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Socio-economic and environmental effects of concentrated solar power in Spain: A multiregional input output analysis

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ABSTRACT

Concentrated Solar Power (CSP) is receiving increasing attention as a technology with the potential to provide clean electricity in a cost effective and dispatchable manner. Despite its renewable nature, solar power generation generates impacts that need to be adequately evaluated and managed. The objective of this paper is to estimate the socioeconomic and environmental life cycle impacts of the production of electricity by a commercial CSP plant using Multiregional Input Output Analysis.

These effects have been estimated in terms of additional economic activity, value added, employment creation, climate change, acidification, photochemical oxidant formation and primary energy consumption. Additionally, the economic sectors and countries with higher effects in the value chain have been identified. The results are presented both in gross and net terms, including not only the effects of the system's life cycle, but also the avoided effects derived from the displacement of other technologies in the Spanish electricity market. The effects of the displaced electricity have been calculated by estimating the Levelized Cost Of Energy of the mix of marginal technologies displaced by the CSP plant. The results indicate that producing electricity in a CSP plant and selling it into the Spanish electricity market results in net positive impacts on the economy, the employment and the environment both at a national and global scale. Taking into consideration the electricity technologies displaced by the CSP plant, the socioeconomic net effects amount to 167 €/MWh of goods and services generated, 87.9 €/MWh of value added and 4.67 h/MWh of employment creation. The global and net environmental impacts on climate change, photochemical oxidant formation, acidification and primary energy consumption amount to −188 kg eq CO_2/MWh, 8 g eq NMVOC/MWh, −389 g eq SO_2/MWh and −4169 MJ/MWh, respectively, implying a net prevention of pollutant emissions and primary energy consumption.

1. Introduction

Global energy consumption has been growing exponentially since the Industrial Revolution [1]. Over 80% of this demand is currently met by fossil fuels, a situation that is starting to show not only the severe detrimental consequences to the global environment and the instability of the existing economic model but it also puts at risk the living standards of future generations. In an attempt to change this trend, governments worldwide are implementing policies intended to promote the use of locally available renewable energy resources [2,3]. One of the technologies receiving increasing scientific and commercial attention is Concentrating Solar Power (CSP) [4]. CSP plants use mirrors or lenses to generate heat from concentrated solar radiation, which is subsequently employed to drive a thermodynamic cycle (usually Rankine) for power generation. The deployment of this technology has been very rapid during the last decade primarily in Spain (2304 MWe installed capacity in 2015) and the USA (approximately 1730 MWe in 2015), due to a favourable regulatory framework. New plants are also under construction or under consideration in other countries with good solar resources like India, China, Chile, Australia, South Africa and MENA (Middle East and North Africa) region [5,6].

Regardless of their renewable nature, the collection, transformation and use of energy resources generate impacts on our environment. Hence, estimating the sustainability of alternative technologies for power generation is of paramount importance. Different methodologies are applied to achieve this goal, ranging from Life Cycle Assessment (LCA) (including environmental LCA, social LCA and Life Cycle Costing) to economic tools such as Cost Benefit Analysis, Input Output Analysis and Levelized Cost Of Energy (LCOE) calculation [7]. Most of these methodologies focus

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on only one or two dimensions of sustainability (environment, economy or/and society), lacking the capacity to provide a fully integrated perspective of the system. Although significant progress has been achieved in the field of Life Cycle Sustainability Assessment, a holistic methodology intended to cover the three dimensions of sustainability with a life cycle approach, many methodological issues are still unsolved and it remains a time-consuming methodology. In this context, Input Output (IO) Analysis, a methodology intended primarily to investigate the economic pillar of sustainability, may also be extended to calculate social and environmental indicators, considering the same inventory and assumptions in a cost-effective manner [8,9].

IO Analysis emerged originally as a response to international efforts aimed at describing and analysing the interdependence between the different sectors within an economy. While some economists had previously built economic tables pursuing this goal (such as François Quesnay in 1758 and Léon Walras a century later), it was Professor Wassily Leontief who was credited with the development of modern IO methodology at the end of the 1930s, for which he was awarded the Nobel Prize in economics in 1973 [10–12] . Since its inception in 1936, IO Analysis has been developed and extended to the point of including not only economic information, but also data about employment, social metrics, international exchanges, energy consumption and environmental pollution. Its capacity for analysis and economic planning has made IO Analysis a valuable tool used worldwide.

