A hybrid life-cycle inventory for multi-crystalline silicon PV module manufacturing in China

Yuan Yao1, Yuan Chang2 and Eric Masanet1,3

1 Department of Chemical and Biological Engineering, Northwestern University, 2145 Sheridan Road, Evanston, Illinois, USA
2 School of Management Science and Engineering, Central University of Finance and Economics, Beijing 100081, People’s Republic of China
3 Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road, Evanston, Illinois, USA

E-mail: yuanyao2011@u.northwestern.edu and eric.masanet@northwestern.edu

Received 11 May 2014, revised 16 September 2014
Accepted for publication 29 September 2014
Published 3 November 2014

Abstract
China is the world’s largest manufacturer of multi-crystalline silicon photovoltaic (mc-Si PV) modules, which is a key enabling technology in the global transition to renewable electric power systems. This study presents a hybrid life-cycle inventory (LCI) of Chinese mc-Si PV modules, which fills a critical knowledge gap on the environmental implications of mc-Si PV module manufacturing in China. The hybrid LCI approach combines process-based LCI data for module and poly-silicon manufacturing plants with a 2007 China IO-LCI model for production of raw material and fuel inputs to estimate ‘cradle to gate’ primary energy use, water consumption, and major air pollutant emissions (carbon dioxide, methane, sulfur dioxide, nitrous oxide, and nitrogen oxides). Results suggest that mc-Si PV modules from China may come with higher environmental burdens that one might estimate if one were using LCI results for mc-Si PV modules manufactured elsewhere. These higher burdens can be reasonably explained by the efficiency differences in China’s poly-silicon manufacturing processes, the country’s dependence on highly polluting coal-fired electricity, and the expanded system boundaries associated with the hybrid LCI modeling framework. The results should be useful for establishing more conservative ranges on the potential ‘cradle to gate’ impacts of mc-Si PV module manufacturing for more robust LCAs of PV deployment scenarios.

Keywords: life cycle inventory, multi-crystalline silicon PV, solar power, China

1. Introduction
Solar photovoltaic (PV) technology is a key enabler in the global transition to renewable electric power systems. Numerous life-cycle assessments (LCAs) have been conducted on PV technologies and their results suggest that PV systems can deliver substantially lower life-cycle environmental impacts per kilowatt-hour generated compared to traditional fossil fuel electric power systems [1]. For example, a recent meta-analysis of electric power system LCA studies concluded that PV systems exhibit one to two orders of magnitude lower greenhouse gas (GHG) emissions, water consumption, and conventional air pollutant emissions from a life-cycle perspective compared to coal- and natural gas-fired systems [2]. Such LCAs provide critical quantitative information on the environmental benefits and tradeoffs of PV technologies for the purposes of guiding regional and national energy and environmental policies and identifying technology improvement opportunities within the renewable energy research and development communities.
As global policies that promote greater deployment of PV technologies become commonplace, there is an increasingly strong need for more credible and comprehensive LCAs of PV technologies [3]. For example, in the United States, the Department of Energy’s SunShot Initiative has set targets of generating 14% of US electric power from solar technologies by 2030, and 27% by 2050 [4]. Similarly aggressive targets for solar technology adoption have been set in Canada, Europe and Japan [5, 6]. Crystalline silicon (c-Si) PV technology currently dominates the global PV market and account for 85% of the global installed PV capacity [7]. Although other PV technologies hold promise, such as cadmium telluride thin film PV, their current market shares are small compared to c-Si PV due to lower conversion efficiencies, higher costs, and concerns over critical materials availability [7]. Therefore, it is likely that c-Si PV systems will comprise a large share of installed PV capacity in the near term.

China is the world’s largest manufacturer of c-Si PV technologies, accounting for 69% of the world’s c-Si PV module production in 2012 [7]. While numerous LCAs have been conducted on c-Si PV technologies, past work has focused exclusively on PV manufacturing outside of China [3, 8–10]. Even past LCA studies of c-Si PV installations in China have utilized LCI data from other world regions. For example, Lu and Yang [11] studied the energy payback time of a c-Si PV system installed in Hong Kong using life-cycle inventory (LCI) data for PV manufacturing obtained from European plants, while Nishimura and Hayashi [12] presented a comparative LCA for c-Si PV installed in Japan and China based on module manufacturing LCI data from Japan. Both Diao and Shi [13] and Yue et al [14] presented LCA results for c-Si PV made in China, but both studies relied on materials and manufacturing LCI data from European practices, including proprietary (and therefore non-replicable) data from commercial LCI databases.

The lack of LCI data on c-Si PV modules manufactured in China presents a major barrier to understanding the life-cycle environmental implications of global c-Si PV module deployment. While the direct manufacturing process technologies for c-Si PV modules might be comparable across world regions, lower process efficiencies in China [13, 15] and the country’s reliance on inefficient and polluting coal-fired power plants for the electricity that fuels these processes might lead to higher environmental burdens embodied in each module compared to other regions. Furthermore, inefficient technologies and extensive coal use (for both electric power and process heat) within the supply chains that produce raw materials needed for module manufacturing (e.g., poly-silicon and organic chemicals) may also lead to higher embodied environmental burdens compared to raw materials production systems elsewhere. For example, outdated production technologies and lack of recycling systems [16] within China’s poly-silicon industry may lead to higher energy requirements and greater pollution compared to poly-silicon production systems in the United States and European Union [17].

