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Using the sun to decarbonize the power sector: The economic potential of photovoltaics and concentrating solar power ☆

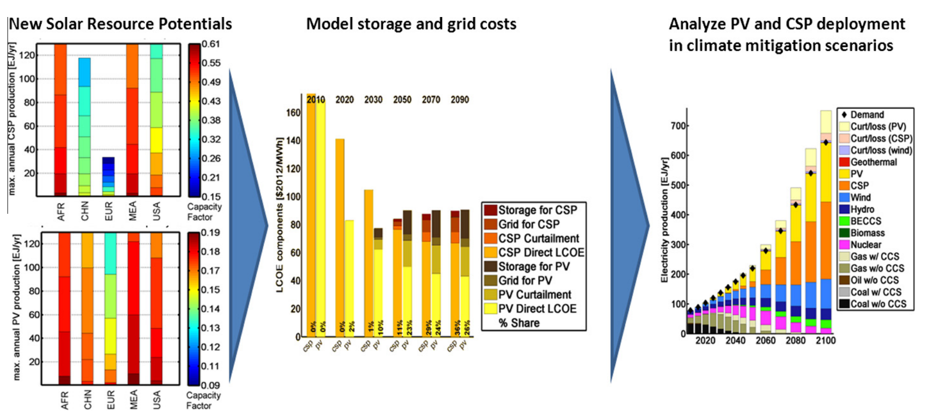
Robert Carl Pietzcker [a,*], Daniel Stetter [b], Susanne Manger [c], Gunnar Luderer [a]

[a] Potsdam Institute for Climate Impact Research, 14412 Potsdam, Germany
[b] DLR-German Aerospace Center, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany
[c] Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany

HIGHLIGHTS

- We calculate a consistent global resource potential dataset for PV and CSP.
- We develop a simplified representation of system integration costs of wind and solar.
- We analyze the economic potential of PV & CSP with the energy-economy-model REMIND.
- Solar power produces 48% of the cumulated 2010–2100 electricity in a 2 °C scenario.
- PV is deployed first, but CSP catches up due to lower system integration costs.

GRAPHICAL ABSTRACT



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ABSTRACT

Photovoltaics (PV) has recently undergone impressive growth and substantial cost decreases, while deployment for concentrating solar power (CSP) has been much slower. As the share of PV rises, the challenge of system integration will increase. This favors CSP, which can be combined with thermal storage and co-firing to reduce variability. It is thus an open question how important solar power will be for achieving climate mitigation targets, and which solar technology will be dominant in the long-term.

We address these questions with the state-of-the-art integrated energy-economy-climate model REMIND 1.5, which embodies an advanced representation of the most important drivers of solar deployment. We derive up-to-date values for current and future costs of solar technologies. We calculate a consistent global resource potential dataset for both CSP and PV, aggregated to country-level. We also present a simplified representation of system integration costs of variable renewable energies, suitable for large-scale energy-economy-models. Finally, we calculate a large number of scenarios and perform a sensitivity study to analyze how robust our results are towards future cost reductions of PV and CSP.

The results show that solar power becomes the dominant electricity source in a scenario limiting global warming to 2 °C, with PV and CSP together supplying 48% of total 2010–2100 electricity. Solar technologies have a stabilizing effect on electricity price: if both solar technologies are excluded in a climate policy scenario, electricity prices rise much higher than in the case with full technology availability. We also

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* Corresponding author. Present address: Potsdam Institute for Climate Impact Research, P.O. Box 60 12 03, D-14412 Potsdam, Germany. Tel.: +49 331 288 2404.
E-mail address: pietzcker@pik-potsdam.de (R.C. Pietzcker).

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analyze the competition between PV and CSP: PV is cheaper on a direct technology basis and is thus deployed earlier, but at high supply shares the PV integration costs become so high that CSP gains a competitive advantage and is rapidly developed, eventually overtaking PV. Even in the most pessimistic scenario of our sensitivity study with no further cost reductions, CSP and PV still supply 19% of 2010–2100 electricity. We conclude that if a stringent climate target of 2 °C is to be met cost-efficiently, solar power will play a paramount role in the long-term transformation of the electricity system.

