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External cost of photovoltaic oriented silicon production: A case in China

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ABSTRACT

The rapidly increasing demand for silicon panels has resulted in severe pollution from its manufacture in the underdeveloped regions of China, where environmental control usually concedes to economic development. The study aimed to estimate the external costs of silicon production to inform policy on the sustainable exploitation of solar energy. Specifically, the study estimated the cost of health damage and agricultural loss resulting from the pollution of silicon production. The data was collected from a silicon industrial zone in Southwest China. The cost of agricultural loss was estimated using a production function method, while the cost of health damage was estimated using dose-response functions, in which the air pollutant concentration was estimated based on a Gaussian dispersion model. The results show that the annual external cost of agricultural loss is CNY 0.76–4.13 million and that of health damage is CNY 26.53–44.63 million, or a total external cost is CNY 27.29–48.76 million. The average external cost is CNY 447.35 (CNY 321.1–473.82) per ton of metallurgical silicon. This information has implication for making policies on the control of pollution and the sustainable development of solar energy industry.

1. Introduction

As a result of the increasing concern about environmental pollution and greenhouse gas (GHG) emissions from fossil fuels, development is moving toward green energy and the generation of power from renewable energy sources that are abundant and free (Abdelaziz et al., 2011; Mekhilef et al., 2011). Solar energy is one of the most promising backup energy sources since it is naturally available and a clean energy source (Saidur, 2010). Many countries have made medium- and long-term plans for the development of their photovoltaic (PV) industries. The International Energy Agency estimates that solar electricity will represent up to 11% of global electricity generation by 2050 (IEA (International Energy Agency), 2010).

Solar electricity is produced using PV panels. Due to its characteristics of photovoltaic effect and semiconductivity, silicon is used to produce PV electricity. Photovoltaic effect refers to the capability of silicon atom in directly transforming solar energy into electric energy. PV panels are usually made from Polycrystalline Silicon, monocrystalline silicon and Organosilicone, which are the downstream products of industrial silicon. Although other elements, such as Germanium, can also be used to produce PV electricity, silicon is the cheapest because of its abundance.

Through time, the dramatic growth in demand has been matched by an expansion of the silicon industry. The world output of polysilicon has increased rapidly since 2007. At least 38.4 gigawatts (GW) of PV systems were installed globally in 2013, up from 30 GW in 2012 (EPIA (European Photovoltaic Industry Association), 2014). Although declining political support for the PV industry in the European Union in 2011 caused a decline of polysilicon output in 2012, the implementation of new feed-in-tariff policies has led to a dramatic increase of the polysilicon markets in other countries, resulting in an increase in the world output in 2013 (EPIA, 2014).

The rapid expansion of the PV market in China is due to the implementation of the Renewable Energy Law (enacted in 2006) and to the 10-year development program that aimed to increase China's total primary energy consumption from non-fossil and renewable sources from around 10% in 2009 to 15% by 2020. In 2013, China became the world's leading installer of photovoltaics, adding 11.3 GW to a cumulative total of 18.3 GW (IEA (International Energy Agency), 2014). Moreover, solar water heating is also being extensively implemented in China.

The demand for silicon products drives more producers to increase their production capacity and explore silicon resources. Since 2011, China has become the biggest supplier of polysilicon, the primary material of solar cells; the country accounts for around one-third of the annual world output of polysilicon.

However, as an input for the production of polyslicon, silicon is produced with characteristics of capital intensiveness, high-energy consumption, and high rate of waste emission. According to life cycle assessments of PV system, the transformation of silica into solar grade

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silicon (with a purity above 99.9999%) is the most critical phase in terms of mass and energy flow and environmental impacts (Stoppato, 2008; Fu et al., 2015). The transformation of metallic silicon into solar silicon is composed of two parts: from silica to metallurgical silicon and for metallurgical silicon to solar grade silicon (Fthenakis et al., 2011). Coupled with China's rapid increase in PV-oriented silicon output, the resulting pollution, especially from the former part, is becoming more and more of a concern.

China produced 1.7 million tons of metallic silicon in 2014, of which 50.59% was exported to other countries. For those used domestically, about 58.83% was used to produce PV panels, of which 22.6% in weight is silicon (Fu, 2015).

In recent years, the number of reported cases of air and water pollution from silicon production, as found from the Chinese searching website "baidu", has continued to increase, mainly in rural and underdeveloped regions in central and western China. Silicon producers prefer these locations for their plants because of the availability of high-quality quartzite sand, and because the environmental pressure is not as stringent as in the eastern and coastal parts of China. On the other hand, the local governments in these areas are eager for the income brought by the establishment of industrial production bases, often at the expense of the environment and with unforeseen health costs due to the rapid expansion of silicon production bases.

The pollution has directly resulted in a sharp decline in agricultural outputs. Likewise, the local residents' health is seriously affected; observed cases of silicosis and cough are increasing. Thus, the local government has to design policy instruments for pollution control or make a trade-off between economic development and environmental protection.