This study aims to address this knowledge barrier by estimating the ‘cradle to gate’ environmental burdens associated with Chinese manufacturing of a multi-crystalline silicon PV (mc-Si) module, which represents the largest PV module technology exported from China [18]. Previous LCAs have shown that the vast majority of life-cycle environmental burdens associated with mc-Si PV installations are attributable to module production [8, 10]. Therefore, this study excludes the balance of system required for installation, the environmental burdens of which can vary depending on the installation region. However, the results of this study can be used in future LCAs of complete mc-Si PV installations within specific regions as they provide much-needed LCI data for the world’s largest manufacturer of mc-Si PV modules.

This study employed a hybrid LCI modeling approach, which combines an input-output (IO) LCI model using 2007 Chinese economic benchmark data with process-based LCI data for the raw materials and energy requirements of direct manufacturing processes associated with poly-silicon and mc-Si PV modules. This hybrid approach leverages the specificity of process-based LCI data while offering a more complete, economy-wide system boundary enabled by the IO approach [19]. Although hybrid LCI studies have been conducted for mc-Si PV modules produced in other world regions, including the United States [20] and Australia [21], this study is the first to develop a hybrid LCI model for mc-Si PV modules manufactured in China. Furthermore, the environmental metrics included in this study—primary energy use, water consumption, GHG emissions, and common air pollutants—should prove useful for understanding burdens across several important environmental impact categories (i.e., non-renewable resource depletion, water scarcity, global warming potential and human health) in future impact assessment studies by the policy and research communities.

2. Methodology

This study focuses on the ‘cradle to gate’ system for producing mc-Si PV modules depicted in figure 1. Process-based LCI data were used to quantify the raw materials, onsite electricity, and water consumption requirements of wafer, cell, and module manufacturing at the PV module plant and onsite electricity use for poly-silicon production. All process-based LCI data are based on published data from Chinese plants [13]. China IO data [19, 22] were used to estimate the economy-wide environmental burdens associated with the extraction, refining, production, and transport of all raw materials, water, and energy inputs consumed by the module and poly-silicon production plants, including the environmental burdens for the ‘cradle to gate’ systems associated with grid electricity generation. These economy-wide environmental burdens are referred to as indirect (also referred to as ‘upstream’ or ‘embodied’) burdens to distinguish them from the direct burdens attributable to the module and poly-silicon production plants and in keeping with terminology conventions used within the LCA research community.

The process-based LCI data employed in this study are listed in the second and third columns of table 1. These process-based material and energy input quantities, except for water consumption, are based on primary data from Chinese...
silicon PV and poly-silicon plants as published in [13]. Onsite water consumption was estimated using data from European plants with similar processes [23–25] due to lack of such data for China. The process-based LCI data are presented for two cases [13]: (1) major manufacturers (MMA), which represents average Chinese industrial practice; and (2) advanced practice technology (APT), which represents state-of-the-art practice.

The wafer manufacturing LCI data in table 1 are inclusive of the processes necessary to produce silicon wafer feedstocks for cell manufacturing, i.e., quartz melting, silicon ingot formation, and wafer cutting processes [25]. The LCI data are based on electricity-driven processes for quartz melting (induction heating), silicon ingot formation (motor-driven rotating and pulling), and wafer cutting (wire sawing) and assume a typical thickness for Chinese wafer production of 200 μm [26, 27]. The cell manufacturing LCI data are inclusive of etching (chemical and heat treatment), phosphorus diffusion, and screen printing (used by 90% of cell manufacturers), which are dominantly electricity-driven processes [28, 29]. The module manufacturing data LCI include the final fabrication processes of combining cells and interconnects under glass into a final PV module ready for sale to installers, which includes module encapsulation and assembly [29]. Lamination is the most frequent used method for encapsulation in which ethyl vinyl acetate (EVA) serves as the agent to encapsulate the solar cell within glass and a backsheet [30].

To model indirect environmental burdens, this study employed a previously-published IO-LCI model of the Chinese economy [19, 22], which was developed based on 2007 135-sector Chinese input-output table [31]. The 2007 China IO-LCI model contains environmental coefficients for each sector that include fuel inputs, water consumption, and emissions of CO₂, CH₄, SO₂, N₂O and NOₓ that were derived based on data in statistical yearbooks published by Chinese government agencies [32, 33]. Further details on the China IO-LCI model are available in the model documentation [19, 22]. The China IO-LCI model was used to estimate the economy wide, indirect environmental burdens associated with the ‘cradle to gate’ supply chains for extracting, refining, producing and delivering the raw materials, water and electricity required by the mc-Si PV module manufacturing plant.

