts have been assessed as described in the method and materials section. Additionally, the hot spots stages in each system part have been identified. The summary of the environmental impact assessment for hybrid power plant analyzed in this study is presented in Table 5 and Figure 3.

Table 5. Environmental impact results

Impact category		**Amount**	**Unit Per MWh**
Climate change	CC	21.74	kg CO_2 eq
Ozone depletion	ODP	3.29E-06	kg CFC11 eq
Ionising radiation, HH	IR	2.91E+00	kBq U-235 eq
Photochemical ozone formation, HH	POF	1.79E-01	kg NMVOC eq
Respiratory inorganics	RI	9.37E-06	disease inc.
Non-cancer human health effects	NC-HHE	6.43E-06	CTUh
Cancer human health effects	C-HHE	7.01E-07	CTUh
Acidification terrestrial and freshwater	AT-FW	1.50E+00	mol H+ eq
Eutrophication freshwater	EFW	1.77E-02	kg P eq
Eutrophication marine	EM	2.79E-02	kg N eq
Eutrophication terrestrial	ET	3.15E-01	mol N eq
Ecotoxicity freshwater	ECFW	2.23E+01	CTUe
Land use	LU	9.60E+01	Pt
Water scarcity	WS	2.00E+03	m^3 depriv.
Resource use, energy carriers	RU-E	2.98E+02	MJ
Resource use, mineral and metals	RS-M	4.14E-04	kg Sb eq
Climate change – fossil	CC-F	21.70	kg CO_2 eq
Climate change – biogenic	CC-B	4.03E-02	kg CO_2 eq
Climate change - land use and transform.	CC-LUT	2.25E-03	kg CO_2 eq

Source: own elaboration.

Global warming emissions per MWh of electricity generated in this plant are quantified in around 22 kg of CO_2 eq. This value is lower than the values published in the literature. San Miguel and co-workers (San Miguel and Corona, 2014) found values ranging from 34 to 64 kg CO_2 eq/MWh for different biomass fuels (wheat straw, wood pellets and biomethane). (Piemonte et al., 2011) found global warming emissions of 190 kg CO_2 eq/MWh. Reasons for these discrepancies can be found in the residual nature of the biomass used in this prototype (olive oil cake) that does not entail any embodied environmental impact other than those of transporting it to the power plant. Another reason could be the fact that the pyrolysis process used to produce the syngas avoids the release of digestion emissions considered in their study. Corona and coworker (Corona and San Miguel, 2015) found values ranging from 68 to 96 kg CO_2 eq/MWh for the hybrid operation of a CSP plant with biomethane from different substrates (grass, sewage, biowaste and mixed manure), with the highest impacts corresponding to grass (energy crop) due to the impacts originated in the cultivation phase. And also Corona (Corona et al., 2016) found values ranging from 29 to 46 kg CO_2 eq/MWh for a CSP hybrid power plant using biomethane, with different values depending on the location of the power plant and their respective DNI.

Graphically, Figure 4 shows the contributions made to the different impacts, by the different parts of the system.

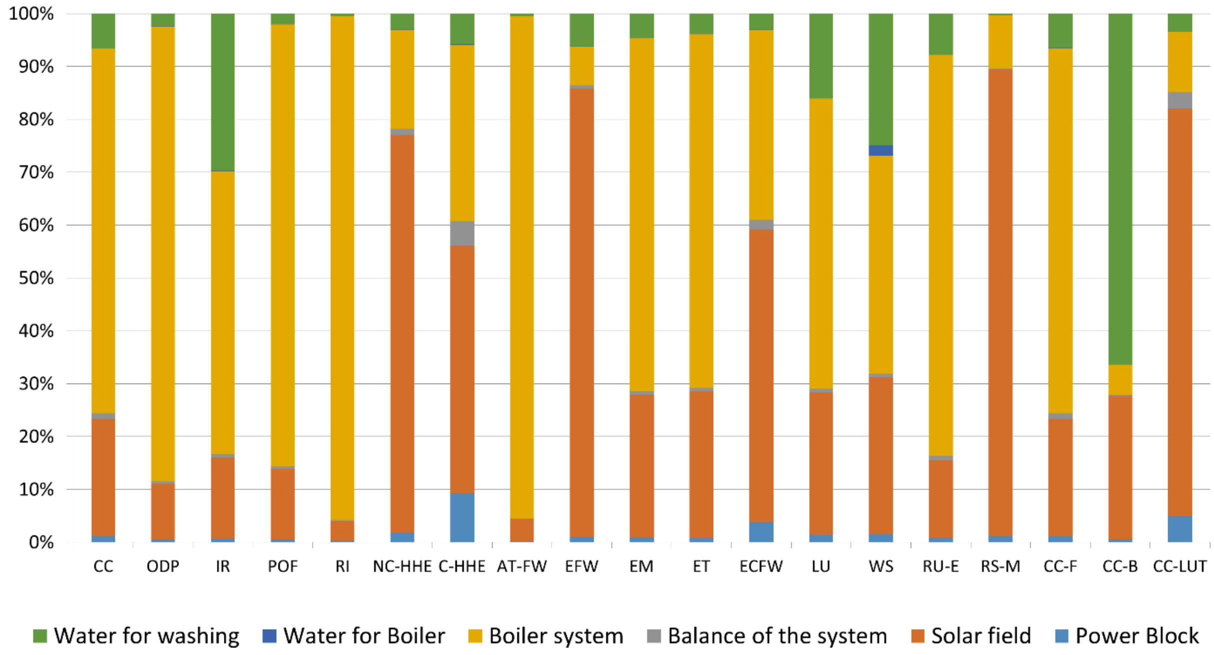


Figure 4. Distribution of the contributions by the different parts of the system.

Both the solar field and the boiler system account for most of the impacts in all the impact categories. The solar field dominates the impacts related to non-cancer human health effects (NC-HHE), freshwater eutrophication impacts (EFW), freshwater ecotoxicity (ECFW), mineral and metals resource use (RS-M) and land use change GHG emissions (CC-LUT). The boiler system highlights in the rest of the impact categories with the notable exception of the CC-B where the provision of water for washing dominates.

In terms of energy, fossil energy demand has been quantified in 298 MJ/MWh, a value substantially lower than other published studies ranging from 757 MJ/MWh (Corona et al., 2016) and 1,400 MJ/MWh (Piemonte et al., 2011) up to 3,026 (Corona and San Miguel, 2015) but in the range of the values found by San Miguel in (San Miguel and Corona, 2014).

Figures 4 to 6 show in a graphic form the main contributions to the different impact categories of each component: power block, solar field and the boiler system, and its percentage participation.

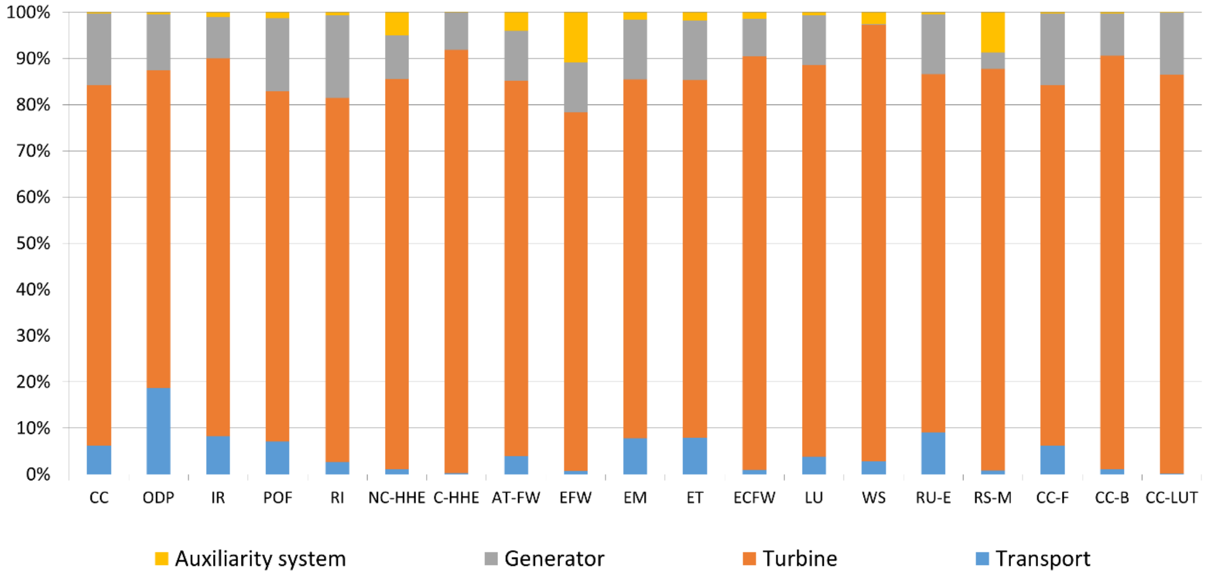


Figure 3. Distribution of the contributions by the different parts of the power block system.

In the power block, the steam turbine is the cause of most of the impacts. In this case, the influence of the steam turbine is due to the production of the steel used for its manufacture. In terms of human toxicity, it is the extraction of copper from the turbine fabrication which generates most of the impacts.

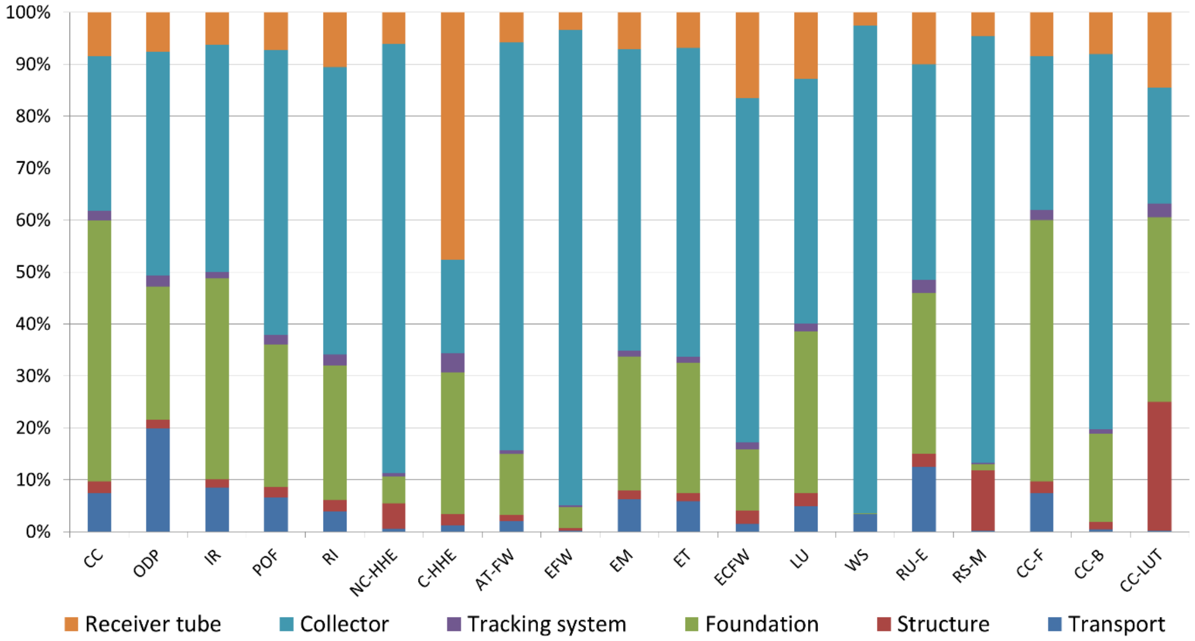


Figure 4. Distribution of the contributions by the different parts of the solar field system.

Regarding the solar field, the foundations and the collectors are the major contributors. There is an important contribution of the solar collectors and the structure to the impact resource use minerals and metals. Similar results have also been found by others (Corona et al., 2016; Lechón et al., 2008). The collectors and the foundations contribute to climatic change due to the production of glass and the production of concrete, respectively. In the rest of the environmental impacts, the collectors are the major contributor due to the extraction of copper.

