Energy Balance of the Global Photovoltaic (PV) Industry - Is the PV Industry a Net Electricity Producer?

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ABSTRACT: A combination of declining costs and policy measures motivated by greenhouse gas (GHG) emissions reduction and energy security have driven rapid growth in the global installed capacity of solar photovoltaics (PV). This paper develops a number of unique data sets, namely the following: calculation of distribution of global capacity factor for PV deployment; meta-analysis of energy consumption in PV system manufacture and deployment; and documentation of reduction in energetic costs of PV system production. These data are used as input into a new net energy analysis of the global PV industry, as opposed to device level analysis. In addition, the paper introduces a new concept: a model tracking energetic costs of manufacturing and installing PV systems, including balance of system (BOS) components. The model is used to forecast electrical energy requirements to scale up the PV industry and determine the electricity balance of the global PV industry to 2020. Results suggest that the industry was a net consumer of electricity as recently as 2010. However, there is a >50% that in 2012 the PV industry is a net electricity provider and will “pay back” the electrical energy required for its early growth before 2020. Further reducing energetic costs of PV deployment will enable more rapid growth of the PV industry. There is also great potential to increase the capacity factor of PV deployment. These conclusions have a number of implications for R&D and deployment, including the following: monitoring of the energy embodied within PV systems; designing more efficient and durable systems; and deploying PV systems in locations that will achieve high capacity factors.

INTRODUCTION

The amount of sunlight energy that flows through an area the size of Connecticut (15,000 km²) each second is roughly equal to the average energy demand of the whole of human society (15 TW). Given the magnitude of the solar energy flow, the direct conversion of sunlight to electricity via photovoltaic (PV) systems provides an opportunity for human society to meet a significant amount of its energy needs from a low carbon, renewable source.

The global installed capacity of PV grew at an average rate of 40% per year in the period 2000−2010.1−3 Global installed capacity in 2010 was around 40 GW, split between six main PV technologies: single-crystal (sc-Si) and multicrystalline (mc-Si) silicon (which together comprise around 90% of the market), amorphous silicon (a-Si), ribbon silicon, cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS) as shown in Figure 1. Growth has been particularly rapid (over 100% per year in the period 2008−2010) in thin film technologies, especially CdTe and CIGS.

Because PV-generated electricity emits few greenhouse gases (GHG) during its lifetime operation, governments worldwide promote PV as a GHG emissions reduction strategy (other reasons include energy security, health, and other environmental concerns). Many governments have policies that support renewable energy technologies through mandated proportions of renewable electricity generation, such as California’s Renewables Portfolio Standard (Senate Bill X1-02) of 33% by 2020;4 financial incentives for system installation, such as the California Solar Initiative;5 or guaranteed prices paid on electricity generated and sold back to the grid, such as the Feed-In Tariffs Scheme (FITs) in Germany and the UK.6 Such policies are aimed at providing a market for PV systems to stimulate production and drive down financial costs of PV deployment. The success of these policies is typically judged by monitoring the financial cost of PV modules and the installed capacity of PV systems, not by their success at reducing GHG emissions.

Primary energy ‘consumption’, with associated GHG emissions, occurs throughout the full life-cycle of a PV system from extraction of raw materials, through panel and BOS manufacture, system operation and maintenance, and finally disposal. This life-cycle primary energy consumption is termed the cumulative energy demand (CED).7 The time taken for a
system to ‘pay back’ its CED is termed the energy payback time (EPBT). Issues with definition and usage of EPBT are discussed in refs 8–10.

Energy technologies with long EPBT (due to high CED or low capacity factor) may constrain industry growth and rapid transition to a low GHG emission energy sector.11 A rapidly growing PV industry may even temporarily exacerbate the problem of GHG emissions if operating at a net energy loss, i.e. consuming more energy each year in manufacturing and installing PV systems than is produced by systems in operation.