The application of the China IO-LCI model involved four sequential steps. First, each material and fuel input was assigned to the most appropriate producing sector among the 135 sectors contained in the China IO-LCI model according to Classification of National Economic Industries published by the Chinese government [34]. The assigned producing

![Figure 1. Hybrid approach and system boundary for mc-Si PV module manufacturing in China.](image-url)
Table 1. Summary of process-based quantity data and IO modeling assumptions for inputs into a mc-Si PV module plant.

| Inputs                                    | Quantity | Corresponding China IO sector                      | Consumer price<sup>a</sup> (2007) | Producer/purchaser price ratio | Aggregated producer price (2007) |
|-------------------------------------------|----------|----------------------------------------------------|-----------------------------------|--------------------------------|----------------------------------|
|                                           | MMA      | APT<sup>a</sup>                                   | RMB/kg                           |                                | MMA                             |
| Wafer manufacturing (wafer dimension: 156 mm × 156 mm, thickness 200 mm) |          |                                                    | RMB/wafer                        |                                | APT                             |
| Poly-silicon                              | 41       | 19                                                 | 1572 [38]                        | 0.7                            | 45                              |
| Silicon carbide (SiC)                     | 32       | 43                                                 | 4 [39]                           |                                | 0.4                             |
| Polyethylene glycol (PEG)                 | 36       | 50                                                 | 12 [40]                          | 0.8                            | 0.5                             |
| Hydrogen fluoride (HF)                    | 0.4      | 0.5                                                | 6 [41]                           |                                | 0.2                             |
| Hydrogen chloride (HCl)                   | 0.4      | 0.2                                                | 0.3 [42]                         | 0.8                            | 0.1                             |
| Potassium hydroxide (KOH)                 | 0.02     | 0.02                                               | 6.4 [44]                         |                                |                                 |
| Sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) | 0.00     | 0.06                                               | 0.5 [45]                         |                                |                                 |
| Nitric acid (HNO<sub>3</sub>)             | 0.2      | 0.7                                                | 1.3 [46]                         |                                |                                 |
| Nitrogen (N<sub>2</sub>)                  | 3.6      | 0.6                                                | 4 [47]                           |                                |                                 |
| Argon (Ar)                                | 13       | 10                                                 | 16 [47]                          |                                |                                 |
| Water                                     | 1310     | 1310                                               | 2.4 RMB/ton [48]                 | 0.5                            | 0.002                           |
| Electricity (kWh/wafer)                   | 2.9      | 1.3                                                | 0.5 RMB/kWh [49]                 | 0.7                            | 1.1                             |
| Cell manufacturing (cell dimension: 156 mm × 156 mm; wafer requirements: 1.02 wafer per cell) |          |                                                    | RMB/kg                           |                                | RMB/cell                         |
| Silane (SiH<sub>4</sub>)                  | 0.8      | 0.6                                                | 1 [50]                           | 0.8                            | 0.1                             |
| Phosphoryl chloride (POCl<sub>3</sub>)    | 0.02     | 0.02                                               | 7570 [51]                        |                                |                                 |
| Hydrogen fluoride (HF)                    | 4.0      | 3.9                                                | 6 [41]                           |                                |                                 |
| Hydrogen chloride (HCl)                   | 1.1      | 0                                                  | 0.3 [42]                         | 0.8                            | 0.2                             |
| Potassium hydroxide (KOH)                 | 0        | 1                                                  | 6.4 [44]                         |                                |                                 |
| Oxygen (O<sub>2</sub>)                    | 0.5      | 0.2                                                | 0.01 [47]                        |                                |                                 |
| Nitrogen (N<sub>2</sub>)                  | 76       | 58                                                 | 4 [47]                           |                                |                                 |
| Nitric acid (HNO<sub>3</sub>)             | 2.8      | 7.2                                                | 1.3 [46]                         |                                |                                 |
| Ammonia (NH<sub>3</sub>)                  | 2.3      | 1.2                                                | 2.5 [52]                         | 0.8                            | 0.005                           |
| Silver (Ag)                               | 0.6      | 0.4                                                | 4 [53]                           | 0.8                            | 0.02                            |
| Aluminum (Al)                             | 1.5      | 1.1                                                | 15 [54]                          |                                | 0.015                           |
| Water                                     | 3350     | 3350                                               | 2.4 RMB/ton [48]                 | 0.5                            | 0.004                           |
| Electricity (kWh/cell)                    | 0.7      | 0.3                                                | 0.5 RMB/kWh [49]                 | 0.7                            | 0.3                             |
| Module manufacturing (module dimension: 992 mm × 1956 mm; cell requirements: 72 cells/module) |          |                                                    | RMB/kg                           |                                | RMB/module                       |
| Copper wire                               | 36       | 36                                                 | 44 [55]                          | 0.8                            | 33                              |