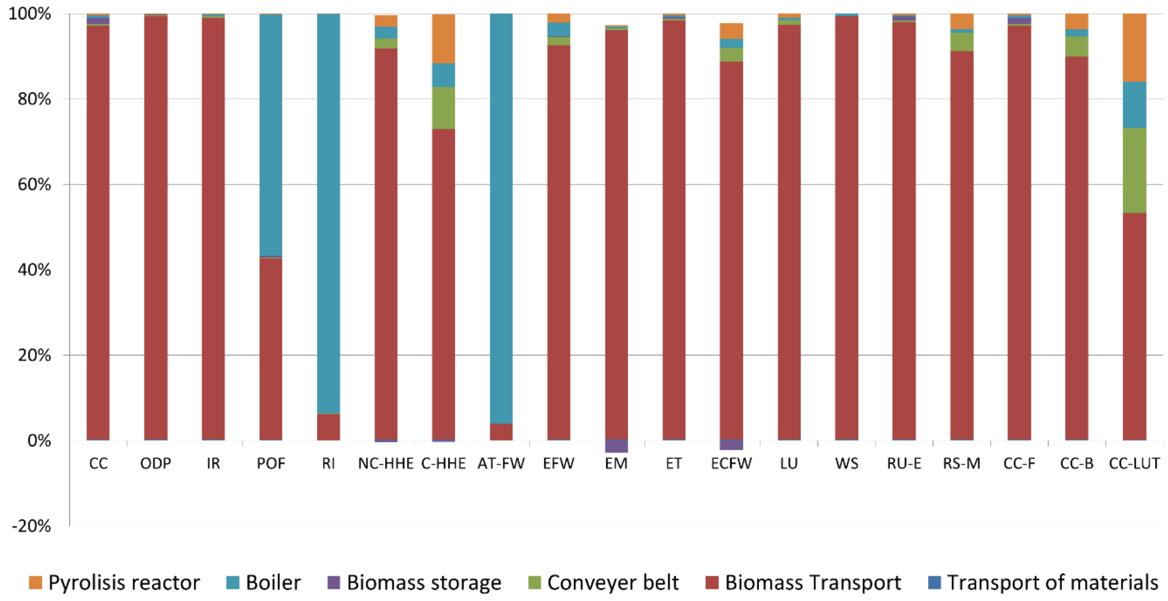


Figure 5. Distribution of the contributions by the different parts of the boiler system.

Environmental impacts of the boiler system are dominated by the impacts due to biomass transport activities with the exception of photochemical ozone formation (POF), respiratory inorganics (RI) and terrestrial and freshwater acidification (AT-FW) that are mainly caused by the manufacturing of the boiler.

According to the results presented in this paper, the assessed CSP and biomass hybrid power plant is an attractive option. In a country where olive production is so relevant, using the residual olive pomace (a second generation biofuel) (Naik et al., 2010) as a fuel for producing electricity may reduce the main biomass disadvantages coming from water and land footprint (Mahlooji et al., 2019). However, the boundaries of scaling up the system should be considered: for much higher installed capacities, the need for biomass can be such that the facility cannot be operated. Nevertheless, this technology could be used for sustainable energy provision in the agricultural sector (Mekhilef et al., 2013). For example, exploring activities such as supplying energy to the irrigation systems in the olive production (Todde et al., 2019) or thermal energy for the olive industry or the residential sector (Masghouni and Hassairi, 2000) could bring additional benefits to this exporting sector.

3.2. Socioeconomic assessment results

According to our results, BIOSOL project plant requirements create an estimated global economic stimulation 2.4 times larger than the initial investment. This multiplier effect gives information about the total stimulation produced from direct effects (Caldés et al., 2009). Nonetheless, the largest impact in terms of production and value added is generated outside Tunisia. Despite the higher initial investment participation (34.3%), total effects in production and value-added creation are only 22.6 and 28.9%, respectively (see Table 6). Each indicator corresponds to the overall (direct and indirect) socioeconomic/environmental effect (sum of *F* matrix, see Eq. 2).

Table 6. BIOSOL effects on production, value added, employment and CO_2 emissions

Phase/Indicator	**Production ($2015)**	**Value added ($2015)**	**Employment (FTE)**	**Emissions (Gg CO_2)**
Investment	17,084,857	6,603,827	179	3.01
O&M	3,132,611	1,381,701	111	0.93
Fuel costs (biomass)	*2,668,209*	*1,185,157*	*97*	*0.73*
Total effects	20,217,468	7,985,528	290	3.94
Tunisian share	*22.6%*	*28.9%*	*63.3%*	*33.9%*
Jobs in power plant			227	

Source: own elaboration.

Table 7 shows how the value added is generated along the value chain. Tunisian value added in imports from Italy, France and the rest of the world account for only 0.07% of the total value added creation, pointing out the low insertion of this country in forward linkages (Sammoud and Dhaoui, 2019). This high dependency of imported components could be undermining the GDP and employment growth potentialities in Tunisia. In this sense, policy actions developed towards either foreign direct investments (FDI) attraction or the promotion of a domestic business and technological network of energy-related components become an interesting option for the Tunisian economy in order maximize the economic growth in the country, the creation of jobs and the access to other markets such as the MENA region.

Table 7. Value added creation along the BIOSOL project value chain

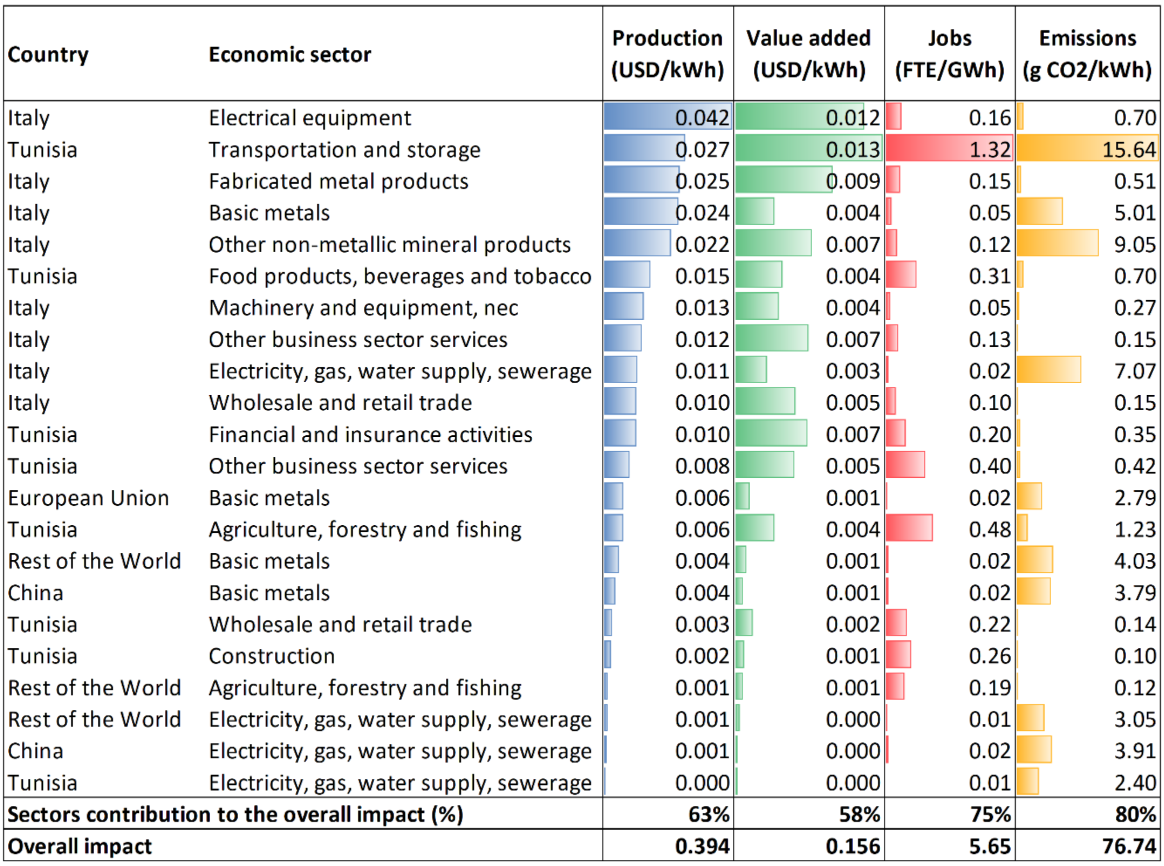
Value chain	**Country-origin**	**Participation**
Domestic value added	Tunisia	28.9%
In Tunisian direct and indirect requirements		28.83%
In imports		0.07%

Foreign value added		71.1%
In intermediates		6.60%
	Italy	*8.7%*
	France	*17.2%*
	Rest of Europe	*23.2%*
	China	*4.4%*
	Rest of the World	*46.5%*
In final goods and services		64.50%
	Italy	*67.7%*
	France	*5.2%*
	Rest of Europe	*11.8%*
	China	*2.8%*
	Rest of the World	*12.5%*

Source: own elaboration.

Even though Tunisia has not a relevant role in the investment phase, the O&M phase is remarkable for the country as a host of the power plant, benefiting local long-term employment. Total employment created is estimated in 11.6 FTE jobs/year (290 FTE during the lifetime of the power plant). From that amount, Tunisia is creating 7.4 FTE (63.3%). The O&M phase would create 4.4 FTE jobs/year for 25 years (111 FTE). Fuel costs (olive pomace) are the main reason as an estimated 3.8 FTE jobs/year (97 FTE) would be created in Tunisia as a consequence of the the management and transportation of olive oil residues needed to feed the biomass boiler. The rest is expected to come from the replacement of the components (boiler, power block, solar field and contingencies). Direct employment (personnel costs related to the operation phase) can be estimated based on engaged people and compensation of employees provided by OECD, ILOSTAT and the direct personnel costs provided in Table 3. Engaged people in the electricity sector Tunisia was almost 20.7 thousand workers in 2015. Compensation of employees in this sector was 293.2 million dollars. Thus, an average employee in the Tunisian electricity sector was paid 14,160 dollars that year. An amount of 3,219,877.6 dollars of personnel costs (2015 prices) is assumed to take place in Tunisia during the lifespan of the power plant. This would result in 227.4 additional FTE in the Electricity sector during the 25 years of the hybrid power plant lifespan. Hence, the annual job direct requirements would be 9.1 employees. Altogether with the investment (3) and the O&M phase (4.4), the overall annual employment in Tunisia would be 16.5 direct and indirect jobs per year.

Figure 7 below shows the sectors and countries that contribute the most to the socioeconomic impacts. Neither induced effects nor direct jobs in the power plant are accounted for. The *Transport and storage* sector in Tunisia is the most important sector in terms of production, value added, employment creation and CO_2 emissions when measured altogether. The Solar Field and the Power Block coming from Italy are reflected in sectors such as *Electrical equipment*, *Basic metals* and *Fabricated metals*, as well as *Other non-metallic mineral products*. Since these components account for the largest investments, effects in production and value added are high (33.1% and 23.7%, respectively). Services (*Other business sector services*; *Financial and insurance activities*; *Wholesale and retail trade*) are considered essentials in the process of manufacturing – a phenomena called *servicification* of manufacturing (Lanz and Maurer, 2015) – contributing to value added creation not only in developed but also in developing countries (Banacloche, 2017). Finally, in terms of employment, apart from the *Transportation and storage* sector, the main indirect sectors benefited correspond to *Agriculture, forestry and fishing, Wholesale and retail trade*, related to the biomass process.



Country	Economic sector	Production (USD/kWh)	Value added (USD/kWh)	Jobs (FTE/GWh)	Emissions (g CO2/kWh)
Italy	Electrical equipment	0.042	0.012	0.16	0.70
Tunisia	Transportation and storage	0.027	0.013	1.32	15.64
Italy	Fabricated metal products	0.025	0.009	0.15	0.51
Italy	Basic metals	0.024	0.004	0.05	5.01
Italy	Other non-metallic mineral products	0.022	0.007	0.12	9.05
Tunisia	Food products, beverages and tobacco	0.015	0.004	0.31	0.70
Italy	Machinery and equipment, nec	0.013	0.004	0.05	0.27
Italy	Other business sector services	0.012	0.007	0.13	0.15
Italy	Electricity, gas, water supply, sewerage	0.011	0.003	0.02	7.07
Italy	Wholesale and retail trade	0.010	0.005	0.10	0.15
Tunisia	Financial and insurance activities	0.010	0.007	0.20	0.35
Tunisia	Other business sector services	0.008	0.005	0.40	0.42
European Union	Basic metals	0.006	0.001	0.02	2.79
Tunisia	Agriculture, forestry and fishing	0.006	0.004	0.48	1.23
Rest of the World	Basic metals	0.004	0.001	0.02	4.03
China	Basic metals	0.004	0.001	0.02	3.79
Tunisia	Wholesale and retail trade	0.003	0.002	0.22	0.14
Tunisia	Construction	0.002	0.001	0.26	0.10
Rest of the World	Agriculture, forestry and fishing	0.001	0.001	0.19	0.12
Rest of the World	Electricity, gas, water supply, sewerage	0.001	0.000	0.01	3.05
China	Electricity, gas, water supply, sewerage	0.001	0.000	0.02	3.91
Tunisia	Electricity, gas, water supply, sewerage	0.000	0.000	0.01	2.40
Sectors contribution to the overall impact (%)		**63%**	**58%**	**75%**	**80%**
Overall impact		**0.394**	**0.156**	**5.65**	**76.74**

Figure 6. Main economic sectors in terms of socioeconomic effects.
Source: own elaboration.