Previous research has addressed the material constraints on PV system deployment.12 There has been a long-standing myth that PV systems are unable to generate a positive net energy return over their lifetime.13 While it is clear that individual PV systems can generate a positive net energy yield, the present analysis focuses on the industry-scale issue by addressing the question “Is the global PV industry a net electricity producer?”. If solar PV is to make an important contribution to the global energy system, the industry must eventually deliver more energy to society than it consumes, i.e. it must produce a positive net energy yield. When the PV industry is a small proportion of the overall energy sector, the effects of its being a net energy consumer or provider are negligible. As the industry grows the burden on the overall energy sector becomes greater. This burden may even stifle growth of the PV industry. Hence, there is a large benefit to the PV industry in reducing energetic costs of PV deployment.

This article first explores the general relationship between energy inputs and energy production at the system level and the energy balance of an industry with installed capacity of a number of such systems. This relationship is then explored for the specific case of the global PV industry by looking at the energy consumed in manufacture and installation of PV systems using an analogy of the CED metric.

The PV industry is changing rapidly, both in terms of growing installed capacity and decreasing energy inputs to PV system deployment. In order to track this evolution requires a dynamic perspective that goes beyond the static measures often employed in PV technology assessment. A model is presented to track the change in electrical energy costs of PV system deployment and is applied to historic data for the PV industry between 2000 and 2010. This model is then used to forecast electrical energy costs of future PV system deployment in order to determine the gross and net electricity production of the PV industry to 2020 to determine when the PV industry will become a net electricity provider. Finally, implications for R&D and technology deployment are discussed.

A number of useful definitions are outlined in Table 1.

### ENERGY BALANCE AND INDUSTRY GROWTH

**Inputs and Output from a Single Energy System and an Energy Industry.** Figure 2 depicts energy flows into and out of a single energy production device or system. Flows may be in either primary energy or electricity but must be consistent between inputs and outputs. Construction begins at time, \( t=0 \), requiring a total energy input to construction of \( \dot{E}_{\text{con}} \), assumed to flow at a constant rate, \( \dot{E}_{\text{con}} \). Once the project starts producing energy it is assumed to produce a constant gross flow of energy at rate \( \dot{E}_g \) over the whole lifetime, \( t_L \). An energy flow, \( \dot{E}_{\text{o-r}} \), is required to operate and maintain the system. At the end of the system lifetime, some energy, \( \dot{E}_\text{ret} \), is required for decommissioning; again assumed to flow at a constant rate, \( \dot{E}_\text{ret} \). Two ratios used to characterize the scale of energy inputs and outputs at the system level are the EPBT and EROI (both defined in Table 1). To compute these ratios, energy flows are levelized over the full lifecycle of the energy system, comparing energy inputs - investment - with energy produced by the system. Turning instead to the industry-scale, both the timing and magnitude of energy inputs and output are important to determine the energy balance of the whole industry. A rapidly growing industry may deploy new systems before previous deployment has ‘paid off’ its initial investment, thereby driving the whole industry into deficit. Energy must be imported from outside the industry. The term energy subsidy is used to define this energy input, to distinguish from the energy investment at the system level. An industry composed of individual systems, each with a positive net energy contribution over their lifetimes, could still be a net energy consumer, when it grows rapidly.

An energy production industry is based on sequential installation of many of these energy production systems. Growth of the industry normally proceeds exponentially at rate \( r \). Grimmer (1981) defines the relationship between the fractional reinvestment, \( f \) [\%] of a technology, and the growth rate, \( r \) [\%/yr] of an energy production industry based on deployment of that technology as \( f = r \text{EPBR} = r \frac{(CED)}{(\dot{E}_g)} \). Using this relationship, Figure S1 shows the relationship between EPBT, industry growth rate, and fractional reinvestment. A fractional reinvestment, \( f = 100\% \), marks the breakeven threshold. If \( f < 100\% \), then this means the industry is a net energy producer. If \( f > 100\% \), then the industry is a net energy sink, i.e. consumes more energy than it produces. If an industry is a net energy sink, then there are three means by which it may cross the breakeven threshold: (1) decrease the EPBT of system production by either reducing CED or by increasing the energy output of the system; (2) decrease the rate of growth; or (3) some combination of (1) and (2).