<sup>a</sup> MMA, APT, and IOA stand for Mainland China, Asia-Pacific, and other regions, respectively.
| Inputs                        | Quantity | Corresponding China IO sector                                      | Consumer price\(^{(2007)}\) | Producer/purchaser price ratio | Aggregated producer price\((2007)\) |
|------------------------------|----------|-------------------------------------------------------------------|-------------------------------|-------------------------------|-----------------------------------|
| MMA\(^{a}\)                  | APT\(^{a}\) |                                                                  |                               |                               |                                   |
| Aluminum frame               | 3400     |                                                                  | 12 [54]                       |                               |                                   |
| Glass (area m\(^{2}\))      | 2        |                                                                  | 18 RMB/m\(^{2}\) [51]         | 0.7                           | 26                                |
| Back foil (area m\(^{2}\))  | 2        |                                                                  | 69 RMB/m\(^{2}\) [51]         | 0.8                           | 127                               |
| Ethylene vinyl acetate (EVA) | 1850     |                                                                  | 12 [56]                       |                               |                                   |
| Silicone                     | 110      |                                                                  | 16 [57]                       | 0.8                           | 1.5                               |
| Water                        | 41800    |                                                                  | 2.4 RMB/ton [48]               | 0.5                           | 0.05                              |
| Electricity (kWh/module)     | 18       |                                                                  | 0.5 RMB/kWh [49]               | 0.7                           | 7                                 |

\(^{a}\) MMA = Major manufacturers; APT = advanced practice technology. ^Non-2007 prices were first converted to year 2007 value using the Producer Price Index (PPI) ratio of year 2007 to its year (i.e., year 2013). PPI data were obtained from the National Bureau of Statistics of the People’s Republic of China [58].
sector for each input is listed in the fourth column of table 1. Second, the average 2007 purchaser price of each input (in RMB) was established based on a comprehensive search of the literature. Third, the 2007 purchaser price for each input was converted into 2007 producer prices (in RMB) by subtracting out the value added margins for each sector from the China national IO table [31] to derive a producer price to purchaser price ratio. The estimated 2007 purchaser prices, producer-to-purchaser price ratios, and producer prices for each input are summarized in the remaining columns of table 1, along with supporting literature citations. Fourth, the 2007 producer prices were entered into the China IO-LCI model to estimate the economy-wide, indirect environmental burdens associated with the ‘cradle to gate’ supply chains for production and delivery of each required input into the mc-Si PV module manufacturing plant. The resulting LCI estimates for each input are summarized in table 2.

Poly-silicon represented a special case in this analysis. While reliable process-based LCI data were available for the onsite electricity use of Chinese poly-silicon production [13], such data were not available for the various raw materials inputs required for poly-silicon production. Therefore, this study utilized a hybrid IO structural path replacement technique to estimate both the direct and indirect impacts of poly-silicon production [35, 36]. First, the average producer price per kg for solar-grade poly-silicon was estimated, as listed in table 1. Second, this producer price was employed to estimate the direct and indirect impacts of one kg of poly-silicon production using ‘manufacture of graphite and other non-metallic mineral products’ as the producing sector in the China IO model, which is the aggregated IO sector that contains poly-silicon production. Third, the IO direct energy use results from the producing sector were replaced by the process-based energy use data for Chinese poly-silicon production [13, 37]. In this manner, the accuracy of the process-based LCI data from Chinese plants were maintained for the direct energy use of poly-silicon production while still using IO-based data, by necessity, to estimate the indirect impacts associated with the extracting, refining, and transporting the various raw materials inputs into poly-silicon production. Fourth, the direct and indirect impacts of poly-silicon production were added together to estimate the total embodied impacts associated with poly-silicon material inputs into wafer manufacturing.

3. Results and discussion

Table 3 summarizes the ‘cradle to gate’ hybrid LCI estimates derived in this study as well as ‘cradle to gate’ LCI data from previous studies of mc-Si PV manufacturing available in the literature. It should be noted that the results summarized in table 3 are difficult to compare directly due to differences in system boundaries, technology assumptions, and LCI methods employed in each study. Rigorous direct comparisons require extensive LCI harmonization efforts to rectify differences in analysis assumptions between studies, which is beyond the scope of this paper. Despite this limitation, the data in table 3 can be useful for establishing plausible ranges on the potential ‘cradle to gate’ impacts of mc-Si PV manufacturing that have been estimated using different LCI approaches and data assumptions. The use of such ranges is a practical necessity for robust LCAs of PV deployment scenarios given the lack of accurate LCI data for specific PV module technologies in the literature, and to acknowledge the uncertainties associated with LCA results in general. To facilitate such ranges, the data in table 3 have been normalized to per kWh of generation based on the assumptions detailed in the notes below the table. For context, table 3 also includes previous LCI estimates for natural gas and coal-fired electricity generation.