Assessing the BIOSOL project carbon footprint, the most important impacts in terms of CO_2 emissions are originated by the Tunisian transportation of both, olive oil waste and components, accounting for 0.8 Gg CO_2 (15.6 g CO_2/kWh produced) out of 3.94 Gg (76.7 g CO_2/kWh). Since Italy is the main provider of components (Solar Field and Power Block), the country produces 33.2% of the overall emissions, mainly from sectors such as *Other non-metallic mineral products*; and the *Electricity, gas and water supply* sectors (see Figure 7). The latter sector has been usually identified as one of the most important in terms of CO_2 emissions. Global value chains phenomena determines the role of regions such as China and the Rest of the World as intermediates providers. Although no direct investments are made (see Table 3), intermediates are needed (i.e. basic metals and electricity) to produce the final components. Developing countries are identified to have a more carbon intensive electricity mix. Hence, emissions embodied in these intermediates have a notable impact in the installation of the BIOSOL power plant. Transport efficiency and a renewable energy sources (RES) intensive electricity mix of the countries involved in the BIOSOL project value chain would reduce CO_2 emissions substantially.

Induced effects capture the effect in the consumption of goods and services derived from changes in the economic compensation of employees. As a resulting increase of final demand, households are paid for their work force. Received payments are used for consumption and saving purposes. Consumption will further stimulate final demand and production. Assuming that every income is spent (propensity to consume equal to 1) the multiplier effect becomes 3.5 instead of 2.4. Salaries earned by the payment of labour services needed to satisfy the project demand have an additional and very important stimulus in the global economy. When induced effects are included, the installation of 11,652,290 dollars BIOSOL project in Tunisia, along with the personnel costs required during the lifespan of the installation, would have an estimated impact in production of 40,624,268 dollars. Direct and indirect income-generation per unit of income originated can also be assessed. In this project, since only Tunisia is hiring personnel directly, the initial 3,219,878 dollars income earned by personnel gives an indirect rise of 4,477,803 dollars income in the region itself, plus 3,342,813 incomes in Italy, 892,912 in France, 1,758,498 in the rest of Europe, 399,144 in China and 2,352,358 in the rest of the world.

Figure 8 represents the total effects of BIOSOL investment, when induced impacts are considered. The income generated as a consequence of the labour payments during the investments and later spent in the economy has a larger boost when compared to the direct and indirect effects in the production of goods and services, value-added creation and employment generation. In terms of CO_2 induced emissions are a 45% of the total figure. These induced emissions are largely disregarded in the literature and could be, as demonstrated in this work, very important.

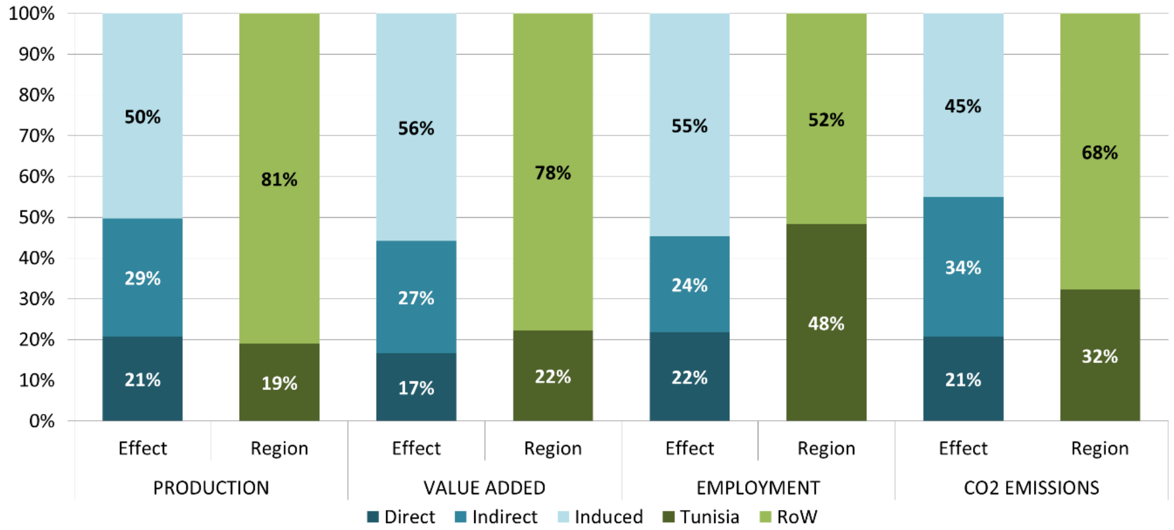


Figure 7. Total effects on production, value added, employment and CO_2 emissions (induced effects included)

Source: own elaboration.

In order to deploy RES investments, foster local employment and reduce carbon emissions, Tunisia must face an initial increase in CO_2 emissions. However, the main origin of emissions comes from outside the country due to the import dependency. Future green investments, compatible with the national package of RES deployment and the Paris Agreement, can be targeted to promote domestic value added. When looking at these results, it is worth considering the limitations of this analysis that has assumed that every dollar received by the personnel is reinvested in the economy and that nothing is saved.

3.3. Comparison of CO_2 emissions calculated by both methodologies

In terms of CO_2 emissions, the 77 gCO_2 eq/kWh calculated by the IOA contrast with the 22 gCO_2 eq/kWh that result from the LCA. Although results are consistent with the literature and in the range of published results, differences between the LCA and the IOA come from the assumptions made by each methodology and have been extensively discussed in the literature (Crawford et al., 2018; Lenzen, 2000; Rowley et al., 2009; Suh et al., 2004). In principle, it is expected that IOA gives higher results than LCA since IOA avoids the specification of limits to the system. However, there could be other reasons for the high discrepancies observed. First, LCA here analyses the production processes for imported components as if they were produced in Europe, disregarding the country-origin of the intermediate products needed for these components. Hence, CO_2 emissions are calculated with the characteristics of the European technological and energy supply systems. By contrast, IOA considers the country-origin of the components and captures all the successive rounds of production and the trade relations between countries and sectors. Carbon-intensive economies such as China and other developing countries have an important role under the IOA, due to global value chains and the importance of intermediates in the fragmentation of production. Thus, CO_2 emissions will have a larger impact under this approach. Second, LCA can capture the technological details of all the processes involved in the value chain of the technology, while IOA only provides sector averaged results. This sector aggregation could distort the correct calculation of emissions by IOA and could be overestimating them. And third, the sources of the emission data in both methodologies are completely different. LCA relies on technology specific calculation of emissions while IOA uses national inventories of emissions per sector.

4. Conclusions

The development of this system contributes to bringing to the market energy-efficient, renewable electricity generation systems. The environmental sustainability and economics of the prototype systems have been assessed, and the results obtained should be disseminated to industry and research, as a proof-of-concept of renewable electricity generation solutions.

The hybrid system shows a result of GHG emissions close to 22 gCO_2eq/kWh. By component, the boiler system is the major contributor to this impact due mainly to the biomass transport. After an analysis of the whole system, it is observed that, in general, the boiler system and the solar field are the parts of the installation that most influence have in the calculated environmental impacts. On one hand, the boiler system has an influence on all the impacts that are related mainly to the emissions caused by the transport of biomass, which could be reduced by the definition of shorter biomass transport distances. On the other hand, the solar field has a lot of influence in human toxicity, freshwater ecotoxicity and resource use minerals and metals. The major contribution of the solar field to these impacts is due to the manufacturing process of the solar collectors and the extraction of the copper needed in the manufacturing process. From an energy point of view, the system shows very low demand for fossil energy.

From the socioeconomic analysis performed, the investment assessed creates a stimulation of production of goods and services of 2.4 (3.5 when induced effects are accounted for). Employment and emissions become the most important impacts for Tunisia. In terms of CO_2 emissions, the 77 gCO_2 eq/kWh contrast with the results of the environmental analysis. Differences have been discussed and are related to the different assumptions made by each methodology.

The O&M phase becomes an important stage in the generation of domestic long-term employment mainly due to the biomass supply activities. In all the socioeconomic impacts, the imported content is high, highlighting the Tunisian dependency in installing a hybrid CSP-biomass power plant. Europe offers a strong technology base, being home of some of the world’s leading multinational energy and systems integration companies, as well as many smaller research institutions and specialized companies. In order to maximize the positive socioeconomic effects, the national content of the investments has to be maximized (e.g. producing the main components and attracting FDI).

Results remain highly explorative, as the technology has not been deployed. Limitations of data, both at a macro and project specific level must be stressed. Besides, calculated effects are gross estimations. Net effects would result if the economic and employment effects of alternative ways of generating electricity and heat were also analyzed and subtracted. Despite these uncertainties, this paper points out the role of CSP in Tunisia as part of the solution to energy demand and Climate Change.

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Annex I. Life Cycle Inventory results (LCI)

Tables below show data and results of the LCI of the studied system. All these data are referred to one year of operation of the plant.

Table A1. Solar field inventory

Item	Value	Unit
Collector		
Flat glass coated	3,485	kg
Copper, at regional storage	1,100.48	kg
Synthetic rubber, at plant	43.90	kg
Collectors	19	p
Receiver tube		
Steel, chromium steel 18/8, hot rolled production	291.20	kg
Flat glass, uncoated production	221	kg
Aluminium oxide, at plant	3	kg
Copper, at regional storage	30	kg
Receiver tube	19	p
Structure		
Reinforcing steel production	61.12	kg
Aluminium oxide, treatment of aluminium scrap	414.88	kg
Structure	19	p
Foundation		
Concrete	73,728	kg
Reinforcing steel	1,103.36	kg
foundation	19	p
Tracking system		
Reinforcing steel	138.4	kg
Nickel, 99.5% nickel mine operation, sulfidic ore	0.074	kg
Lubricating oil production	13.335	kg
Chromium production	0.074	kg
Polyethylene, high density, granulate production	10.08	kg
Wire drawing, copper processing	8.32	kg
Pump, 40W production	2	p
Tracking system	19	p

Source: own elaboration.

Table A2. Life cycle inventory of the power block.

Item	Value	Unit
Turbine system		
Reinforcing steel	1,248.63	kg
Copper, at regional storage	57.63	kg
Ceramic tile {CH}|production	29.2	kg
Steel, chromium steel 18/8, hot rolled	1,128.25	kg
Aluminium, production mix, at plant	145.99	kg

Turbine	1	p
Generator		
Reinforcing steel	832.63	kg
Ceramic tile{CH}	19.47	kg
Generator	1	p
Generator auxiliaries		
Copper, at regional storage	19.47	kg
Generator auxiliaries	1	p

662 Source: own elaboration.

663

664 **Table A3.** Balance of the system inventory

Item	Value	Unit
Steam drum		
Sanitary ceramics, at regional storage	17.58	kg
Cast iron /	135.64	kg
reinforcing steel production	818.25	kg
Aluminium,	17.58	kg
Transport, lorry 7.5-16 t, EURO5	979.63	tkm
Expansion tank		
Sanitary ceramics, at regional storage	44.81	kg
Cast iron, at plant/	345.65	kg
Reinforcing steel	2,085.08	kg
Aluminium, production mix, at plant	20.8	kg
Transport, lorry 7.5-16 t, EURO5	2496.33	tkm
Feed water tank		
Sanitary ceramics, at regional storage	17.58	kg
Cast iron, at plant	135.64	kg
Reinforcing steel {RER}| production	818.25	kg
Aluminium, production mix, at plant/ RER U	17.58	kg
Transport, lorry 7.5-16 t, EURO5	979.63	tkm

665 Source: own elaboration.

666

667 **Table A4.** Life cycle inventory of the boiler system.

Item	Value	Unit
Digester		
Concrete, normal	1.75	m^3
Reinforcing steel, at plant	476.91	kg
Chromium steel 18/8, at plant	52.29	kg
Copper, at regional storage	6.12	kg
Polyethylene, high density, granulate production	4.52	kg
Polyvinyl chloride, at regional storage	0.59	kg
Synthetic rubber, at plant	1.56	kg
Transport, lorry 7.5-16 t, EURO5	542.76	tkm
Boiler		
Sanitary ceramics, at regional storage	46.37	kg
Cast iron, at plant	357.71	kg
Reinforcing steel	2157	kg

Aluminium, production mix, at plant	21.53	kg
Transport, lorry 7.5-16 t, EURO5	2,583.43	tkm
Electricity, medium voltage,	872,960	kWh
Methane biogenic emission	113.78	kg
Nitrogen monoxide	44.7	kg
Carbon dioxide	97,9	t
Waste food	127.75	ton/year
Gas natural	1,574.74	kg/year
Decanter		
Polyvinyl chloride	70	kg
Transport, lorry 7.5-16 t, EURO5	70	tkm
Mixing tank		
Reinforcing steel	215	kg
Transport, lorry 7.5-16 t, EURO5	215	tkm

Source: own elaboration.

Table A5. End of life scenario

Item	Value	Unit
Landfill	15	km
Solar field	80.48	ton
Power block	3.48	ton
Biogas system	4.74	ton
Balance of the system	4.47	ton

Source: own elaboration.

