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Material requirements and availability for multi-terawatt deployment of photovoltaics

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ABSTRACT

This study investigates growth rates and material flows required to reach and sustain multi-terawatt installed capacity of photovoltaics (PV). The dynamics of material flows over time are captured, taking account for the life expectancy of PV technology. Requirements of solar grade silicon and silver for crystalline silicon (c-Si) technology, as well as indium, gallium, selenium, tellurium, and cadmium for currently commercial thin film (TF) technology are explored, accounting for different technology choices and potential improvements in material intensities. Future availability of these materials from primary resources, as well as secondary resources from end-of-life recycling, is also analyzed. Rapid deployment of c-Si technologies would require a major expansion of solar grade silicon production, and significant quantities of silver. Availability of materials such as indium and tellurium could become problematic for major implementation of TF technology, unless production can be scaled up significantly, or material intensities radically decreased. Availability of secondary resources from end-of-life recycling have little impact on material availability during the growth phase, but could be important for sustaining a low-carbon energy system over longer time perspectives. Material availability could cause problems for rapid PV growth, but does not necessarily limit total PV deployment, especially if material intensities are decreased.

1. Introduction

Solar energy is expected to play an essential role in future low-carbon energy systems. There are different ways of converting solar energy into useful energy carriers, but solar photovoltaics (PV) have been suggested as the leading candidate for meeting prospective growing global demand for electrical energy, by reaching terawatt (TW) scale installed capacity by the middle of the current century (Jean et al., 2015). It has been argued that technologies such as PV must be possible to scale up to the TW-level to make a relevant impact on the global scale, but also that the potential for this can be limited by the availability of chemical elements or materials for these technologies (Vesborg and Jaramillo, 2012). Low-carbon energy technologies, including PV, are significantly more metal intensive than the currently common technologies, which mostly depend on fossil fuels, and a transition to a non-fossil electrical energy system would require the mining of a wide range of metals to be scaled up significantly (Kleijn et al., 2011). The objective of this study is to further investigate if availability of materials is likely to become an issue for scaling up and sustaining PV capacity at TW-levels. In addition, the objective is also to propose new methods to analyze these issues in a dynamic way accounting for potential contributions from end-of-life (EOL) recycling, as well as different technology choices, and improvements in material intensity.

Solar PV could be considered a collection of several different technologies capable of transforming energy from the sun directly into electrical energy, which can be divided into groups according to their light absorbing material or different stages of development. A common distinction is between wafer-based and thin film (TF) solar cells, where the TF technologies can be further divided into commercial and emerging technologies (Jean et al., 2015). Silicon based wafer solar cells, commonly referred to as crystalline silicon (c-Si), including mono-crystalline and multi-crystalline silicon PV, have made up the vast majority of the PV capacity commissioned to date and make up most of the currently existing PV commissioning capacity (Fraunhofer ISE, 2015).

A number of studies explore material availability for both c-Si and TF technologies (Feltrin and Freundlich, 2008; Jean et al., 2015; Kavlak et al., 2015; Tao et al., 2011; Zuser and Rechberger, 2011), while others focus on TF technologies (Andersson, 2000; Andersson

Abbreviations: AER, Advanced Energy Revolution; c-Si, crystalline silicon; CIGS, copper indium gallium selenide; CdTe, cadmium telluride; EOL, end-of-life; GW, gigawatt; PV, photovoltaics; SC, sustained commissioning; SoG-Si, solar-grade silicon; t, metric ton; TF, thin film; TW, terawatt; USGS, United States Geological Survey

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et al., 1998; Candelise et al., 2011; Fthenakis, 2009), or one specific material used for a TF technology such as indium for copper indium gallium selenide (CIGS) (Choi et al., 2016; Stamp et al., 2014) or tellurium for cadmium telluride (CdTe) PV technologies (Houari et al., 2014; Zweibel, 2010). Several studies propose that availability of materials, especially indium for CIGS and tellurium for CdTe technologies, could constrain future deployment potential (Andersson et al., 1998; Feltrin and Freundlich, 2008; Tao et al., 2011). However, Candelise et al. (2011) state that the availability of tellurium and indium will not necessarily limit the ability for CdTe and CIGS technologies to meet expected future PV market growth. A few studies mention silver used as an electric contact material as a potentially problematic material for c-Si technology (Feltrin and Freundlich, 2008; Tao et al., 2011). An array of earlier studies has explored the requirements and availability of solar materials for reaching varying levels of PV capacity. Multi-TW installations of PV are commonly seen as a necessity for a global energy system based on 100% renewable energy. This present study analyzes such multi-TW deployments using a more dynamic time perspective to enable a thorough analysis of to what extent end-of-life (EOL) recycling could contribute to reaching, as well as sustaining, multi-TW PV capacity. Furthermore, to what extent different possible technology choices and potential technological progress can affect the required material flows are explored. This highlights the implications of choices made on PV designs and continued improvements in material intensities. Combined, these factors provide alternative perspectives of material issues for PV deployment.

