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Life cycle assessment of a future central receiver solar power plant and autonomous operated heliostat concepts

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ABSTRACT

Up-scaling in power plant size and new innovative concepts in the solar field design are among the most promising ways to reduce the costs of future concentrated solar tower power plants. Besides the economic benefits, the knowledge about the ecological impacts of new concepts is of increased interest in view of the climate targets set.

This paper aims to assess the ecological impacts of two autonomous operated heliostat concepts within a future solar tower power plant. Both concepts include a photovoltaic (PV) energy supply for the heliostats, combined with either an $LiFPO_4$ or an LiNMC battery system. Both are compared with a conventional energy supply system. The analysis for comparing the different heliostat concepts is embedded in a life-cycle assessment (LCA) of a 440 MW solar tower plant with a 12,166 MWh_{th} molten salt thermal storage. For the solar tower power plant and the autonomous operated heliostat concepts new LCA inventories were developed. The environmental impacts assessed include the Global Warming Potential (GWP), which is found between 15 and 105 gCO_{2eq}/kWh_{el}, for the entire solar plant depending on the share of fossil fuel co-firing.

Indirect life cycle emissions excluding fossil fuel co-firing and thus associated with the life-cycle of the power plant components show, that the conventional solar field is the main contributor to GWP with 9.5 gCO_{2eq}/kWh_{el}. Results for both autonomous concepts demonstrate, that reductions in the impact on climate change are at about 10% compared to the solar field with conventional heliostats. Thus it is demonstrated, that heliostat concepts with an autonomous renewable energy supply lead to considerable reductions in life cycle emissions.

1. Introduction

The beneficial value of concentrated solar power (CSP) plants with storage lies in the provision of low carbon energy and the capacity to provide dispatchable electricity to the grid. By the end of 2016 approximately 5 GW of CSP were installed worldwide (NREL, 2016). Whereas the majority of the current CSP projects deployed are parabolic trough power plants (about 4.2 GW), an increase in the deployment of solar tower power plants (about 0.6 GW) is seen in the last years. The main efforts in the technological development of solar tower concepts are directed toward an improved efficiency while reducing the costs of electricity generated. Among the most promising measures for cost reduction the optimisation in heliostat size, the development of innovative solar field concepts, the improvement of central receiver designs or the introduction of large scale multi-tower concepts are identified (IEA, 2014; IRENA, 2013).

So far, in several studies the environmental impact of concentrated solar tower power plants was analysed. Lechón et al. (2008) assessed the environmental impacts of a 17 MW solar tower plant in the Spanish energy system. Weinrebe (2000) investigated the ecological impacts of the 30 MW PHOEBUS tower concept, which uses an open volumetric air receiver. Whitaker et al. (2013) performed an LCA on a 115 MW molten salt tower system with dry cooling system in south-western Arizona.

The aim of this study is to evaluate the environmental life cycle based impacts of a future large scale multi-tower power plant using an innovative concept for heliostat propulsion. Thus, this paper provides a quantitative assessment of two alternative concepts for heliostat fields, as the solar field is expected to hold further potential for material and cost reductions. Moreover, we have selected a solar tower plant with larger system components (with respect to the solar field size and molten salt storage) to address

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the currently pursued technology targets, aiming for cost reduction through up-scaling and higher capacity factors to provide firm renewable generation capacity (Bolinger and Seel, 2015; IEA, 2014; Mehos et al., 2016).

As heliostat fields contribute about 25% to 50% of investment costs of tower power plants, heliostat field optimisation and cost reduction is of paramount importance to make power towers economically viable (Coventry and Pye, 2013; Kelly et al., 2010; Kolb et al., 2007; Telsnig, 2015). However, the optimum size and design of the heliostat is still an area of intensive research and development.

The most widespread design today is the T-type glass-metal heliostat with an elevation-over-azimuth drive configuration (Mancini, 2000). Other concepts that have been realised are stretched membrane heliostats (Benz et al., 1989; Weinrebe et al., 1994) and, more recently, the axisymmetric pentagonal Stellio design, which has a different concentrator shape and an innovative axes arrangement (Balz, 2015). However, there is no general agreement on the most suitable heliostat design (see Fig. 1).

Regarding the optimum heliostat size, there is also no general agreement, as can be seen from Fig. 2. The figure shows that the reflector size of heliostats built until today have a wide range: Size ranges from below 1 m^2 to 200 m^2.

