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Shedding light on solar technologies—A techno-economic assessment and its policy implications

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A B S T R A C T

Solar power technologies will have to become a major pillar in the world's future energy system to combat climate change and resource depletion. However, it is unclear which solar technology is and will prove most viable. Therefore, a comprehensive comparative assessment of solar technologies along the key quantitative and qualitative competitiveness criteria is needed. Based on a literature review and detailed techno-economic modeling for 2010 and 2020 in five locations, we provide such an assessment for the three currently leading large-scale solar technologies. We show that today these technologies cannot yet compete with conventional forms of power generation but approach competitiveness around 2020 in favorable locations. Furthermore, from a global perspective we find that none of the solar technologies emerges as a clear winner and that cost of storing energy differs by technology and can change the order of competitiveness in some instances. Importantly, the competitiveness of the different technologies varies considerably across locations due to differences in, e.g., solar resource and discount rates. Based on this analysis, we discuss policy implications with regard to fostering the diffusion of solar technologies while increasing the efficiency of policy support through an adequate geographical allocation of solar technologies.

1. Introduction

Society is facing serious problems such as climate change, resource depletion, and pollution. To meet these challenges a "technology revolution" (Galiana and Green, 2009) in the field of clean energy technologies is required in order to decouple economic growth from adverse environmental impacts. Solar power has the potential to become a protagonist in this "revolution". According to forecasts of the International Energy Agency, solar technology could contribute 20% to global electricity generation in 2050 (IEA, 2010a). However, in 2010 the share of solar power has been well below 0.5% as the cost of solar technologies cannot yet compete with other forms of electricity generation. Significant innovations in solar power technologies are a prerequisite to unlocking the enormous potential of solar energy. A wide set of solar technologies is available in the field of photovoltaics (PV) and concentrating solar power (CSP) with differing performance characteristics.

Which technology is and will prove most viable in our electricity systems is heavily contested among scholars and industry experts (Fthenakis et al., 2009; PricewaterhouseCoopers, 2010). While the competitiveness of solar power generation differs by technology, time and location the extant literature lacks a holistic assessment of solar power based on these three dimensions. Integrating existing studies into one overall picture is not possible since they rely on a variety of methods and mostly inconsistent assumptions. Hence, there is a clear need to holistically and accurately assess key solar technologies on a common basis to guide users, investors, technology providers and policymakers in terms of investment and policy funding. In this paper we concentrate on recommendations for future policymaking as policy is likely to be the single most important lever to lead solar power towards competitiveness.

In order to provide a sound basis for our policy discussion (see Section 6), this paper, therefore, focuses on the following research question: What is the competitiveness of leading solar technologies depending on time and location? Building on Tushman and Rosenkopf (1992), we assess solar technologies based on their key merit dimensions. While the levelized cost of generating and storing electricity (LCOE) is undisputedly the most important dimension of merit, qualitative aspects of solar technologies also impact their overall competitiveness. Therefore, we will focus more specifically on the following four sub research questions:

(1) In 2010, how do PV and CSP technologies compare in terms of LCOE?
(2) In 2020, how will PV and CSP technologies compare in terms of LCOE?

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(3) How do 2010 and 2020 LCOE of PV and CSP technologies change depending on local financing and weather conditions in present and future leading solar markets?
(4) How do PV and CSP technologies compare along qualitative merit dimensions?

Methodologically, we construct a LCOE model, which is capable of quantifying the generation as well as the storage cost of PV and CSP electricity. To assure accuracy we choose a high degree of granularity in the input data. For projections we use a combination of bottom-up and top-down estimates (Neij, 2008). The qualitative evaluation of the remaining merit dimensions is conducted based on an extensive literature review and expert interviews.

This paper is structured as follows: In the subsequent section, we provide a short overview of solar technologies and markets. In Section 3 the existing literature on techno-economic assessments of solar power technologies is reviewed. We describe the method and assumptions used in Section 4. Based on the results, presented in Section 5, we derive policy recommendations in Section 6 before concluding in Section 7.

2. An overview of solar technologies and markets

Solar power technologies can be divided into two main classes: photovoltaics (PV) and concentrating solar power (CSP). PV exploits the photovoltaic effect exhibited by semiconductors and thus directly converts solar irradiation into electricity. CSP systems use mirrors to focus sunlight onto a receiver in which a fluid (e.g., thermo oil or molten salt) is heated up to several hundred degrees Celsius. In a heat engine (e.g., a steam turbine) this thermal energy is then converted into electricity (Jacobson, 2009).