Another way this study differs from close to all similar studies is that the use of silicon for c-Si PV is included in the analysis. Silicon can be considered an abundant material not likely to suffer from resource constraints (Andersson et al., 1998), neither is it investigated in many studies, with the exception of Kavlak et al. (2015). The total silicon production in 2014 was 7680 kt (USGS, 2015), but only a small fraction was converted into high purity polysilicon. For silicon to be useful for c-Si PV manufacturing it needs to be purified to at least 99.9999% purity, commonly referred to as solar-grade silicon (SoG-Si) (De Sousa et al., 2016). Bye and Ceccaroli (2014) estimate that the SoG-Si production capacity was 250 kt at the end of 2012, with 80 kt of new development that should have been ready by the end of 2015, indicating a current SoG-Si production capacity of around 330 kt. Producing SoG-Si is an energy intensive process, and the large requirements of electrical energy connected to SoG-Si production have even been suggested to be a potential constraint for c-Si PV growth (Tao et al., 2011). Although silicon is an abundant element, understanding future requirements of polysilicon can still be crucial for understanding potential growth of c-Si PV and related implications of such a development.

If, and when, material availability is likely to become an issue for deployment of either specific PV technologies or total PV capacity to varying levels of installed capacity has been investigated in several previous studies, but remains somewhat disputed. This study aims to further explore potential future material flows of both c-Si and TF PV technologies, not restricted to materials commonly pointed out as potentially problematic for PV growth. Potential technology choices, improvements in material intensity, and potential contributions from recycling are given special focus. Future flows of solar grade silicon, silver, indium, gallium, selenium, tellurium, and cadmium potentially required for reaching multi-TW PV levels are investigated, as well as potential availability issues of these materials, including what could be available from EOL recycling.

2. Methods

2.1. Material requirements for PV growth

2.1.1. Total PV growth

Projections and visions of future PV capacity vary significantly among published studies, ranging from insignificant PV deployment due to severe material constraints to hundreds of TW (Davidsson et al., 2014). In this study, one single case of total PV electrical energy generation capacity is modelled to highlight other factors than diverging assumptions on future capacities. PV capacity is assumed to rise from the 2014 level and reach 9.3 TW by 2050, based on the Advanced Energy [R]evolution (AER) scenario presented by Greenpeace (2015), where cumulative PV capacity grows from 97 Gigawatts (GW) in 2012 to 9295 GW in 2050. Whether this level of deployment should be considered high or not depends on the perspective. For instance, Kavlak et al. (2015) summarize a few scenarios for 2030 from reputable institutions spanning from 0.7 TW to 5.5 TW, while the AER scenario suggests 3.7 TW of PV capacity in 2030. So, while 9.3 TW of PV in 2050 can appear high compared to future scenarios, it is well within the range of many mainstream scenarios, especially those envisioning 100% renewable energy by mid-century.

Annual capacity additions of PV have averaged over 40% of relative growth from 1996 to 2014, but a steady drop can be seen from the peak at almost 74% in 2011 down to around 29% in 2014 (BP, 2015). In the model, relative growth rates of global PV capacity is assumed to continue to decrease and reach 26% in 2016, and then grow exponentially at this level until reaching 0.31 TW, when a linear growth takes over at this level. Assuming a 30 year service life of PV modules, which is the recommended life expectancy for life cycle assessments (Frischknecht et al., 2016), an annual commissioning of 1/30 of 9.3 TW, or 0.31 TW, of PV commissioning is required to sustain this capacity in longer time perspectives. Capacity reaching its end of life will make the net additions stop after reaching 9.3 TW and continued commissioning at this level can theoretically sustain the system indefinitely. This growth pattern is based on the *sustained commissioning* (SC) framework described by Davidsson et al. (2014). Fig. 1 depicts the PV installations to 2070, so that two full life cycles of PV technology are visualized. The specified cumulative installed capacities in the AER scenario described in Greenpeace (2015) for the years leading up to 2050 are at very similar levels as what is generated by a SC model (Fig. 1a).

2.1.2. Technology market shares

A wide range of currently commercial and emerging solar PV technologies are known (Jean et al., 2015), although only four of them have had any tangible commercial success to date. The estimates of historical PV installations can vary somewhat, and most data sources do not separate different PV technologies. One study that does publish estimates for currently commercial PV designs estimates that the total installation in the year 2014 was 43.1 GW c-Si, 1.7 GW CIGS, 1.9 GW CdTe and 0.8 GW a-Si, totaling 47.5 GW (Fraunhofer ISE, 2015). This implies that c-Si solar cells had a market share of almost 91% in 2014. The potential market adoption for a-Si is likely limited by its low efficiency and high light-induced degradation, making them most suited for small-scale and low power applications (Jean et al., 2015), and none of the scenarios assumes any significant contributions from a-Si designs.

In this study, two different cases, one *c-Si case* and one *TF case,* are created to explore the resulting material flows depending on choice of technologies. In the c-Si case (Fig. 1b), c-Si technology contributes with all future PV capacity growth. In the TF case, CIGS (Fig. 1c) and CdTe (Fig. 1d) make up half of the growth in annual commissioning each, but current c-Si commissioning capacity is assumed to still be around during the exponential growth phase to avoid too extreme growth rates of the individual TF technologies. Figs. 1b–d also depict which PV commissioning that actually contributes with a net addition of cumulative capacity, and when the commissioned PV capacity starts to replace old discarded technology at the end of its service life instead. These two cases are not attempts to predict future technology choices, but merely describe two potential outlier scenarios if different technologies were to dominate the future markets.