The ranges in table 3 shed light on the importance of considering China-specific results as an upper bound estimate when evaluating the life-cycle implications of mc-Si PV module installations. Importantly, the results of this study suggest that major manufacturer average mc-Si PV modules from China may come with substantially higher ‘cradle to gate’ environmental burdens that one might estimate if one were using LCI results for PV modules manufactured elsewhere. Moreover, the hybrid LCI results presented here offer estimates for environmental burdens (i.e., water consumption, SO2, and NOx) that have received less attention in past studies. The differences between the MMA and APT cases in this study’s results also shed light on the potential for Chinese manufacturers to reduce their impacts through the adoption of best practices. However, even under best practice assumptions, in most cases the environmental burdens associated with mc-Si modules from China still exceed those estimated by previous studies for modules produced in other world regions, which is likely due to China’s heavy reliance on coal for electricity and process heat throughout its supply chains.

Yue and You [14] represents the only previous study specifically focused on China, yet their results for energy payback time and GHG emissions are substantially lower than those estimated by the present study. These differences can likely be explained by the more limited system boundary utilized in the Yue and You [14] process-based LCI study, and the fact that their study partly employed European-based LCI data for PV manufacturing and background materials processes. Compared with the results of previous studies for the US, Europe, Australia, and other countries in table 3, the higher environmental burdens estimated by this study for China might have three primary explanations.

First, the results in tables 1 and 2 suggest that the largest environmental burdens in the ‘cradle to gate’ system are attributable to the manufacture of poly-silicon, which accounts for 65–90% of the ‘cradle to gate’ total for each environmental burden. The hybrid LCI results for poly-silicon in table 2 also include the economy-wide primary energy use and emissions for upstream production of raw materials (e.g., silicon mining), electricity, water, and fuels consumed by the poly-silicon manufacturing process, which raises the primary energy and emissions footprints of poly-silicon manufacturing considerably. The dominance of poly-silicon manufacturing in the overall environmental burdens is consistent with the previous LCAs of mc-Si PV modules listed in
Table 2. IO-based LCI data summary.

| Inputs                                               | Primary energy (MJ/module) | Water consumption (kg/module) | CO₂ Emissions (kg/module) | CH₄ Emissions (g/module) | N₂O Emissions (mg/module) | SO₂ Emissions (g/module) | NOₓ Emissions (g/module) |
|------------------------------------------------------|----------------------------|--------------------------------|---------------------------|--------------------------|----------------------------|---------------------------|--------------------------|
|                                                      | MMA  | APT | MMA  | APT | MMA  | APT | MMA  | APT | MMA  | APT | MMA  | APT | MMA  | APT | MMA  | APT |
| Aluminum frame and copper ribbons                    | 151  | 121 | 113  | 91  | 14   | 11  | 98   | 79  | 761  | 610 | 46   | 37  | 20   | 16  |
| Ethylene vinyl acetate and back foil                 | 560  | 560 | 505  | 505 | 40   | 40  | 359  | 359 | 5110 | 5110| 188  | 188 | 68   | 68  |
| Glass                                                | 149  | 149 | 88   | 88  | 15   | 15  | 88   | 88  | 738  | 738 | 52   | 52  | 30   | 30  |
| Nitric acid, gas and other basic chemicals            | 176  | 136 | 120  | 93  | 15   | 12  | 130  | 100 | 1670 | 1290| 60   | 46  | 22   | 17  |
| Water                                                | 2    | 2   | 9    | 9   | 0.6  | 0.6 | 0.7  | 0.7 | 19   | 19  | 0.7  | 0.7 | 0.7  | 0.7 |
| Poly-silicon                                          | 1100 | 6660| 10 200| 5760| 1190 | 700 | 10 800| 5010| 70200| 34 200| 5300 | 3410 | 2530 | 1680 |
| Silicon carbide                                       | 36   | 49  | 24   | 32  | 4    | 5   | 22   | 29  | 156  | 211 | 13   | 18  | 8    | 11  |
| Hydrogen fluoride, silane and other special chemicals | 242  | 306 | 239  | 303 | 15   | 19  | 138  | 174 | 2990 | 3780| 60   | 76  | 28   | 35  |
| Electricity (at PV module plant)                      | 3530 | 1760| 849  | 423 | 409  | 204 | 366  | 182 | 8240 | 4110| 1420 | 707 | 1060 | 527 |
| Silver and aluminum                                   | 6    | 5   | 4    | 3   | 0.6  | 0.5 | 8    | 6   | 29   | 22 | 3    | 2   | 0.9  | 0.7 |
| Ammonia                                               | 2.0  | 1.0 | 1.3  | 0.7 | 0.1  | 0.1 | 2    | 0.8 | 19   | 10 | 0.6  | 0.3 | 0.2  | 0.1 |
| Total                                                 | 16 000 | 9750| 12 100| 7310| 1710 | 100 | 12 000| 6030| 90 000| 50 100| 7150 | 4540 | 3760 | 2390 |
| Study                  | Methodology | Country         | Scenarios | Energy payback time (years) | Water consumption (kg/kWh) | GHG emissions (gCO₂e/kWh) | SO₂ emissions (gSO₂/kWh) | NOₓ emissions (gNOₓ/kWh) |
|-----------------------|-------------|-----------------|-----------|----------------------------|----------------------------|---------------------------|--------------------------|--------------------------|
| Present Study         | Hybrid      | China           | MMA       | 4.7                        | 1.3                        | 207                       | 0.7                      | 0.4                      |
|                       |             |                 | APT       | 2.5                        | 0.7                        | 103                       | 0.4                      | 0.2                      |
| Hsu et al [3]         | Harmonized  | 13 studies in the US, Europe, Japan, Australia and Brazil | Mean (min, max) | —                         | —                          | 52 (26, 183)              | —                        | —                        |
| IPCC [2]              | Review of 26 studies in the US, Europe, Japan and Australia | Mean (min, max) | — (0.2, 8) | —                         | —                          | 46 (5, 217)              | ≤0.3                     | ≤0.2                     |
| Lenzen [21]           | Hybrid      | Australia       | Base      | 2.5                        | —                          | 111                       | —                        | —                        |
|                       |             |                 | High      | 4.5                        | —                          | 159                       | —                        | —                        |
|                       |             |                 | Low       | 1.3                        | —                          | 77                        | —                        | —                        |
| Zhai and Williams [20] | Hybrid      | US              | —         | 2.1                        | —                          | 30                        | —                        | —                        |
| Pecca et al [8]       | Process-based | US              | —         | 2.6                        | —                          | 67                        | 0.4                      | 0.2                      |
| Fthenakis and Alsema [10] | Process-based | European countries | 1.9      | —                          | —                          | 30                        | —                        | —                        |
| Yue and You [14]      | Process-based | China and Europe | China     | 2.2                        | —                          | 65                        | —                        | —                        |
|                       |             |                 | Europe    | 1.5                        | —                          | 30                        | —                        | —                        |
| Coal-powered         | Process-based | IPCC [2] reviewed 52 papers worldwide, water consumption is for US [59] | Mean (min, max) | — (0.5, 3.7) | — (2, 4.1) | 1000 (675, 1690) | — (0.7, 27) | — (0.7, 4.3) |
| Natural-gas-powered  | Process-based | Mean (min, max) | — (1.2, 3.9) | — (0.6, 2) | 469 (290, 930) | ≤5.8                     | — (0.2, 1) |