Annex II. Input-output analysis supplementary material

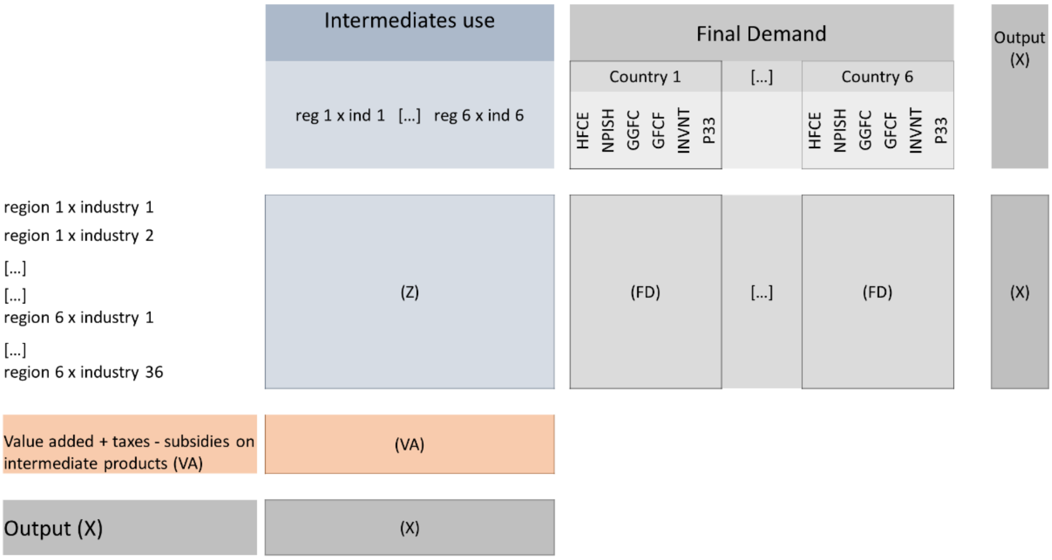
Equation A1. Socioeconomic/environmental impacts

We assume two regions (m=r,s) and two sectors (n=1,2) identified in the superscripts and subscripts, respectively. The first position corresponds to the region/sector origin. The second position to the destination. Taking in example $L = (I - A)^{-1}$, the Leontief inverse matrix, $L^{rs}_{2,1}$ is interpreted as the total requirements originated in sector 2 from country *r* and destinated to satisfy sector 1 in country *s*. Direct requirements (goods and services needed for the deployment) provided by both regions, *r* and *s*, are captured in matrix $\hat{y}_I$. Assuming that the project installation takes place in country *r*, the second position of country-origin will always be *r*, that is, the country that demands the goods and services.

$$F = \begin{bmatrix} \hat{f}^r_1 & 0 & 0 & 0 \\ 0 & \hat{f}^r_2 & 0 & 0 \\ 0 & 0 & \hat{f}^s_1 & 0 \\ 0 & 0 & 0 & \hat{f}^s_2 \end{bmatrix} \begin{bmatrix} L^{rr}_{1,1} & L^{rr}_{1,2} & L^{rs}_{1,1} & L^{rs}_{1,2} \\ L^{rr}_{2,1} & L^{rr}_{2,2} & L^{rs}_{2,1} & L^{rs}_{2,2} \\ L^{sr}_{1,1} & L^{sr}_{1,2} & L^{ss}_{1,1} & L^{ss}_{1,2} \\ L^{sr}_{2,1} & L^{sr}_{2,2} & L^{ss}_{2,1} & L^{ss}_{2,2} \end{bmatrix} \begin{bmatrix} \hat{y}^{rr}_1 & 0 & 0 & 0 \\ 0 & \hat{y}^{rr}_2 & 0 & 0 \\ 0 & 0 & \hat{y}^{sr}_1 & 0 \\ 0 & 0 & 0 & \hat{y}^{sr}_2 \end{bmatrix}$$

$$= \begin{bmatrix} \hat{f}^r_1 L^{rr}_{1,1} \hat{y}^{rr}_1 & \hat{f}^r_1 L^{rr}_{1,2} \hat{y}^{rr}_2 & \hat{f}^r_1 L^{rs}_{1,1} \hat{y}^{sr}_1 & \hat{f}^r_1 L^{rs}_{1,2} \hat{y}^{sr}_2 \\ \hat{f}^r_2 L^{rr}_{2,1} \hat{y}^{rr}_1 & \hat{f}^r_2 L^{rr}_{2,2} \hat{y}^{rr}_2 & \hat{f}^r_2 L^{rs}_{2,1} \hat{y}^{sr}_1 & \hat{f}^r_2 L^{rs}_{2,2} \hat{y}^{sr}_2 \\ \hat{f}^s_1 L^{sr}_{1,1} \hat{y}^{rr}_1 & \hat{f}^s_1 L^{sr}_{1,2} \hat{y}^{rr}_2 & \hat{f}^s_1 L^{ss}_{1,1} \hat{y}^{sr}_1 & \hat{f}^s_1 L^{ss}_{1,2} \hat{y}^{sr}_2 \\ \hat{f}^s_2 L^{sr}_{2,1} \hat{y}^{rr}_1 & \hat{f}^s_2 L^{sr}_{2,2} \hat{y}^{rr}_2 & \hat{f}^s_2 L^{ss}_{2,1} \hat{y}^{sr}_1 & \hat{f}^s_2 L^{ss}_{2,2} \hat{y}^{sr}_2 \end{bmatrix}$$

Figure A1. ICIO-OECD table scheme



Source: OECD

Table A1. ICIO-OECD region and sector classification

Region (69)				**Sector (36)**	**ICIO Code**	**ISIC Rev.4**
AUS	Australia	ARG	Argentina	Agriculture, forestry and fishing	D01T03	01, 02, 03
AUT	Austria	BRA	Brazil	Mining and extraction of energy producing products	D05T06	05, 06
BEL	Belgium	BRN	Brunei Darussalam	Mining and quarrying of non-energy producing products	D07T08	07, 08
CAN	Canada	BGR	Bulgaria	Mining support service activities	D09	09
CHL	Chile	KHM	Cambodia	Food products, beverages and tobacco	D10T12	10, 11, 12
CZE	Czech Republic	CHN	China (People's Republic of)	Textiles, wearing apparel, leather and related products	D13T15	13, 14, 15
DNK	Denmark	COL	Colombia	Wood and products of wood and cork	D16	16
EST	Estonia	CRI	Costa Rica	Paper products and printing	D17T18	17, 18
FIN	Finland	HRV	Croatia	Coke and refined petroleum products	D19	19
FRA	France	CYP	Cyprus	Chemicals and pharmaceutical products	D20T21	20, 21
DEU	Germany	IND	India	Rubber and plastic products	D22	22
GRC	Greece	IDN	Indonesia	Other non-metallic mineral products	D23	23
HUN	Hungary	HKG	Hong Kong, China	Basic metals	D24	24
ISL	Iceland	KAZ	Kazakhstan	Fabricated metal products	D25	25
IRL	Ireland	MYS	Malaysia	Computer, electronic and optical products	D26	26
ISR	Israel	MLT	Malta	Electrical equipment	D27	27
ITA	Italy	MAR	Morocco	Machinery and equipment, nec	D28	28
JPN	Japan	PER	Peru	Motor vehicles, trailers and semi-trailers	D29	29
KOR	Korea	PHL	Philippines	Other transport equipment	D30	30
LVA	Latvia	ROU	Romania	Other manufacturing; repair and installation of machinery and equipment	D31T33	31, 32, 33
LTU	Lithuania	RUS	Russian Federation	Electricity, gas, water supply, sewerage, waste and remediation services	D35T39	35 – 39
LUX	Luxembourg	SAU	Saudi Arabia	Construction	D41T43	41, 42, 43
MEX	Mexico	SGP	Singapore	Wholesale and retail trade; repair of motor vehicles	D45T47	45, 46, 47
NLD	Netherlands	ZAF	South Africa	Transportation and storage	D49T53	49 – 53
NZL	New Zealand	TWN	Chinese Taipei	Accommodation and food services	D55T56	55, 56
NOR	Norway	THA	Thailand	Publishing, audio-visual and broadcasting activities	D58T60	58, 59, 60
POL	Poland	TUN	Tunisia	Telecommunications	D61	61
PRT	Portugal	VNM	Viet Nam	IT and other information services	D62T63	62, 63
SVK	Slovak Republic	ROW	Rest of the World	Financial and insurance activities	D64T66	64, 65, 66
SVN	Slovenia	MX1	Mexico Non-Global Manufacturing	Real estate activities	D68	68
ESP	Spain	MX2	Mexico Global Manufacturing	Other business sector services	D69T82	69 – 82
SWE	Sweden	CN1	China Domestic sales only	Public admin. and defence; compulsory social security	D84	84
CHE	Switzerland	CN2	China Processing goods exporters	Education	D85	85
TUR	Turkey			Human health and social work	D86T88	86, 87, 88
GBR	United Kingdom			Arts, entertainment, recreation and other service activities	D90T96	90 – 96
USA	United States			Private households with employed persons	D97T98	97, 98

Source: OECD

Table A2. BIOSOL project cost breakdown

Cost breakdown	Country-origin	Costs ($)	Sector allocation	Cost distribution
Investment costs		**7,015,052.0**		
A. Total solar field: electrical components installation and commissioning; solar collectors (including metal structures, mirrors and receiver tubes); Instrumentation sensors (radiation, wind speed, GPS); solar field terrain drainage; others.	Italy	4,505,027	Other non-metallic mineral products	22%
			Electrical equipment	39%
			Basic metals	18%
			Fabricated metal products	18%
			Computer, electronic and optical products	4%
B. Power block: turbine, generator, heat exchangers, expander	Italy	896,333	Machinery and equipment, nec	57%
	Tunisia		Construction	11%
	Italy		Fabricated metal products	5%
	Italy		Electrical equipment	27%
C. Total pyrolysis system: burner design, burner construction	France	8,964.8	Other business sector services	13%
			Machinery and equipment, nec	87%
D. Total gasifier system costs	France	224,120	Machinery and equipment, nec	100%
E. Components transportation	Tunisia	509,763	Transportation and storage	100%
F. Other costs: project design and implementation	Tunisia	870,845	Financial and insurance activities	55%
			Other business sector services	45%
O&M costs (annual)		**412,509.7**		
A. Labour costs	Tunisia	301,634.2	Included in induced impacts only	
B. Resources and energy costs: transportation, olive-oil waste	Tunisia	95,000	Transportation and storage	50%

			Food products, beverages and tobacco	50%
C. Anaerobic Digestor	Tunisia	8,858.5	Other manufacturing; repair and installation of machinery and equipment	100%
D. Solar Field	Tunisia	3,825.9	Other non-metallic mineral products	22%
			Electrical equipment	39%
			Basic metals	18%
			Fabricated metal products	18%
			Computer, electronic and optical products	4%
E. Boiler	Tunisia	31.8	Other manufacturing; repair and installation of machinery and equipment	100%
F. Power Block	Tunisia	3,159.2	Machinery and equipment, nec	57%
			Construction	11%
			Fabricated metal products	5%
			Electrical equipment	27%

Source: own elaboration on the basis of BIOSOL project

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Table 1. Solar field, boiler system and power block data.

	Value	Unit
DNI	1,922	kWh/(m^2 year)
Annual heat generated - solar field	7,750	MWhth
Specific thermal field output	771	kWhth/m^2
Mean annual solar field efficiency	40.1	%
Solar share	27.5	%
Solar field dumped heat	232	MWhth
Annual heat generated - boiler	2,112	MWhth
Mean annual boiler efficiency	85	%
Annual biogas consumption	0.57	hm^3
Average biogas consumption	1,564	m^3/day
Annual useful heat from solar field and boiler	9,862	MWhth
Annual power generated	2,052	MWhel
Mean annual power block efficiency	20.81	%

Source: own elaboration by data from REELCOOP project (Oliveira, 2018; Soares et al., 2018b).

Table 2.
Impact categories for Environmental Footprint Method

Impact category	Category indicator
Climate change	kg CO_2 eq
Ozone depletion	kg CFC11 eq
Ionising radiation, HH	kBq U-235 eq
Photochemical ozone formation, HH	kg NMVOC eq
Respiratory inorganics	disease inc.
Non-cancer human health effects	CTUh
Cancer human health effects	CTUh
Acidification terrestrial and freshwater	mol H+ eq
Eutrophication freshwater	kg P eq
Eutrophication marine	kg N eq
Eutrophication terrestrial	mol N eq
Ecotoxicity freshwater	CTUe
Land use	Pt
Water scarcity	m^3 depriv.
Resource use, energy carriers	MJ
Resource use, mineral and metals	kg Sb eq
Climate change - fossil	kg CO_2 eq
Climate change - biogenic	kg CO_2 eq
Climate change - land use and transform.	kg CO_2 eq

Source: own elaboration based on (Fazio et al., 2018).

Table 3.
BIOSOL investment cost disaggregation and manufacturing country.