The symmetric IO table is used as the base for calculations in IO Analysis; it represents the relationship between production and consumption of goods and services corresponding to the different economic sectors/branches within one region or country. Globalisation of the world economy has led to increasingly separated supply chains where extraction of raw materials and manufacturing of components may take place in certain countries or regions of the world, while distribution and consumption of services/products take place in others. In this context of international supply chains, Multiregional IO (MRIO) modelling provides the opportunity to analyse the consequences under a global economy by including different regions or countries with different economic structures and their trading relationships within a single IO table [13].

As in the case of LCA, the results of an IO Analysis conducted with Life Cycle Thinking can describe gross effects or net effects depending on the scope of the study. The gross effects are the most commonly calculated, since they describe the relevant effects derived from the activities generated by the project or system under study. The gross approach is useful when identifying the most impacting processes and life cycle stages, or to calculate the life cycle footprints. Conversely, the net approach takes into account not only the system under study, but also the consequences that this system has on other systems' displacement when it is included into the market. The net calculation in IO Analysis is analogous to the consequential approach in LCA modelling, and it is useful to evaluate the impact of decisions, such as choosing between two products or whether promoting one technology instead of others. Despite the higher relevance and utility of this latter approach, researchers are less prone to apply this net approach in I/O analysis due to the uncertainty involved when data is not adequate and the complexity associated with the estimation of the displaced technologies.

This paper describes a case study in the application of Multiregional IO Analysis to calculate the gross and net economic, socioeconomic and environmental effects of a 50 MWe commercial CSP plant based on parabolic trough technology that sells electricity into the Spanish electricity market. The results obtained are the first ones to reveal not only the socio-economic effects of producing electricity in a CSP plant, but also the avoided effects that take place when substituting electricity generation with other sources.

The objectives of this study are as follows:

1. To calculate the gross effect of a commercial CSP plant on a series of socio-economic indicators including production of Goods and Services (G&S) (direct, indirect and induced), value added, multiplier effect and employment creation using Multiregional IO Analysis. These indicators will be obtained for Spain and the rest of the world.
2. To calculate the gross impact of the system on climate change, acidification, photochemical oxidant formation and energy consumption using the IO methodology.
3. To calculate the socio-economic and environmental effects (both national and global) of the CSP plant using a consequential approach, which takes into consideration avoided effects derived from displacing marginal technologies in the Spanish electricity market.

2. Methodology

2.1. System description

This case study is based on a commercial wet-cooled 50 MWe Concentrating Solar Power (CSP) plant based on parabolic trough technology and located in Ciudad Real (Spain). The CSP plant occupies 200 ha, has a life expectancy of 25 years and benefits from a Direct Normal Irradiation (DNI) of 2200 KWh/m^2 yr. The facility uses synthetic oil as Heat Transfer Fluid (HTF) and incorporates a 7.5 h Thermal Energy Storage (TES) system based on two-tank molten salt technology. Sixteen percent of the electricity generated is consumed onsite. The installation also consumes a fixed 550 MWh/yr from the grid and $6.80 \cdot 10^6$ MJ/yr of natural gas to enable essential start-up and maintenance operations. The plant generates 147821.5 MWh/yr of net power that is poured into the Spanish grid. The environmental impact of this CSP power plant was analysed previously by the authors using Life Cycle Assessment (LCA) methodology [14].

2.2. Multiregional input–output modelling

IO Analysis describes, through symmetric tables, the monetary relationships between activity sectors within a given economy [8,12].

The columns of the IO tables represent the monetary value of goods and services (inputs) from every sector required to produce the goods and services of one sector, while each row represents the distribution of goods and services production (outputs) of one sector to every sector of the economy.

The analysis is based on the A matrix, or technical coefficient matrix, which represents the monetary amount required from each sector to produce one monetary unit of products or services of every sector, according to Eq. (1)

$$X = (I - A)^{-1} Y \tag{1}$$

where X is the production of Goods and Services (G&S) measured in monetary units, $(I-A)^{-1}$ is the Leontief inverse matrix describing the direct and indirect requirements per unit of final demand, and Y is the required final demand.

The basis of the MRIO modelling used in this project is the World Input Output Database (WIOD) developed within the WIOD project funded by the European Commission [15]. WIOD is a public database that provides time-series of world IO tables for thirty five economic sectors of forty countries worldwide and a model for the rest-of-the-world, covering the period from 1995 to 2011. These tables are standardized according to the European System of Accounts 2010 [16] and have been constructed based on officially published IO tables together with national accounts and