Energy Economics 38 (2013) 186–203

Contents lists available at SciVerse ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

An assessment of the optimal timing and size of investments in concentrated solar power

Emanuele Massetti [a,b,c,*], Elena Claire Ricci [b,c,d]

[a] *Yale University, United States*
[b] *Fondazione Eni Enrico Mattei, Italy*
[c] *CMCC, Italy*
[d] *University of Milan, Italy*

ARTICLE INFO

Article history:
Received 13 September 2011
Received in revised form 17 February 2013
Accepted 18 February 2013
Available online 26 February 2013

JEL classification:
Q2
Q43
Q54

Keywords:
Climate policy
Integrated assessment
Renewable energy
Concentrated solar power
Super-grids
Electricity trade

ABSTRACT

We extend the WITCH model to consider the possibility to produce and trade electricity generated by large-scale concentrated solar power plants (CSP) in highly productive areas that are connected to demand centers through High Voltage Direct Current cables. We test the attractiveness of the CSP option by imposing a global cap on Greenhouse gases concentration equal to 535 ppm CO_2-eq in 2100, with and without constraints to the expansion of nuclear power and IGCC coal with carbon capture and storage (CCS). We find that it becomes optimal to produce with CSP from 2040 and to trade CSP electricity across the Mediterranean from 2050. Therefore projects like DESERTEC seem to be premature. After 2050, CSP electricity shares become significant. CSP has a high stabilization cost option value: depending on the constraints, it ranges between 2.1% and 4.1% of discounted GDP in the Middle East and North Africa (MENA), between 1.1. and 3.4 in China, between 0.2% and 1.2% in the USA, between 0.1 and 1.3% in Eastern Europe and between 0.1 and 0.4% in Western Europe. A moderate level of subsidy to invest more and earlier in CSP might increase welfare. However, large-scale deployment should occur after 2040. We also show that MENA countries have the incentive to form a cartel to sell electricity to Europe at a price higher than the marginal cost. This suggests that a hypothetical Mediterranean market for electricity should be carefully regulated.

1. Introduction

This study assesses the role of concentrated solar power (CSP) as a technology option in long-term scenarios of climate change mitigation policy. The paper examines the economic attractiveness of CSP, the optimal timing and size of investments, how CSP affects the optimal mix of power sector technologies, and it carefully discusses the timing, size and institutional requirements of an electricity trade across the Mediterranean.

CSP is an attractive option in climate change mitigation scenarios because electricity is generated by means of solar radiation, an almost infinite energy source, with no direct emissions of CO_2 nor of other pollutants. Compared to other zero-carbon renewable resources, it has an advantage as in CSP plants' heat can be stored (up to fifteen hours) in order to generate a constant flow of electricity.

However, CSP needs direct solar beams (direct normal irradiance, DNI[1]) while photovoltaic also relies on horizontal irradiation. Therefore, one of the most critical issues for CSP is the location of the power plants. The best sites for this power generating technology are found in dry regions near the equator – e.g. the Sahara Desert – which are typically far away from where electricity is consumed.[2] A large expansion of CSP thus requires the deployment of high-efficiency and high-capacity transmission cables that can cover long distances with minimal losses. High-voltage direct current (HVDC) cables – sometimes referred to as super-grids (SG) – have these characteristics and can be used to transmit electricity at very long distances, connecting supply of CSP in remote areas of the world to demand in dense urban and industrialized areas. The future of CSP and the development of future power grids are therefore strictly intertwined.

The possibility of using CSP to generate electricity with no CO_2 emissions and very low intermittency is clearly very attractive and explains the growing interest that surrounds this technology option. Researchers,

---

* Corresponding author at: Yale School of Forestry& Environmental Studies, 195 Prospect Street, New Haven, CT 06511, USA. Tel.: +1 203 436 5783.
E-mail address: emanuele.massetti@yale.edu (E. Massetti).

[1] Direct Normal Irradiation (DNI) is the amount of solar radiation received per unit area by a surface that is oriented perpendicular (or normal) to the sun rays. It is measured in kWh/m^2 over a period of time.

[2] A list of cities that are close to areas with high DNI is found in IEA (2011, p. 22).

0140-9883/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.eneco.2013.02.012

government agencies and environmental activists are supporting very ambitious deployment plans for CSP on both the sides of the Atlantic. For example, the Desertec project foresees a large number of CSP plants in Northern Africa connected to the European power network by means of a SG that stretches across the Mediterranean supplying up to 15% of the electricity consumed in Europe (Trieb and Müller-Steinhagen, 2007). The Mediterranean Solar Plan, sponsored by the Union for the Mediterranean, has the aim to set up a trade between the European Union (EU) and developing countries belonging to the newly established international organization by 2020, with electricity generated from 10 to 12 GW of installed capacity.[3] The U.S. Department of Energy (DOE) has ambitious plans for solar energy and CSP in particular. The objective is to make CSP competitive in the intermediate power market by 2015. By developing advanced technologies that will reduce system and storage costs, the goal is to make CSP competitive in the base-load power market by 2020 (US DOE, 2008).[4] Also the International Energy Agency (IEA) sees a bright future for CSP. In the CSP Technology Roadmap (IEA, 2010b), the IEA depicts a scenario that foresees 148 GW of capacity installed globally by 2020 to supply electricity for intermediate and peak loads. This requires a 200-fold expansion of the global installed capacity, equal to 0.7 GW at the beginning of 2009. 2300 new power plants the same size of the recently built “Nevada Solar One” plant need to start operating in less than ten years. According to the same scenario, in 2020 CSP technologies are expected to become competitive with coal-fired base-load power plants (IEA, 2010b). According to the IEA, Europe will finance the expansion of CSP in Northern Africa because of limited land availability and low DNI. Global installed capacity reaches 337 GW in 2020 and 1089 GW in 2050, supplying 11% of global electricity production. The only limit to further expansion is a constraint in supply before 2020 and a limit on exports to areas with high demand and low DNI between 2020 and 2050.