1. Introduction

In the last decade, photovoltaic (PV) has seen an unprecedented boom. Driven by feed-in tariffs in many countries, deployment both at residential and utility scale has risen at a remarkable pace, leading to a hundred-fold increase of the global PV market from 2000 to 2011 [1] and a cumulative capacity[1] of ~140 GW in 2013. Although silicon shortages lead to temporary price increases between 2005 and 2010 [2,3], PV has seen continual price decreases over the last 40 years, resulting in a price drop by more than 85% in the last 25 years [4]. In contrast, concentrating solar thermal power (CSP) has seen a much slower growth. After the construction of the 354 MW SEGS plants from 1981–1991, commercial deployment only restarted in 2007, leading to a 2012 global capacity estimated at 2.5 GW [5].

During the same period, climate mitigation has become an increasingly prominent item on the international agenda, with the goal of limiting global warming below 2 °C above pre-industrial temperatures. Achieving this goal requires a fundamental restructuring of the global energy system, with most studies pointing to the electricity sector as the first mover [6–11]. A large number of technologies potentially allow to produce low-carbon electricity, but most of them face technical, economical or societal risks that may slow or hinder a substantial scale-up – be it public opposition to CCS and nuclear power, limited resource potential to expand hydropower, sustainability issues and competition from the transport sector for biomass, or noise and nature conservation concerns about wind power.

Given these developments and the restrictions on other low-carbon power sources, two questions come to mind: What is the role of solar power for decarbonizing the electricity sector? And second: Have the impressive reductions of PV capital costs decided the competition between PV and CSP in favor of PV, or might CSP see resurgence and become more important in the future?

This study sets out to answer these questions with the help of the global, long-term energy-economy-climate model REMIND. Since this requires up-to-date knowledge about technology costs and resource potentials, as well as a representation of the relevant integration challenges, we augmented the model in several aspects. First, we develop a novel approach for including integration costs associated with both temporal variability and spatial heterogeneity of variable renewable energies (VRE) into large-scale energy-economy models. Second, we derive updated technology costs and learning parameters based on a comprehensive survey of the techno-economic literature on both technologies. Finally, we also develop a new and consistent global data set of resource potential data for PV and CSP.

Using the augmented model, we perform a large number of scenario runs to investigate the deployment of solar power under various cost assumptions and to determine the relevance of solar technologies for the power sector. For a deeper understanding of the role of solar technologies, we analyze several metrics, namely amount of electricity production, influence on electricity price, levelized costs of electricity (LCOE) and share in total cumulated electricity production.

There have been numerous studies analyzing the importance of solar technologies that have either focused exclusively on CSP [12–14] or PV [16,17]. Other studies have performed a comparison purely based on LCOE analysis [18–21], or have limited their analysis to only one region [22–26], and most of the studies have not explicitly looked at scenarios without climate policy.

Our study improves the understanding of the economic potential of solar power along several dimensions. Firstly, REMIND calculates inter-temporal optimal technology investment paths, taking into account all costs for investment, fuel, and emissions of the complete technology portfolio. The model fully accounts for endogenous technological learning, thus the competition for capital between the two technologies is captured within the model. While some energy-economy models include both solar technologies, they usually do not model the competition for installation sites with high solar irradiation. Finally, an important characteristic differentiating PV and CSP is the possibility of CSP to use thermal storage and co-firing of gas or hydrogen, thus capable of providing both dispatchability and firm capacity and thereby reducing the need for additional electricity storage. For a sensible analysis, a model needs to internalize this crucial difference between the integration challenges for PV and CSP, as was implemented in REMIND.

The paper proceeds as follows: We start by discussing the basic design setup in Section 2, including a description of the REMIND model and the scenario design. In Section 3, an approach for representing integration costs of variable renewable energies in large-scale energy-economic models is presented. In Section 4, current and future costs for PV and CSP are derived, while a consistent resource potential dataset for PV and CSP is calculated in Section 5. Section 6 presents and analyzes the REMIND scenario results, while Section 7 concludes.

2. Study design

In this section, we present the building blocks that we need to analyze the role of solar technologies for the decarbonization of the power sector. We start with a brief technology description to acquaint the reader with the relevant characteristics of PV and CSP, and then sketch the main features of the REMIND model that was used to explore future energy systems. We describe the scenario groups that we employ to understand the effects of solar power on the energy system and to analyze the robustness of the results. Finally, we discuss the calculation of a metric relevant for the analysis, namely levelized cost of electricity.

2.1. Solar power technology description

Solar energy can be converted directly into electricity using PV, or indirectly using thermal CSP plants. In the following we briefly describe the main characteristics of these two classes of solar

[1] "Cumulative capacity" is the sum over all capacity that was ever installed – thus cumulative capacity increases monotonously, while capacity can increase or decrease over time, as capacities are newly built or retired.