Cost data	Cost breakdown	Country	2015 US$
Investment	Solar Field (SF)	ITA	4,505,027.4
	Boiler System (BS)	FRA	233,084.8
	Pyrolysis burner	*FRA*	*8,964.8*
	Gasifier	*FRA*	*224,120.0*
	Power Block (PB)	ITA (89%), TUN (11%)	896,332.6
	Contingencies and other costs	TUN	1,380,607.2
	Total		**7,015,052.0**
O&M (annual costs)	Resources and energy costs (transport & biomass)		95,000.0
	Personnel costs		301,634.2
	O&M and replacement of Anaerobic Digestor		8,858.5
	O&M and replacement of Solar Field		3,825.9
	O&M and replacement of Boiler		31.8
	O&M and replacement of Power Block		3,159.2
	Total		**412,509.7**
Total life cycle costs (personnel costs not considered)			**8,432,412.8**

Source: data provided by EU ERANETMED consortium.

Note: Italy (ITA), France (FRA), Tunisia (TUN).

Table 4.

BIOSOL Final demand vector for ICIO-OECD database ($2015).

Country	Sector allocation	Investment costs	O&M costs	Total costs
ITA	Electrical equipment	1,988,794		1,988,794
ITA	Other non-metallic mineral products	976,234		976,234
ITA	Fabricated metal products	852,396		852,396
ITA	Basic metals	806,643		806,643
ITA	Machinery and equipment, nec	512,633		512,633
ITA	Computer, electronic and optical products	167,417		167,417
FRA	Machinery and equipment, nec	231,964		231,964
FRA	Other business sector services	1,121		1,121
TUN	Construction	97,243	4,381	101,625
TUN	Transportation and storage	509,763	607,209	1,116,972
TUN	Financial and insurance activities	475,006		475,006
TUN	Other business sector services	395,838		395,838
TUN	Food products, beverages and tobacco		607,209	607,209
TUN	Other non-metallic mineral products		10,599	10,599
TUN	Basic metals		8,757	8,757
TUN	Fabricated metal products		10,819	10,819
TUN	Computer, electronic and optical products		1,818	1,818
TUN	Electrical equipment		29,823	29,823
TUN	Machinery and equipment, nec		23,097	23,097
TUN	Other manufacturing; repair and installation of machinery and equipment		113,648	113,648
Total costs		**7,015,052**	**1,417,361**	**8,432,413**

Source: own elaboration on the basis of (Rodríguez-Serrano et al., 2017).

Table 5. Environmental impact results

Impact category		Amount	Unit Per MWh
Climate change	CC	21,74	kg CO_2 eq
Ozone depletion	ODP	3,29E-06	kg CFC11 eq
Ionising radiation, HH	IR	2,91E+00	kBq U-235 eq
Photochemical ozone formation, HH	POF	1,79E-01	kg NMVOC eq
Respiratory inorganics	RI	9,37E-06	disease inc.
Non-cancer human health effects	NC-HHE	6,43E-06	CTUh
Cancer human health effects	C-HHE	7,01E-07	CTUh
Acidification terrestrial and freshwater	AT-FW	1,50E+00	mol H+ eq
Eutrophication freshwater	EFW	1,77E-02	kg P eq
Eutrophication marine	EM	2,79E-02	kg N eq
Eutrophication terrestrial	ET	3,15E-01	mol N eq
Ecotoxicity freshwater	ECFW	2,23E+01	CTUe
Land use	LU	9,60E+01	Pt
Water scarcity	WS	2,00E+03	m^3 depriv.
Resource use, energy carriers	RU-E	2,98E+02	MJ
Resource use, mineral and metals	RS-M	4,14E-04	kg Sb eq
Climate change - fossil	CC-F	21,70	kg CO_2 eq
Climate change - biogenic	CC-B	4,03E-02	kg CO_2 eq
Climate change - land use and transform.	CC-LUT	2,25E-03	kg CO_2 eq

Source: own elaboration.

Table 6. BIOSOL effects on production, value added, employment and CO_2 emissions

Phase/Indicator	Production ($2015)	Value added ($2015)	Employment (FTE)	Emissions (Gg CO_2)
Investment	17,084,857	6,603,827	179	3.01
O&M	3,132,611	1,381,701	111	0.93
Fuel costs (biomass)	*2,668,209*	*1,185,157*	*97*	*0.73*
Total effects	20,217,468	7,985,528	290	3.94
Tunisian share	*22.6%*	*28.9%*	*63.3%*	*33.9%*
Jobs in power plant			227	

Source: own elaboration.

Table 7. Value added creation along the BIOSOL project value chain

Value chain	Country-origin	Participation

Domestic value added	Tunisia	28.9%
In Tunisian direct and indirect requirements		28.83%
In imports		0.07%
Foreign value added		71.1%
In intermediates		6.60%
	Italy	*8.7%*
	France	*17.2%*
	Rest of Europe	*23.2%*
	China	*4.4%*
	Rest of the World	*46.5%*
In final goods and services		64.50%
	Italy	*67.7%*
	France	*5.2%*
	Rest of Europe	*11.8%*
	China	*2.8%*
	Rest of the World	*12.5%*

Source: own elaboration.

Table A1. Solar field inventory

Item	**Value**	**Unit**
Collector		
Flat glass coated	3,485	kg
Copper, at regional storage	1,100.48	kg
Synthetic rubber, at plant	43.90	kg
Collectors	19	p
Receiver tube		
Steel, chromium steel 18/8, hot rolled production	291.20	kg
Flat glass, uncoated production	221	kg
Aluminium oxide, at plant	3	kg
Copper, at regional storage	30	kg
Receiver tube	19	p
Structure		
Reinforcing steel production	61.12	kg
Aluminium oxide, treatment of aluminium scrap	414.88	kg
Structure	19	p
Foundation		
Concrete	73,728	kg
Reinforcing steel	1,103.36	kg
foundation	19	p
Following system		
Reinforcing steel	138.4	kg
Nickel, 99.5% nickel mine operation, sulfidic ore	0.074	kg
Lubricating oil production	13.335	kg
Chromium production	0.074	kg
Polyethylene, high density, granulate production	10.08	kg
Wire drawing, copper processing	8.32	kg

Pump, 40W production	2	p
Following system	19	p

Source: own elaboration.

Table A2. Life cycle inventory of the power block.

Item	**Value**	**Unit**
Turbine system		
Reinforcing steel	1,248.63	kg
Copper, at regional storage	57.63	kg
Ceramic tile {CH}|production	29.2	kg
Steel, chromium steel 18/8, hot rolled	1,128.25	kg
Aluminium, production mix, at plant	145.99	kg
Turbine	1	p
Generator		
Reinforcing steel	832.63	kg
Ceramic tile{CH}	19.47	kg
Generator	1	p
Generator auxiliaries		
Copper, at regional storage	19.47	kg
Generator auxiliaries	1	p

Source: own elaboration.

Table A3. Balance of the system inventory

Item	**Value**	**Unit**
Drum tank		
Sanitary ceramics, at regional storage	17.58	kg
Cast iron /	135.64	kg
reinforcing steel production	818.25	kg
Aluminium,	17.58	kg
Transport, lorry 7.5-16 t, EURO5	979.63	tkm
Expansion tank		
Sanitary ceramics, at regional storage	44.81	kg
Cast iron, at plant/	345.65	kg
Reinforcing steel	2085.08	kg
Aluminium, production mix, at plant	20.8	kg
Transport, lorry 7.5-16 t, EURO5	2496.33	tkm
Feed water tank		
Sanitary ceramics, at regional storage	17.58	kg
Cast iron, at plant	135.64	kg
Reinforcing steel {RER}| production	818.25	kg
Aluminium, production mix, at plant/ RER U	17.58	kg
Transport, lorry 7.5-16 t, EURO5	979.63	tkm

Source: own elaboration.

Table A4. Life cycle inventory of the boiler system.

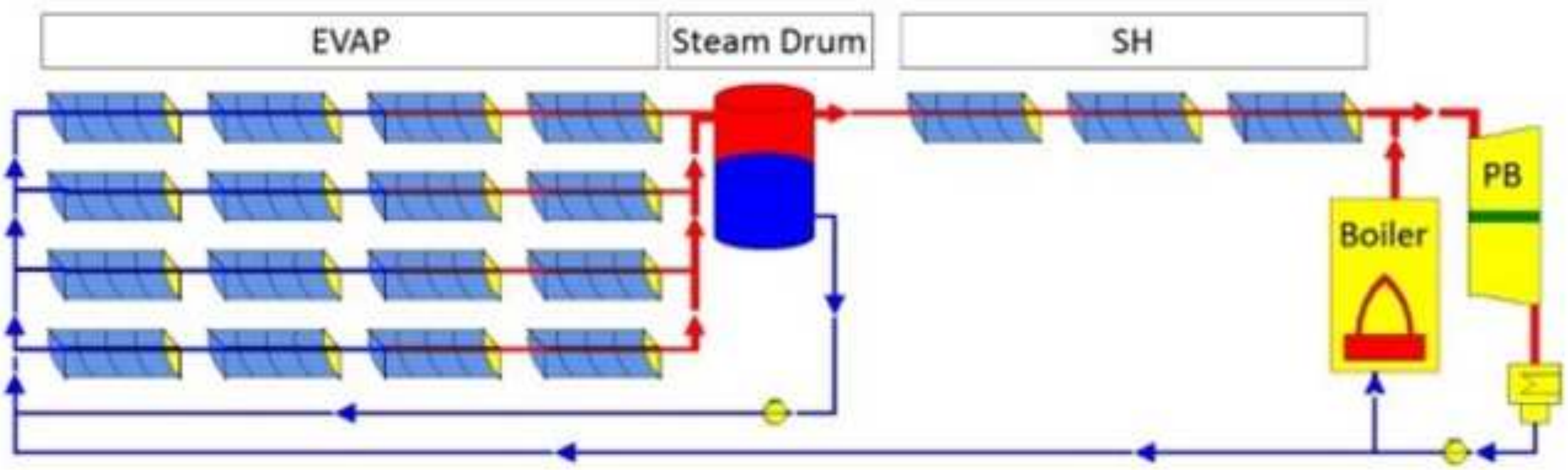
Item	Value	Unit
Digester		
Concrete, normal	1.75	m^3
Reinforcing steel, at plant	476.91	kg
Chromium steel 18/8, at plant	52.29	kg
Copper, at regional storage	6.12	kg
Polyethylene, high density, granulate production	4.52	kg
Polyvinyl chloride, at regional storage	0.59	kg
Synthetic rubber, at plant	1.56	kg
Transport, lorry 7.5-16 t, EURO5	542.76	tkm
Boiler		
Sanitary ceramics, at regional storage	46.37	kg
Cast iron, at plant	357.71	kg
Reinforcing steel	2157	kg
Aluminium, production mix, at plant	21.53	kg
Transport, lorry 7.5-16 t, EURO5	2583.43	tkm
Electricity, medium voltage,	872960	kWh
Methane biogenic emission	113.78	kg
Nitrogen monoxide	44.7	kg
Carbon dioxide	97,9	t
Waste food	127.75	ton/year
Gas natural	1574.74	kg/year
Decanter		
Polyvinyl chloride	70	kg
Transport, lorry 7.5-16 t, EURO5	70	tkm
Mixing tank		
Reinforcing steel	215	kg
Transport, lorry 7.5-16 t, EURO5	215	tkm

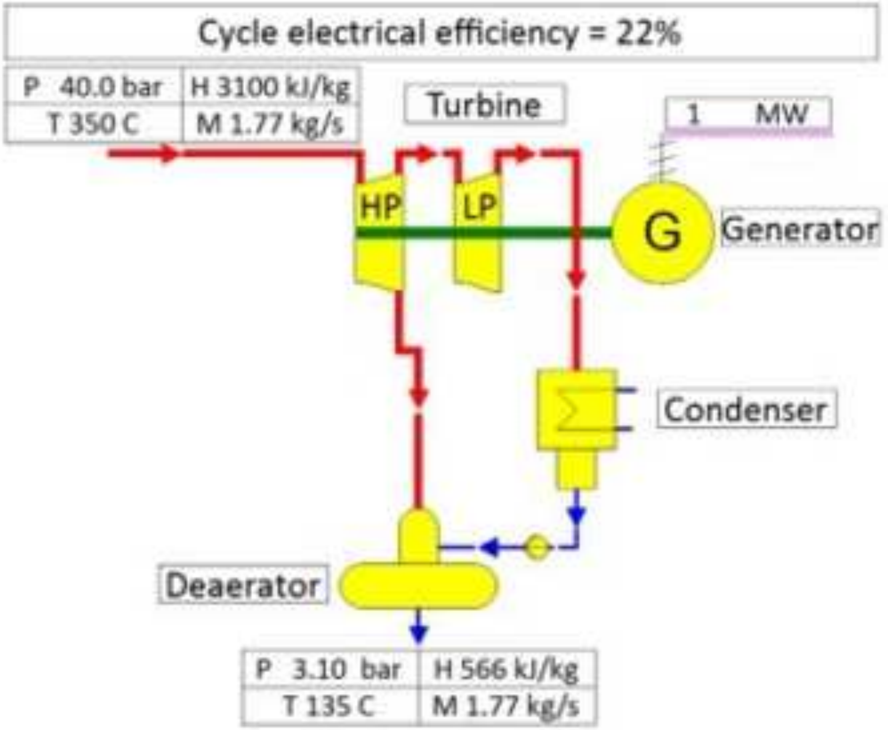
Source: own elaboration.