Studies on heliostat costs and their size dependency have been undertaken by (Blackmon, 2012), (Bhargav et al., 2013), (Pfahl, 2013) and (Kolb et al., 2007). Blackmon (2012) demonstrated a way to estimate the size dependent heliostat costs by classifying the costs in different categories – constant costs per unit area (e.g. costs of reflector panels), size dependent costs (e.g. structure costs), and fixed costs (e.g. controls). As stated in (Blackmon, 2012) it would be misleading to simply scale up the costs along with the shape of a heliostat. Therefore, a holistic method to identify the most cost efficient heliostat size in combination with a suitable support structure was developed by von Reeken et al. (2016). Thus, total costs were calculated for every size and design, since the effort for assembly, erection and maintenance depends on size and on the corresponding number of heliostats required for a given power capacity. From this literature the authors conclude, that the optimum heliostat size with conventional power supply through cabled connections lies in the range of 40 m^2 to 60 m^2. Nevertheless, in the current paper a heliostat size of 20 m^2 was chosen, as this is currently one of the most frequently used concept design (see Table 1). Moreover, the reduced reflector area and mass of the heliostat structure allows the use of standard battery systems for the power supply of the investigated autonomous solar heliostat concepts.

The common feature of current solar field design is that power supply and communication of heliostats are realised using cabled connections covering many square kilometres of the heliostat field. In view of increasing solar field sizes, wireless and autonomous energy supply concepts are becoming attractive to reduce both material demand and costs (Blackmon, 2013; Coventry and Pye, 2013; Kutscher, 2013; Pfahl, 2013).

One key feature of power towers is that heliostat field layout and receiver geometry (size and height above ground) are closely related. In order to be able to take a decision on the optimum heliostat field based on all key environmental aspects, this paper combines a technical analysis with a detailed life cycle assessment.

2. Methodology

2.1. Description of investigated solar tower power plant

The baseline for this investigation is a 440 MW_{el} solar tower plant concept with subcritical Rankine cycle, which was selected as a reference solar tower concept in a detailed cost study by Abengoa Solar on advanced thermal storage options for central receivers (Kelly et al., 2010). The plant uses a nitrate salt as heat transfer fluid in the receiver and as a thermal storage fluid in the storage system. Compared to actual concentrated solar tower plants, this future concept is characterized by an up-scaled receiver and solar field aperture area. This enlargement in the overall dimensions and power rating results in boundary conditions which make a single tower concept inefficient because the optical efficiencies of heliostats, which are located far away of the tower, would decrease. Therefore, the proposed concept includes two separate solar towers surrounded by two circular solar fields. The power block including the storage tanks is located outside the both heliostat fields.

The two separate collector fields are dimensioned with a total aperture area of 1,796,300 m^2 each. Kelly et al. (2010) calculated the net annual energy yield of the plant and the total auxiliary energy demand of the 'Abengoa 122′ heliostats with 1567 GWh_{el}/a and 7.9 GWh_{el}/a, respectively. For the purpose of this study, the heliostat reported in Kelly et al. (2010) is replaced by the LH 2.3 Brightsource heliostat to achieve results on the investigated autonomous heliostat concepts, which can be compared. The auxiliary energy demand for heliostat operation was calculated at 1.2 GWh_{el}/a. The heliostats concentrate the incoming irradiance onto the two receivers located at the top of the two towers at 260 m height. In this concept each receiver is designed for a thermal power capacity of 910 MW_{th} and uses a binary nitrate salt mixture (60% $NaNO_3$ and 40% KNO_3) to transfer the heat towards a Rankine cycle or a molten salt storage tank. The storage option of this concept plant consists of three pairs of molten salt storage

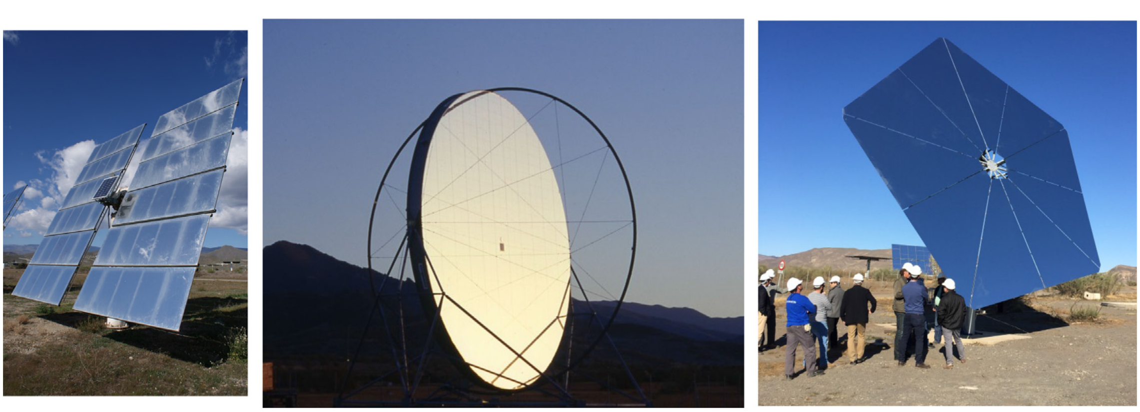

Fig. 1. Heliostat types: T-Type (left), ASM 150 stretched membrane (centre), Pentagonal slope drive 'Stellio' (right).