The question then is, "How much is the external cost of pollution from silicon production?" This study aims to estimate the external costs of metallurgical silicon production in order to provide information for drafting policies for the sustainable exploitation of solar energy. Specifically, this study estimates the cost of health damage and agricultural loss. The information on external costs is not only needed for determining the appropriate fines for pollution in accordance with the laws on pollution control, but is also needed for making new policies, such as environmental tax, for pollution control, and for the cost-benefit analyses of additional investment. Moreover, unlike the rapid increase in installed PV capacity, literature on the economic externalities of silicon production remains scarce, especially in China. This study is thus expected to fill this gap in the literature.

2. Literature review

2.1. External cost of power generation

Industrial pollution usually affects human health, agricultural output, and ecosystem health. The impacts result in external costs, which are non-internalized economic costs imposed on society that are not accounted for in the producer's and consumer's economy. That is, external cost is not included in the market prices, and is thus considered a market failure (Fahlen and Ahlgren, 2010).

As there is no information of external cost, the control of industrial pollution has usually applied the command and control tools. However, these instruments produced large deadweight losses because inter-firm differences in marginal damages and marginal costs are not considered (Mulluer and Mendelsohn, 2009), and thus economists have advocated market-based approaches to regulate pollution including emission taxes or tradable permits in both a first best setting (Montgomery, 1972; Tietenberg, 1980; Baumol and Oates, 1988) and a second best setting with prior distortionary taxes (Goulder, 1999). In either setting, the information of external costs can not only be used for the design of economic instruments (Fahlen and Ahlgren, 2010), but also provide useful inputs for damages/benefit analysis, and trade-off assessment between different energy options (Fouquet et al. (2001)). Moreover, studies have shown that accounting for external costs may improve the competitiveness of certain renewable energy sources (El-Kordy et al., 2002; Roth and Ambs, 2004), and reduce negative impacts of energy supply and use (Rafaj and Kypreos, 2007).

Well-known studies on the externality of power generation are the ExternE project in EU (Bickel and Friedrich 2005), the Environmental Protection Agency's project on social cost of carbon (SCC) and the review of the National Academy of Sciences on the hidden cost of energy (HCE) in the United States of America (Stoellinger et al., 2016). These projects provided basic references for many other studies (e.g., Vrhovcak et al., 2005; Machol and Sarah, 2013; Streimikiene and Alisauskaite-Seskiene, 2014; and Corona et al., 2016). In China, Zhang et al. (2007) studied the external cost of electricity generation by referencing to the data in ExternE.

Generally speaking, the external cost of power generation is not well studied because externality is technology and site specific. The reference case studies in SCC, HCE, or ExternE (including Kaspar et al., 1995 and Hartmann, 2001) may be not suitable for other studies as the technology and site changes. In particular, the life cycle emission rates of different environmental indicators cannot be directly applied in China. One important reason is that the environmental regulation in China is not as stringent as in the most developed countries. Yang et al. (2015) assessed the life cycle environmental impact of the production of multi-crystalline silicon PV modules in China by distinguishing domestic and imported raw materials. They found that the production of multi-crystalline silicon PV modules emits significant amount of GHG, of which more than 94% were from Chinese domestic industries and only 6% was from imported raw materials in 2010.

Most lifecycle analysis of photovoltaic power generation focused on the flow of energy and mass and the accounting of GHG emission (Stoppato, 2008; Hou et al., 2016; Akinyele et al., 2017). Some studies (Fu et al., 2015; Fthenakis et al., 2011) have assessed the lifecycle environmental impacts of a PV system in terms of global warming potential, eutrophication, acidification, toxicity potential and photochemical ozone creation potential. However, few studies considered the external costs of environmental impacts other than GHG emission. Recently, Lin and Li (2015) analyzed the cost of grid-connection of renewable energy development in China. However, the cost that Lin and Li (2015) analyzed is financial cost and the study of the social cost of renewable energy is still a gap in literature, especially in China.

2.2. Impacts of industrial pollution on human health and dispersion model

Researchers have demonstrated that there is a close relationship between human health and pollution. The World Health Organization (WHO) has identified ambient air pollution as a high priority in its global burden of disease (GBD) initiative, estimating that air pollution is responsible for 1.4% of all deaths and 0.8% of disability-adjusted life years (DALYs) globally (WHO (World Health Organization), 2002). A link between respiratory disease and particulate air pollution and/or sulfur oxide pollution had been well established in the 1970s (Pope et al., 1995). After the work of Dockery et al. (1993), researchers have placed more emphasis on fine particles, which are thought to pose a particularly great risk to health. Several epidemiological studies have shown that chronic exposure to PM_{10} and $PM_{2.5}$ increases an individual's risk to cardiovascular and respiratory diseases and lung cancer (Raaschou-Nielsen et al., 2013).

In China, a majority of the literature are about the health effects of total suspended particulates (TSP) and PM_{10}. For example, Chang et al. (2001) found that along with an increase of 100 $\mu g/m^3$ in PM_{10} in Beijing, the incidence rates of lead respiratory disease-related deaths,