---

Note: To facilitate a first-order comparison, previous studies (except for IPCC [2]) were normalized to the same kWh generation by using Hsu et al [3] assumptions as follows: module lifetime of 30 years, solar insolation of 1700 kWh/m²/year, performance ratio of 0.8, and module efficiency of 13.2%.

- Module efficiency in the MMA case is 12.4% and in the APT is 14.4% [13]; for this study’s modeled PV module, the module lifetime, solar insolation, and performance ratio are assumed to be the same as Hsu et al [3] to facilitate comparison to previous studies.

- The IPCC [2] results summarized here are not normalized to the assumptions of Hsu et al [3] given insufficient replicability in the source document and the inclusion of both crystalline and amorphous PV technologies in the ranges.

- Impacts related to balance of system and installation are excluded here (13% of total GHG emissions, 12% of primary energy). Energy payback time has been recalculated here based on the Lenzen [21] assumptions: annual electricity 1750 MWh/Mwp (base), 1500 MWh/Mwp (high), 2000 MWh/Mwp (low); module area per peak MW 9050 m²/Mwp (base), 10 417 m²/Mwp (high), 7937 m²/Mwp (low). GHG emissions are recalculated here based on the Hsu et al [3] assumptions listed in note a.

- The Pecca et al [8] results were converted to per m² of module basis using their original data: 0.93 m²/module with 82 m² of mc-Si modules in the system; impacts results were then recalculated here based on the Hsu et al [3] assumptions listed in note a.

- Impacts related to balance of system are excluded here (0.2 years of entire energy payback time and 4.5 g/kWh is attributed to balance of system) based on data in Fthenakis et al [10].


Table 4. Contributions of electric power (includes direct and indirect electricity use) to ‘cradle to gate’ environmental burdens.

| Primary energy | Water consumption | GHG Emissions | SO₂ Emissions | NOₓ Emissions |
|----------------|------------------|---------------|---------------|---------------|
| 27%            | 5%               | 64%           | 57%           | 47%           |

Table 3, but this finding for China can be further explained by the following reasons:

- Low average material efficiency of poly-silicon used in wafer manufacturing, which is attributable to high polysilicon losses during wafer cutting. In Table 1, the poly-silicon requirement for the APT case is only 46% of that required in the MMA case, which suggests that major Chinese PV manufacturers could improve material efficiency considerably. When poly-silicon requirements drop in the APT case, there is a corresponding 40-50% reduction in all environmental burdens in the APT case. Therefore, improved material efficiency for poly-silicon should be a major priority for Chinese PV manufacturers moving forward.

- Energy inefficient poly-silicon production practices in China. Specifically, China utilizes a Modified Siemens Process [61] for poly-silicon manufacturing, but the efficiency of this process in China is below international standards due to trade and knowledge transfer barriers with countries that manufacture the most advanced Modified Siemens Process equipment [61–63]. Moving forward, energy efficiency improvements to China’s poly-silicon technology should lead to reductions in the environmental burdens of its manufactured mc-Si PV modules.