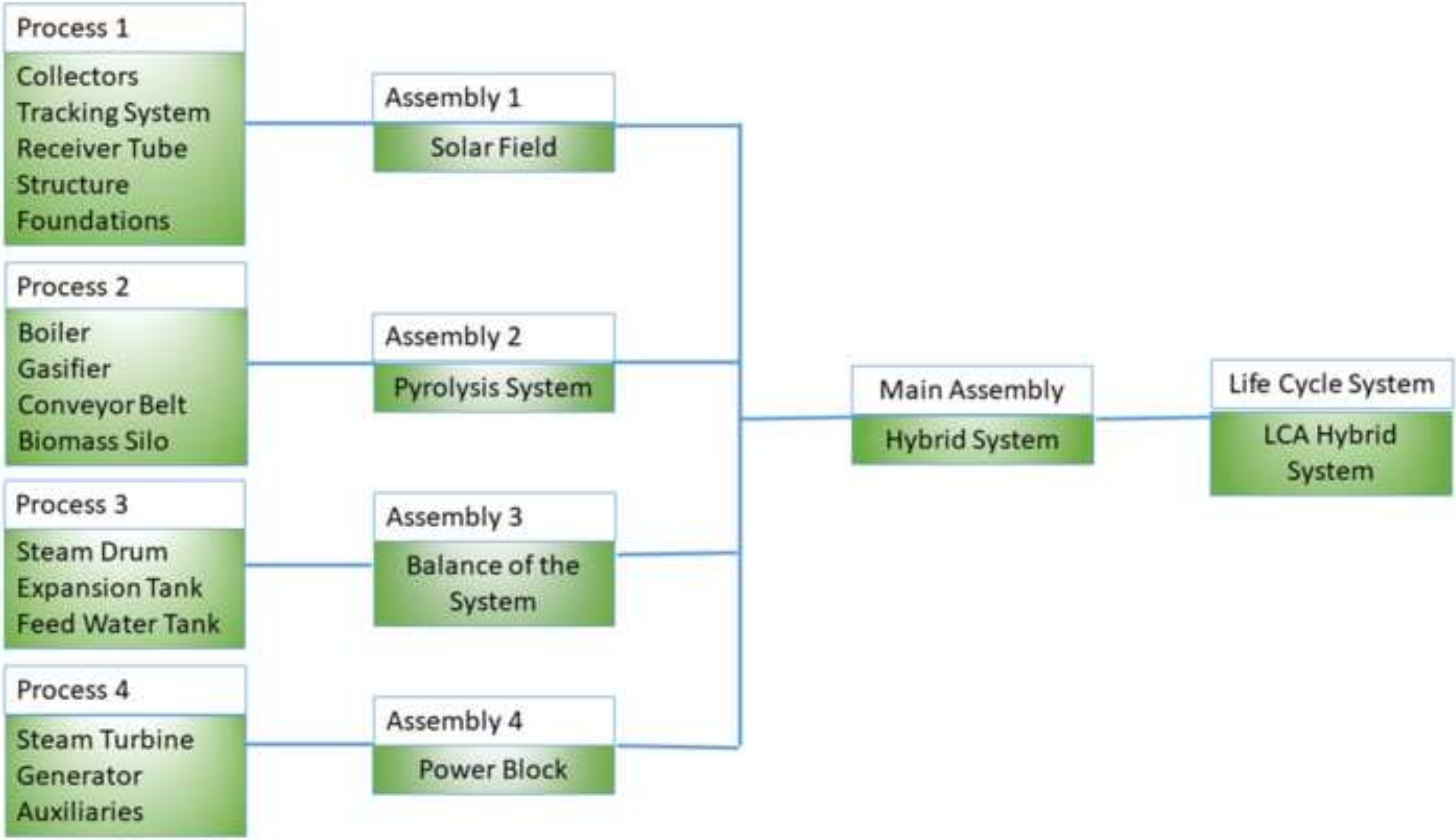
Table A5. End of life scenario

Item	Value	Unit
Landfill	15	km
Solar field	80.48	ton
Power block	3.48	ton
Biogas system	4.74	ton
Balance of the system	4.47	ton

Source: own elaboration.


EVAP
Steam Drum
SH
Boiler
PB


Cycle electrical efficiency = 22%
P 40.0 bar
H 3100 kJ/kg
T 350 C
M 1.77 kg/s
Turbine
1 MW
HP
LP
G
Generator
Condenser
Deaerator
P 3.10 bar
H 566 kJ/kg
T 135 C
M 1.77 kg/s


Process 1
Collectors
Tracking System
Receiver Tube
Structure
Foundations
Process 2
Boiler
Gasifier
Conveyor Belt
Biomass Silo
Process 3
Steam Drum
Expansion Tank
Feed Water Tank
Process 4
Steam Turbine
Generator
Auxiliaries
Assembly 1
Solar Field
Assembly 2
Pyrolysis System
Assembly 3
Balance of the System
Assembly 4
Power Block
Main Assembly
Hybrid System
Life Cycle System
LCA Hybrid System

Figure

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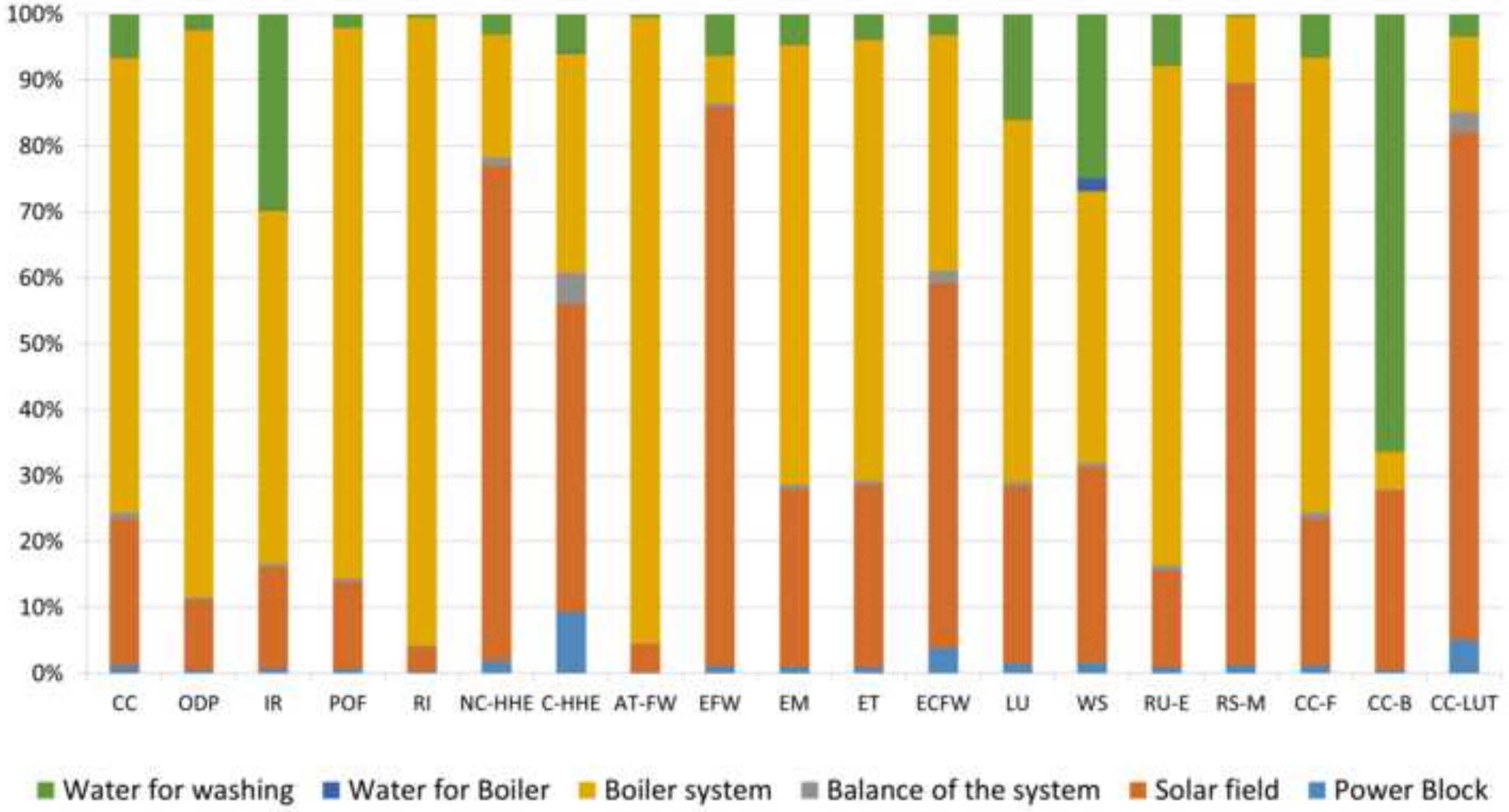

Figure

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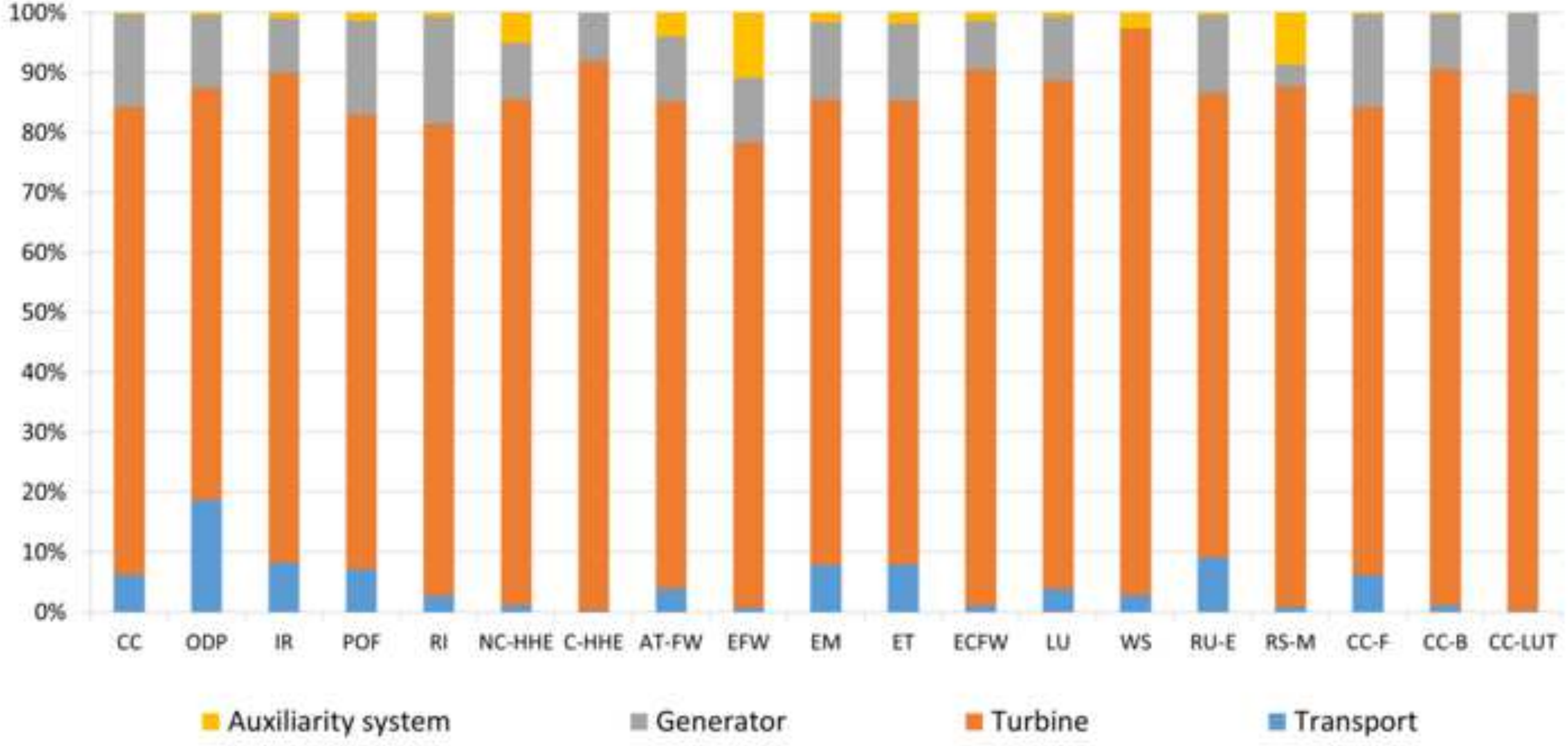