2.1. Photovoltaics

Since the patenting of the first solar cell in 1954 two principal types of PV technologies have emerged: wafer based crystalline silicon (c-Si) and thin film. While the former typically had market shares of 80–90% in previous years, recently thin film technologies have been gaining ground. Even though the efficiencies of thin film modules are poorer, their cost per watt is lower due to less material usage (Bagnall and Boreland, 2008). In particular, cadmium telluride (CdTe) based modules have been successful lately due to their low cost position. Their market share increased from 1% in 2005 to 9% in 2009 (Photon, 2010). Other commercial thin film technologies such as copper indium gallium selenide (CIGS) and thin film silicon also increased their market shares in recent years. Dye sensitized (Graetzel, 2001) and organic solar cells (Brabec and Sariciftci, 2001) have developed quickly. However, these technologies are still in a pre-commercial phase (Photon, 2010). In addition, in the coming decades, so called third generation photovoltaics have the potential to lower the levelized cost of electricity by combining thin film approaches with high efficiency concepts (Green, 2006).

Although annual PV capacity additions have grown, on average, with more than 40% since 2000 (EPIA, 2010a), it is still at a very low level compared to globally installed power plant capacity (Fig. 1). Driven by an attractive feed-in tariff scheme effective since 2000, Germany has gained a 42% share in installed PV capacity while only accounting for 3% of globally installed power plant capacity (Fig. 1). Following the German example, other European countries have also introduced PV feed-in tariffs incentivizing capacity additions. In the past, PV policy support was rather limited outside of Europe resulting in a low non-European share of the world market. However, PV policy support is currently expanding globally which will lead to an increasing share of non-European PV markets—particularly in China and the US (EPIA, 2010a, 2010b).

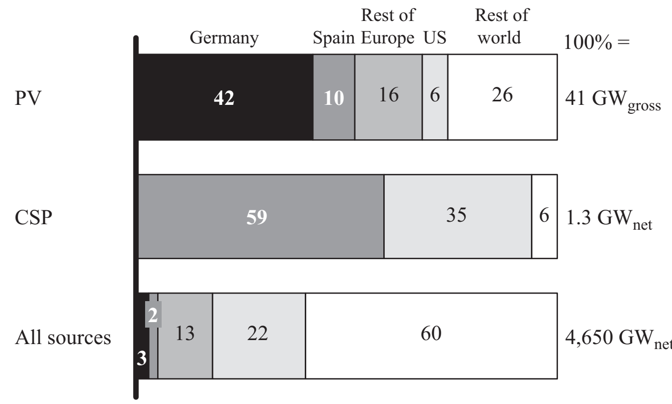

Fig. 1. Share of globally installed capacity in 2010 by countries/regions, in percent; Source: Energy Information Administration (2010), EPIA (2010a), Emerging Energy Research (2010) and Solarbuzz (2011).

In contrast to the market for PV installations, the production of solar cells – the key component of PV plants – mainly occurs outside of Europe. In recent years Asia has emerged as the major production hub for solar cells, accounting for more than ~60% of global production in 2009 (Photon 2010). Amongst other factors, this has been driven by favorable energy and labor costs as well as deep expertise in semiconductor technology. The majority of innovative activity in the field of PV technology has also occurred outside of Europe in recent years, with US, Japanese and Chinese inventors accounting for more than 50% of international patent families (Peters et al., 2011). While it was chiefly large technology providers (like Siemens) and energy companies (such as Shell and BP), which were the first to establish industrial scale production lines in the field of PV, at present the leading PV technology providers are mainly pure-play firms (e.g., First Solar, Suntech Power, SMA). Only in Japan have industry conglomerates such as Sharp or Sanyo been investing in PV technology for several decades.

2.2. Concentrating solar power

In the 1980s the first industrial scale CSP systems were built in the Mojave Desert using the parabolic trough design, which has remained the incumbent CSP design with market shares above 90% until today (CSP Today, 2010). However, three alternative CSP designs exist: tower, linear fresnel and dish engine. In a CSP tower, plant heliostats concentrate irradiation on one single receiver atop a tower. Due to the central receiver such systems benefit from higher steam cycle temperatures and lower energy transport requirements than parabolic trough plants. Yet land requirements are significantly higher (Kaltschmitt et al., 2007). CSP plants using fresnel reflectors focus sunlight on an elevated linear receiver. Compared to a parabolic trough plant, linear fresnel systems exhibit lower costs for reflectors and structural support at the expense of lower solar-to-electric efficiencies (Purohit and Purohit, 2010). Dish engine systems consist of large mirror dishes and a receiver integrated with a combustion engine (e.g., a sterling engine) at the focal point of the dish. While dish engine systems are the most modular CSP design, investment cost and land use are high (Trieb, 2009).

As of 2010 1.3 GW of CSP capacity had been installed worldwide—significantly less than in PV (Fig. 1). The majority of CSP capacity is installed in Spain, due to a favorable feed-in tariff (REN21, 2010) . However, future capacity additions are very likely to occur mainly outside of Europe since other geographies benefit from more favorable irradiation conditions and since Spain has