- The pervasiveness of pollutant-intensive coal-fired electricity and process heat throughout China’s poly-silicon and raw materials supply chains, as discussed below.

Second, all materials and processes in the ‘cradle to gate’ system rely heavily on electricity inputs from China’s relatively inefficient and pollutant-intensive coal-fired electrical power grid compared to ‘cleaner’ electricity grids in the United States or Europe. For example, GHG emissions (0.9 kg CO₂/kWh) [64], SO₂ (2.7 g SO₂/kWh) [65], NOₓ (3.1 g NOₓ/kWh) [66] intensities of China’s electricity grid are 1.2, 3, and 2.4 times the respective intensities of the average electricity mix in the United States [65, 67] (note that this is on-site emission factors in power plants, not life-cycle emission factors presented in Table 3). The dominance of direct electricity inputs into module manufacturing processes can be directly observed in Table 1, whereas the contribution of China’s electric power sector to the indirect environmental burdens associated with module manufacturing inputs in Table 2 (calculated by the China IO-LCI model) is less obvious. Table 4 shows the percent of each environmental burden total that is attributable to electric power use in the ‘cradle to gate’ system, which suggests that China’s coal-fired power grid contributes substantially to each environmental burden besides consumed water. Thus, while PV modules manufactured in China are undoubtedly driving accelerated deployment of PV technologies throughout the world, the comparatively higher environmental burdens associated with Chinese module manufacture may reduce the overall global pollution benefits of renewable energy policies.

Third, the comprehensive system boundary of the hybrid LCI model employed by this study results in greater environmental burdens than studies using process-based LCI methods alone. This outcome is one of the advantages of the hybrid LCI approach [19], and can be seen also in the results of Lenzen [21], which show higher proportions of burdens embodied in their materials than the strictly process-based LCI results in Table 3. Therefore, the comprehensive system boundaries in this study provide more complete estimates of the environmental burdens induced across the entire Chinese economy, which gives a more conservative view of the potential environmental impacts associated with PV modules manufactured in China.

While the environmental burdens of Chinese mc-Si PV modules appear to be significantly higher than those of modules manufactured in other world regions, compared to prevailing fossil fuel-fired electricity plants, they still offer a more environmentally-friendly means of electricity generation. Specifically, compared to both natural gas- and coal-fired impacts in Table 3, the per-kWh impacts of Chinese mc-Si PV modules are much lower for all considered resources and emissions. Thus, the results of this study should be viewed in the proper context of all prevailing electrical power options for society. From that perspective, the aggressive deployment of Chinese mc-Si PV modules is an environmentally-superior strategy compared to deployment of fossil fuel-fired electrical power systems. That said, materials and energy efficiency improvements as well as cleaner electricity use within China’s ‘cradle to gate’ system should be aggressively pursued in the near term to maximize the environmental benefits of PV technologies moving forward.

4. Conclusions

This study yields ‘cradle to gate’ environmental burden estimates for mc-Si PV module manufacturing in China that are significantly higher than LCI estimates from previous studies of other world manufacturing regions. These higher burdens can be reasonably explained by the efficiency differences in China’s poly-silicon manufacturing processes, the country’s dependence on highly polluting coal for electricity and process heat throughout its supply chains, and the expanded IO system boundaries associated with the hybrid LCI modeling framework. These results suggest that policy makers and the research community should consider using higher environmental burdens estimates when evaluating the life-cycle environmental implications of PV technology deployment, given that China comprises the largest share of today’s global silicon PV manufacturing capacity.

However, the environmental burdens associated with Chinese mc-Si modules are still substantially lower than those associated with fossil-fuel fired electrical power systems, and
when compared to coal-fired electrical power in particular. Therefore, the deployment of Chinese PV panels should still lead to life-cycle environmental savings compared to fossil fuels. Maximizing such savings will require a shift to best practice processes technologies in China, as well as cleaner energy sources for fueling those processes. Such shifts might be promoted through the use of green purchasing incentives and/or PV technology environmental standards by the purchasers of China-sourced PV modules moving forward.

Like all hybrid LCI studies, the results of this study are uncertain given temporal and aggregation errors associated with the 2007 China IO-LCI model [31] and the compilation of different data from different sources to build the process-based LCI model. Future analyses should be directed toward greater use of process-based LCI methods based on primary data compiled from Chinese manufacturers and supply chains as such data become available, which would increase the accuracy, temporal correlation, and technology correlation of any ‘cradle to gate’ LCI of Chinese mc-Si PV module manufacturing. Notably, given the high contribution of poly-silicon to the overall results of this study, future work should particularly focus on gathering latest primary data for process-based LCI analysis of poly-silicon manufacture in China. The remaining flows might be modeled using IO-LCI approaches for improved system boundaries, but future work should strive to utilize more recent IO transactions tables and environmental coefficients when such data become available from the Chinese government.