Figure

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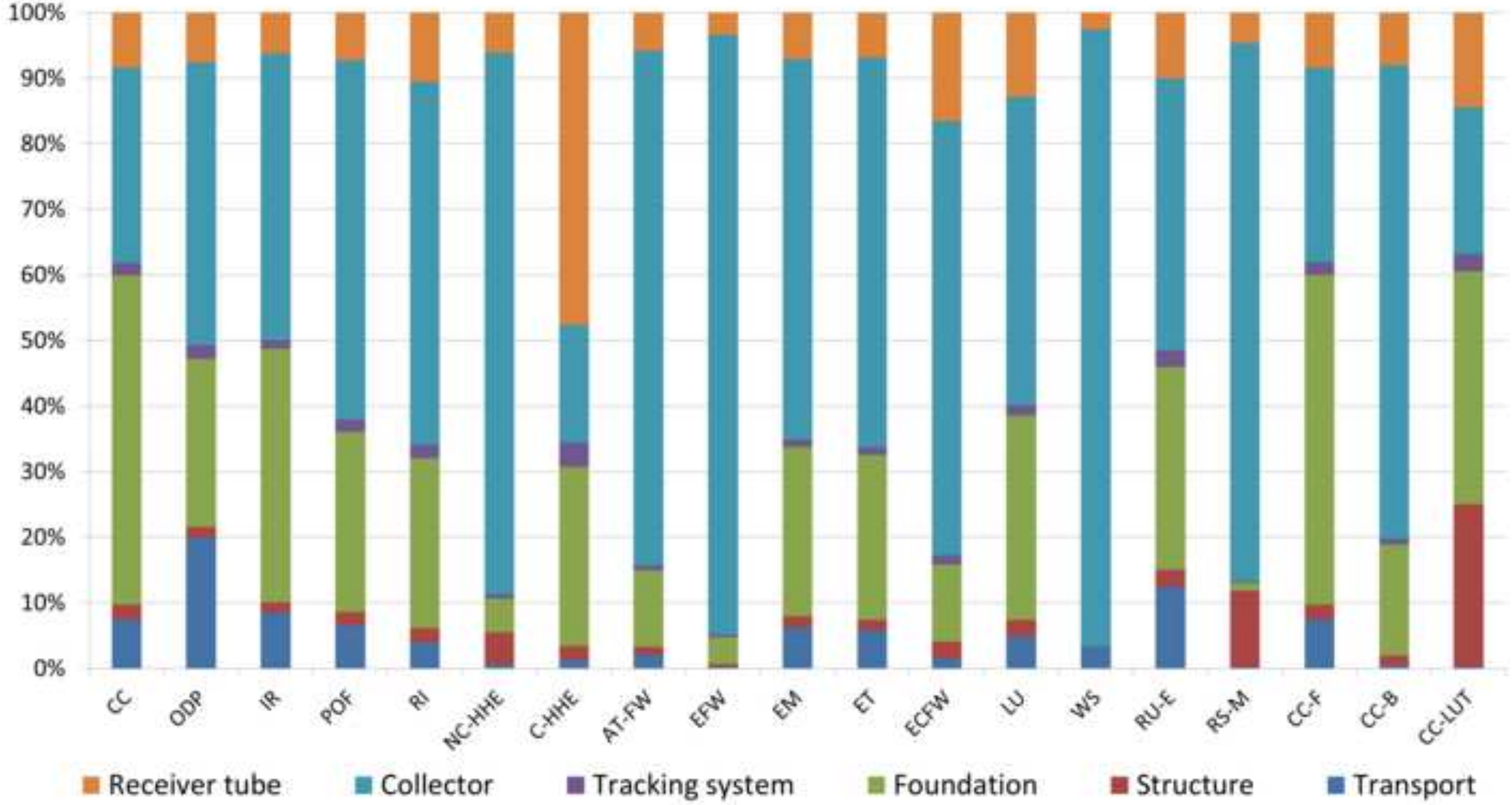
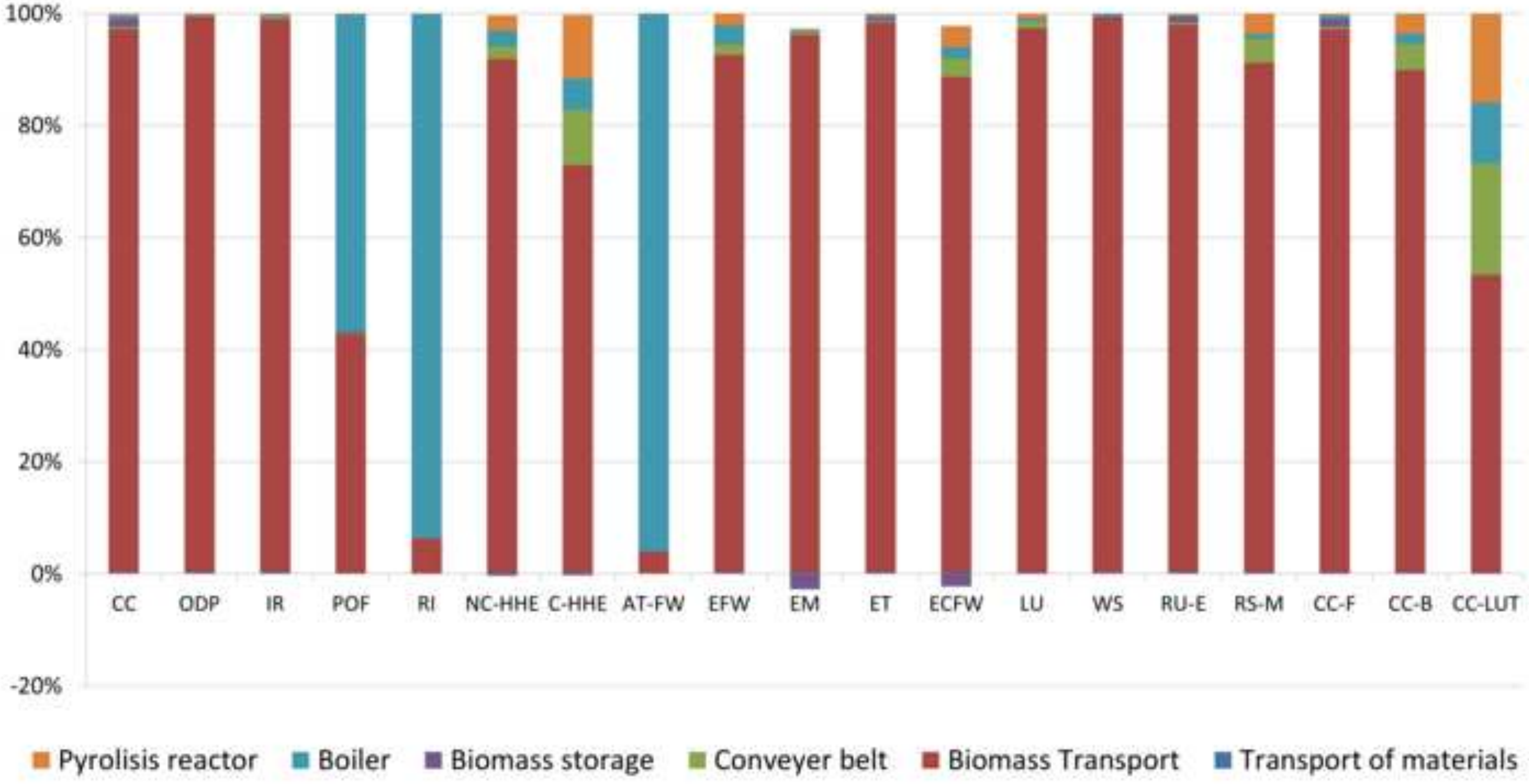
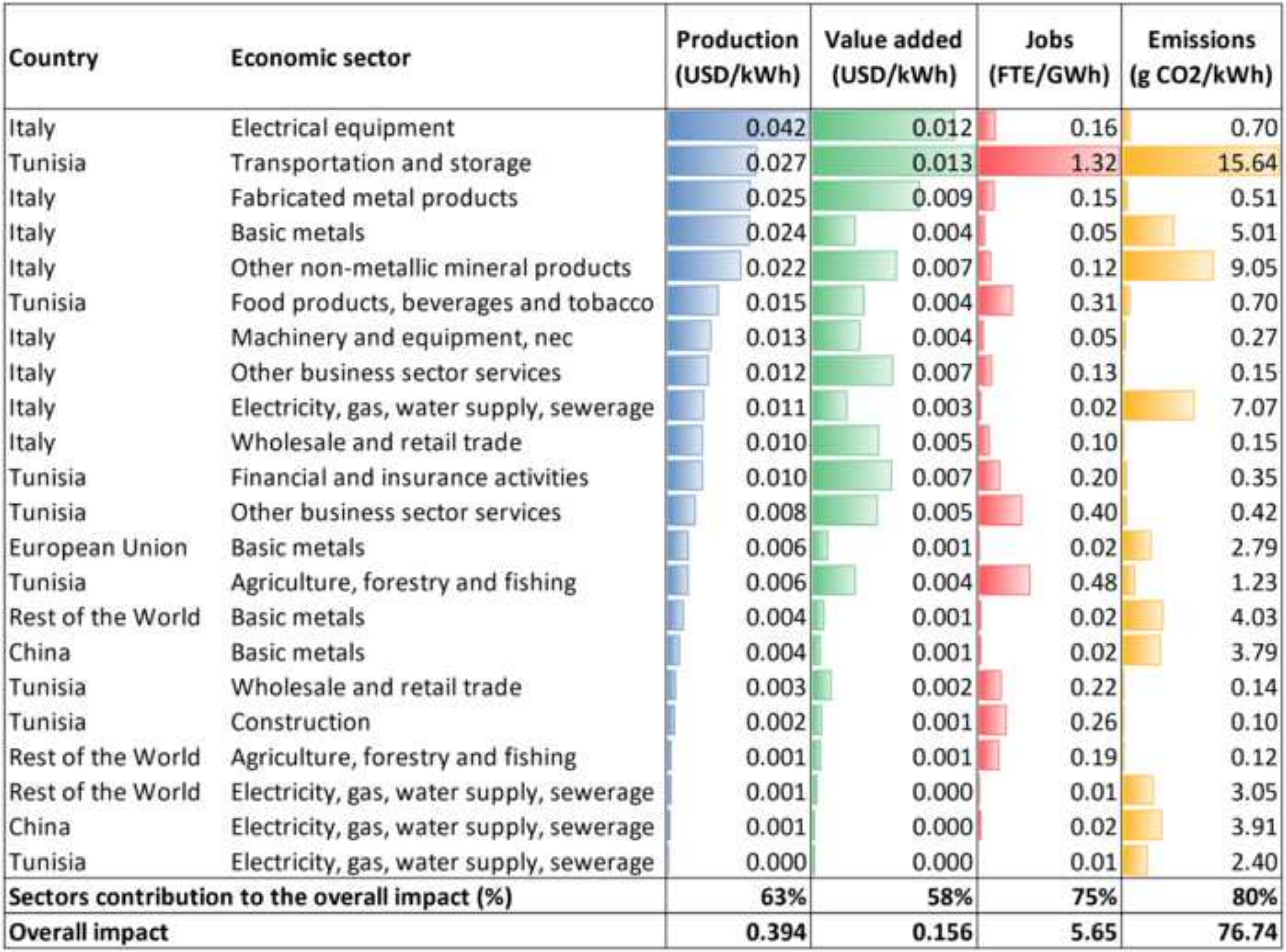


Figure


100%
80%
60%
40%
20%
0%
-20%
CC
ODP
IR
POF
RI
NC-HHE
C-HHE
AT-FW
EFW
EM
ET
ECFW
LU
WS
RU-E
RS-M
CC-F
CC-B
CC-LUT
Pyrolisis reactor
Boiler
Biomass storage
Conveyer belt
Biomass Transport
Transport of materials