The scenario depicted by the IEA requires a level of effort that goes beyond the present prospects for CSP, as documented by Arvizu et al. (2011), which assesses the literature on CSP for the IPCC Special Report on Renewable Energy (SRREN). With heavy subsidies Spain has pre-registered plants for 2.3 GW; in the USA 4.5 GW are under power purchase agreement contracts to deliver electricity between 2010 and 2015. The global installed capacity of CSP is expected to be equal to 10 GW in 2015.

There are very few peer-reviewed studies that assess the role of CSP in future energy systems. Krey and Clarke (2011) use a large recent database of scenarios to assess the role of renewable energy in meeting future climate mitigation targets. This is the only study that shows the range of estimates for CSP electricity generation in 2020, 2030 and 2050. The limit of this study is that of reviewing scenarios with very different assumptions on technological availability, timing of climate policy and fossil fuels costs. It is therefore unclear if the range of estimates is driven by different model characteristics or by the assumptions on the scenarios. Moreover, Krey and Clarke (2011) do not present data on international trade of electricity.

To our knowledge, the only analysis of CSP and of SG in a sophisticated economic model is the paper by Bauer et al. (2008). The main focus of the study concerns the political barriers to the electricity trade between Europe and the Middle Eastern and North African region (MENA), with a focus on the impact on macroeconomic activity, sectoral output and trade relations.

Other studies in the literature are mainly policy analysis and scenario analysis (Jacobson and Delucchi, 2010; Patt et al., 2008; Trieb, 2006; Ummel and Wheeler, 2008; Williges et al., 2010).

With this article we contribute to the literature by assessing the incentives to invest in CSP in a systematic way using the integrated assessment model WITCH (World Induced Technical Change Hybrid – Bosetti et al., 2006, 2007a, 2007b, 2009; www.witchmodel.org).

We examine and disentangle the driving forces that create the incentive to invest in CSP and in SG with a regional detail. In particular, we evaluate how the incentive to invest in CSP changes when we limit the expansion of nuclear power and of Integrated Gasification Combined Cycle (IGCC) coal with carbon capture and storage (CCS). However, we do not limit our analysis to technological aspects. We examine also economic and geo-political issues.

On the technological side we are interested in examining (i) the optimal timing and size of CSP power generation, (ii) the Europe-MENA trade of CSP electricity, (iii) the impact of CSP on the electricity mix. On the economic and geo-political side we examine (iv) investments and cost dynamics, (v) the option value of CSP, (vi) the feasibility of the foreseen expansion of CSP, (vii) the economic and energy-system implications of forcing earlier investments in CSP and (viii) the plausibility, implications and the regulatory requirements of a non-competitive Europe-MENA electricity market.

In this study we restrict the possibility to invest in CSP to MENA, the USA and China. These regions have sites with high DNI and represent a large share of global energy consumption and global emissions (approximately 60% of global primary energy supply and of fossil fuel emissions from 2005 to 2050 in our Business-as-Usual scenario). The Eastern and Western European regions (E-EU and W-EU, respectively) can import CSP electricity from the MENA region if a SG is built across the Mediterranean. Future work will include CSP in Australia, Brazil and Indonesia as these are the other world regions with the most potential for CSP production (Trieb, 2009b).

To our knowledge, our analysis is the most comprehensive in the literature. Compared to previous policy scenarios in the non-peer reviewed literature we use a solid energy–economy modeling framework. Contrary to those studies our analysis has a global scope, the mitigation effort is distributed efficiently across countries, between energy efficiency and decarbonization measures, across technologies and time. With respect to Bauer et al. (2008) we make further considerations on the nature of the electricity trade between the Europe and MENA; we also introduce CSP and SG in the USA and in China, and we study the implications of technological constraints on investments in CSP. Compared to Krey and Clarke (2011) this study assesses in detail the incentives to invest in CSP and provides results on the Euro-MENA trade.

The rest of the paper is structured as follows. Section 2 briefly introduces the reader to the WITCH model. Section 3 illustrates the major modeling assumptions. Section 4 provides technical details and information on the calibration of the model. Section 5 illustrates the scenarios and Section 6 presents and discusses the results. Section 7 explores the implications of forcing earlier investments in CSP and Section 8 examines the possibility that MENA acts as a monopolist and sells to Europe electricity at a price higher than its marginal cost. A final Section summarizes the major findings of the paper and illustrates future research work. The Appendix A contains the full list of equations and variables; the online Appendix B presents the results of the sensitivity analysis.

2. A brief description of the WITCH model

WITCH – World Induced Technical Change Hybrid – is a regional integrated assessment model (IAM) structured to provide normative information on the optimal responses of world economies to climate policies (Bosetti et al., 2006, 2007a).

It is a hybrid model because it combines features of both top-down and bottom-up modeling: the top–down component consists of an intertemporal optimal growth model in which the energy input of the aggregate production function has been integrated into a bottom–up like description of the energy sector. WITCH's top-down framework guarantees a coherent, fully intertemporal allocation of investments, including those in the energy sector.

---

[3] http://www.ufmsecretariat.org/en/energy/ last accessed on August 16, 2011.

[4] Department of Energy, Solar Technologies Program website, last accessed on August 16, 2011: http://www1.eere.energy.gov/solar/csp_program.htm.