Despite the uncertainties of this analysis, the estimates presented here can be used to fill an important knowledge gap on the environmental burdens of Chinese PV module manufacturing until latest primary data emerge. Moreover, given the comprehensive system boundaries of this study, the estimates presented here can be used with greater confidence as conservative values for including environmental burdens from PV modules manufactured in China in regional PV deployment analyses.

References

[1] Masanet E et al 2013 Life-cycle assessment of electric power systems Ann. Rev. Environ. Resour. 38 107–36
[2] Sathaye J et al 2011 Renewable energy in the context of sustainable development ed O Edenhofer et al IPCC Special Report on Renewable Energy Sources and Climate change Mitigation (Cambridge: Cambridge University Press)
[3] Hsu D D et al 2012 Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation J. Ind. Ecol. 16 S122–35
[4] SunShot Initiative. Mission (cited 2013 12/02). Available from: (http://energy.gov/eere/sunshot/mission).
[5] Szabó M et al 2011 Technical Assessment of the Renewable Energy Action Plan (Ispra, VA: European Commission)
[6] Pew charitable trusts 2010 Global Clean Power: A S2.3 Trillion Opportunity (Philadelphia, PA: Pew Charitable Trusts)
[7] EPIA 2013 Global Market Outlook For Photovoltaics 2013–2017 (Brussels: European Photovoltaic Industry Association)
[8] Pacca S, Sivaraman D and Kolecarn G A 2006 Life Cycle Assessment of the 33 kW Photovoltaic System on the Dana Building at the University of Michigan Ann Arbor (Ann Arbor, MI: University of Michigan)
[9] Stoppato A 2008 Life cycle assessment of photovoltaic electricity generation Energy 33 324–32
[10] Fthenakis V and Alesma E 2006 Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004–early 2005 status Prog. Photovolt., Res. Appl. 14 275–80
[11] Lu L and Yang H X 2010 Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong Appl. Energy 87 3625–31
[12] Nishimura A et al 2010 Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system Appl. Energy 87 2797–807
[13] Diao Z and Shi L 2011 Life cycle assessment of photovoltaic panels in China (in Chinese) Res. Environ. Sci. 24 571–9
[14] Yue D, You F and Darling S B 2014 Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis Solar Energy. 105 669–78
[15] Gan D 2002 Production of industrial silicon from coal instead of charcoal Ferrolodol 2 25–7
[16] Aminineh P and Yang G 2012 Secure Oil and Alternative Energy: The Geopolitics of Energy Paths of China and the European Union (Leiden: Brill)
[17] CINN 2012 Two third of poly-silicon plants in china have severe pollution problems (cited 2013 12/02). Available from: (www.cinn.cn/wzgk/wy/261374.shtml)
[18] Marigo N 2007 The Chinese silicon photovoltaic industry and market: a critical review of trends and outlook Prog. Photovolt. Res. Appl. 15 143–62
[19] Chang Y, Ries R J and Wang Y 2011 The quantification of the embodied impacts of construction projects on energy, environment, and society based on I-O LCA Energy Policy 39 6321–30
[20] Zhai P and Williams E D 2010 Dynamic hybrid life cycle assessment of energy and carbon of multicrystalline silicon photovoltaic systems Environ. Sci. Technol. 44 7950–5
[21] Lenzen M 2006 Life Cycle Energy And Greenhouse Gas Emissions of Nuclear Energy in Australia (Sydney, Australia: The University of Sydney)
[22] Chang Y, Huang R, Ries R J and Masanet E 2014 Shale-to-well energy use and air pollutant emissions of shale gas production in China Appl. Energy 125 147–57
[23] Fthenakis V M, Kim H C, Frischknecht R, Raupchi M, Sinha P and Snucki M 2007 The Chinese silicon photovoltaic industry and market: a review of trends LCA Energy Policy 35 1025–33
[24] de Wild-Scholten M J, Alesma E A, ter Horst E W, Bächler M and Fthenakis V A 2006 Cost and environmental impact comparison of grid-connected rooftop and ground-based PV systems 21st European Photovoltaic Solar Energy Conf. (Dresden, Germany, 4–8 September)
[25] Alesma E A, de Wild-Scholten M J and Fthenakis V 2006 21st European Photovoltaic Solar Energy Conf. (Dresden, Germany, 4–8 September)
[26] LDK. Products-wafer-multicrystalline 2011 (cited 2013 08/20). Available from: (www.ldksolar.com/pro_wafer_mal.php).
[27] Li J, Wang S, Zhang M, Yang A, Liu S and Sven T 2007 China Solar PV Report (Beijing: Greenpeace East Asia)
[28] Szulcik J, Sivothithanan S, Nijs J F, Mertens R P and Overstraeten R V 2012 Chapter IB-3—low-cost industrial technologies for crystalline silicon solar cells ed A McEvoy, T Markvart and L Castaifer Practical Handbook of Photovoltaics 2nd edn (Boston, MA: Academic) pp 129–59