Country	Economic sector	Production (USD/kWh)	Value added (USD/kWh)	Jobs (FTE/GWh)	Emissions (g CO2/kWh)
Italy	Electrical equipment	0.042	0.012	0.16	0.70
Tunisia	Transportation and storage	0.027	0.013	1.32	15.64
Italy	Fabricated metal products	0.025	0.009	0.15	0.51
Italy	Basic metals	0.024	0.004	0.05	5.01
Italy	Other non-metallic mineral products	0.022	0.007	0.12	9.05
Tunisia	Food products, beverages and tobacco	0.015	0.004	0.31	0.70
Italy	Machinery and equipment, nec	0.013	0.004	0.05	0.27
Italy	Other business sector services	0.012	0.007	0.13	0.15
Italy	Electricity, gas, water supply, sewerage	0.011	0.003	0.02	7.07
Italy	Wholesale and retail trade	0.010	0.005	0.10	0.15
Tunisia	Financial and insurance activities	0.010	0.007	0.20	0.35
Tunisia	Other business sector services	0.008	0.005	0.40	0.42
European Union	Basic metals	0.006	0.001	0.02	2.79
Tunisia	Agriculture, forestry and fishing	0.006	0.004	0.48	1.23
Rest of the World	Basic metals	0.004	0.001	0.02	4.03
China	Basic metals	0.004	0.001	0.02	3.79
Tunisia	Wholesale and retail trade	0.003	0.002	0.22	0.14
Tunisia	Construction	0.002	0.001	0.26	0.10
Rest of the World	Agriculture, forestry and fishing	0.001	0.001	0.19	0.12
Rest of the World	Electricity, gas, water supply, sewerage	0.001	0.000	0.01	3.05
China	Electricity, gas, water supply, sewerage	0.001	0.000	0.02	3.91
Tunisia	Electricity, gas, water supply, sewerage	0.000	0.000	0.01	2.40
Sectors contribution to the overall impact (%)		**63%**	**58%**	**75%**	**80%**
Overall impact		**0.394**	**0.156**	**5.65**	**76.74**

Figure

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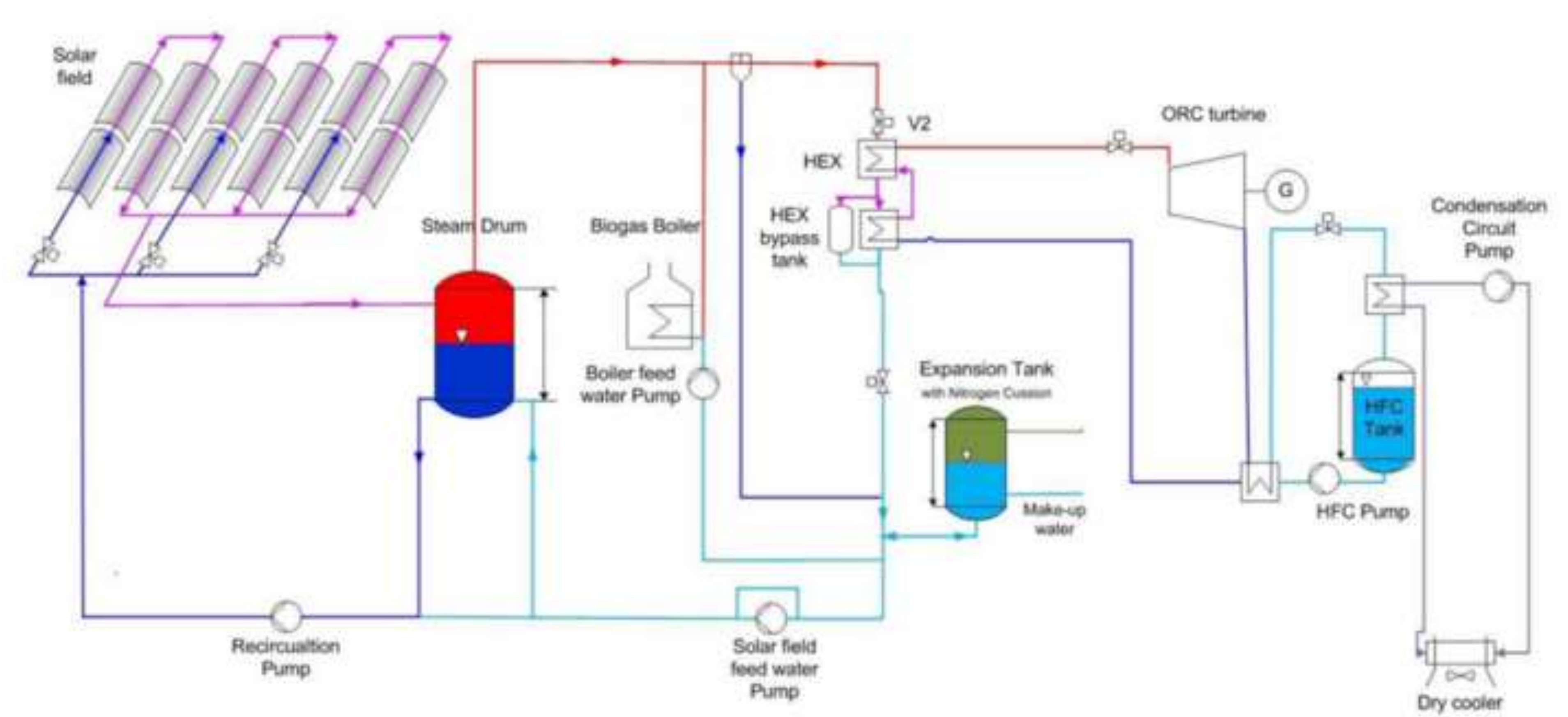

Figure

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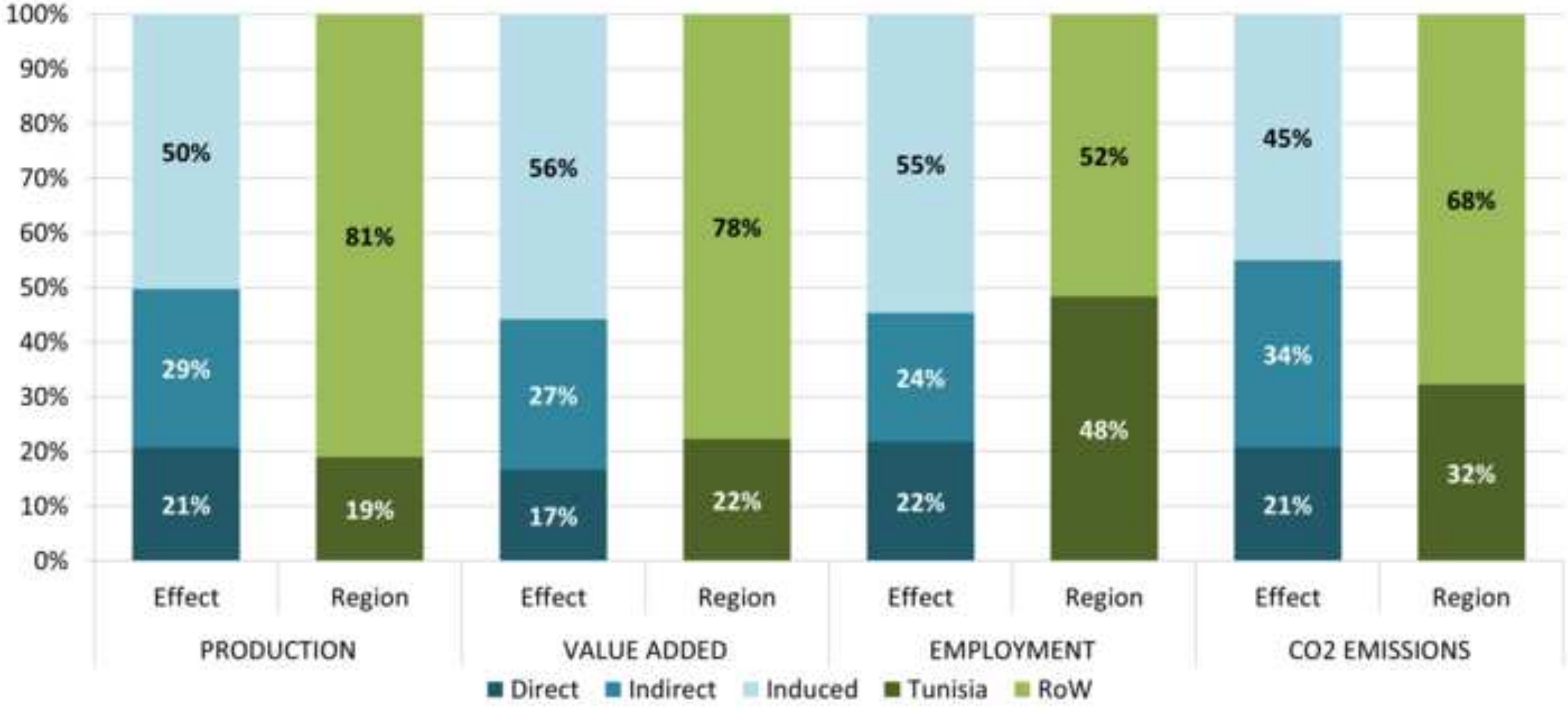

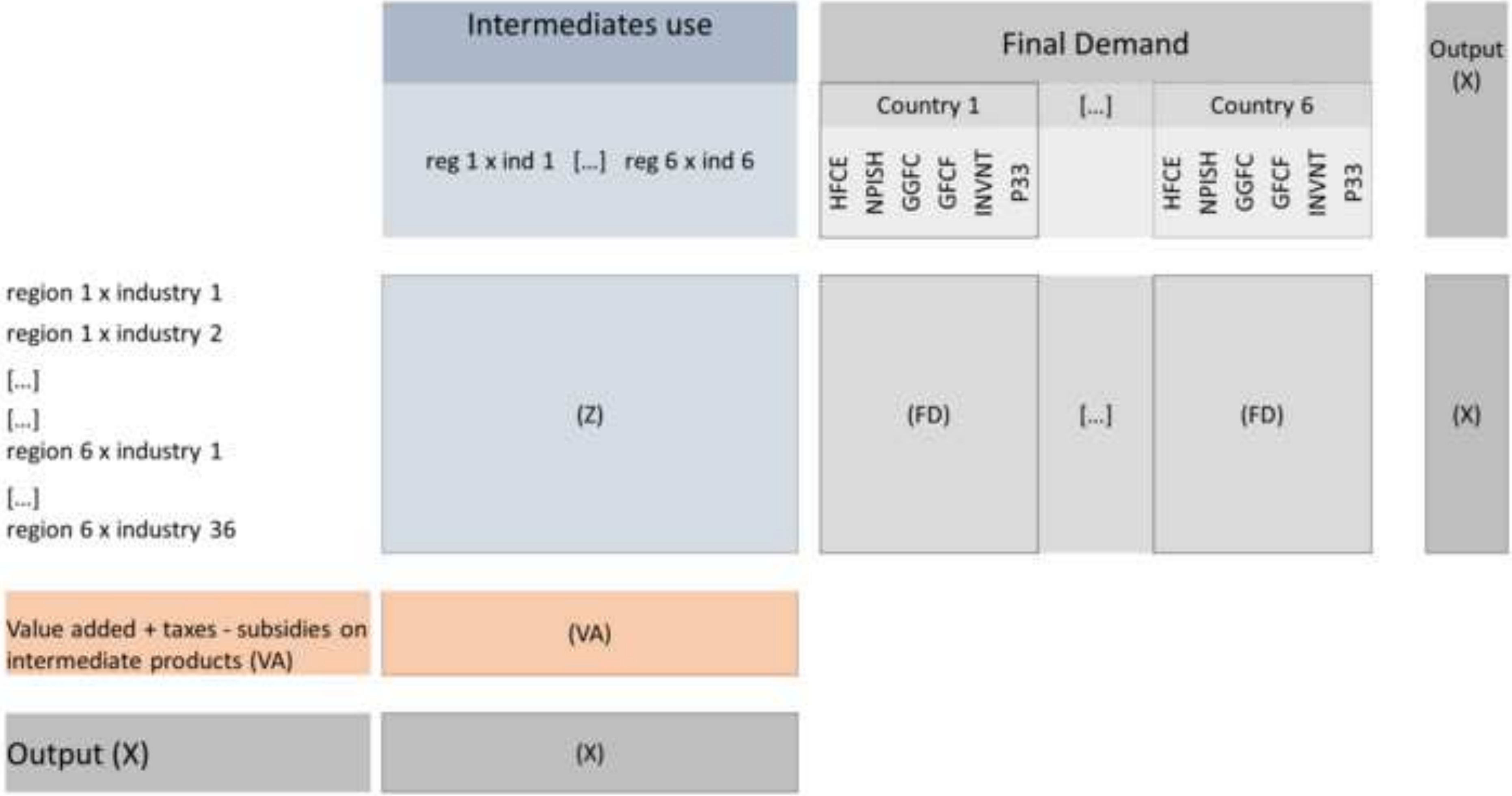
Intermediates use
reg 1 x ind 1 [...] reg 6 x ind 6
Final Demand
Country 1
[...]
Country 6
HFCE
NPISH
GGFC
GFCF
INVNT
P33
HFCE
NPISH
GGFC
GFCF
INVNT
P33
Output (X)
region 1 x industry 1
region 1 x industry 2
[...]
[...]
region 6 x industry 1
[...]
region 6 x industry 36
(Z)
(FD)
[...]
(FD)
(X)
Value added + taxes - subsidies on intermediate products (VA)
(VA)
Output (X)
(X)

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

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Respected Editor,

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- This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.
- The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

If you have any questions or concerns do not hesitate to contact us through the corresponding author in the information presented below.

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