If the industry grows too quickly, such that \( r \gtrsim \frac{\dot{E}_g}{\dot{E}_{\text{con}}} \), the industry is a net energy sink and goes into deficit (see SI Section Derivation of breakeven threshold conditions). Gross and net energy output from this industry growing logistically up to some limit are plotted in Figure 3. Rapid exponential growth of
Table 1. Definitions

We here define a number of useful concepts for analyzing net energy balance that are also illustrated in Figures 2 and 3:

- **Cumulative energy demand** (CED) is the amount of primary energy consumed during the life cycle of a product or a service (7).

- **Cumulative electricity demand** (CE, D) is the amount of primary energy consumed during the life cycle of a product or a service, expressed in terms of electrical energy equivalent.

- **Energy payback time** (EPBT) is the time necessary for an energy technology to generate the equivalent amount of primary energy used to produce it (16), i.e. the ratio of CED to annual primary energy production.

- **Electricity payback time** (E, PBT) is the time necessary for an energy technology to generate the equivalent amount of electrical energy used to produce it, i.e. the ratio of CE, D to annual electricity production.

- **The energy return on investment** (EROI) is defined as “the ratio of the energy in a given amount of the extracted and delivered fuel to the total primary energy used in the supply chain (i.e. the energy that is directly and indirectly required to extract, refine and deliver the fuel)” (17).

- **The electricity-return-on-investment** (E, ROI) is defined as the ratio of the electrical energy produced by an electricity generating system to the total primary energy used in the supply chain, expressed in terms of electrical energy equivalent.

- **Capacity factor** describes the average power output of an electricity generating plant over a period of time (normally one year) relative to the nameplate capacity (18).

- **Net energy** is defined as the amount of energy delivered into the mainstream of economic activity less the amount which is required to bring it there (19).

- **Fractional re-investment** is the proportion of industry energy production that is consumed by the industry to support growth of the industry, i.e. in construction and deployment of new energy production technology.

- **An energy subsidy** occurs when any energy production industry requires more energy for inputs such as capital construction, operating costs, and decommissioning of capital in any one time period than is produced by the industry in that same time period.

- **The break even threshold** is the boundary between an industry having a positive and negative net energy yield, i.e. between being a source or sink of energy and hence requiring an energy subsidy.

- **The break even year** is the year in which a growing energy production industry crosses the break even threshold and makes a positive net energy contribution, i.e. no longer requires an energy subsidy.

- **The payback year** is the year in which the growing industry “pays back” all of the energy subsidy required during its early growth.

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**Figure 2.** Energy inputs and outputs to a single energy production system. Energy inputs (blue) are above the horizontal line, and energy production (yellow) is shown above the line.

**Figure 3.** Energy inputs and outputs for an energy production industry growing asymptotically to some upper limit. Gross output is shown as a bold line; net output is shown with the dashed line.
the industry entails its consuming more energy in system construction and deployment than it produces on an annual basis, thus requiring an energy subsidy. Continued rapid growth drives the industry further into deficit, as shown in Figure 3. If either the industry growth rate or the CED of systems being deployed decrease sufficiently, the industry’s net energy output will pass through a minimum value, after which the industry may then cross the break-even threshold and thereafter produce a positive net energy output. This crossover happens in the break-even year. After some time, the industry produces enough positive net energy to “pay back” the energy subsidy required for its early growth. The year in which this occurs is termed the payback year.

Financial and Energy Costs of PV Systems. Having explored the general case, we now turn to the specific case for the PV industry. Raugei et al. (2012) have compared the energy return on investment (EROI) of PV systems with fossil fuel-based electricity generating technologies. As shown in Table 1, the definition of EROI is the ratio of electricity production to primary energy inputs. In order to make the results commensurate with the metrics developed in our analysis, we have developed the electricity-return-on-investment (EROI) as the ratio of electricity outputs divided by the primary energy inputs converted into electrical energy equivalents assuming a grid conversion efficiency of \(\eta_{\text{grid}} = 0.3\). Raugei et al. have shown that the EROI of electricity production from a single PV system is at least as high as oil-fired electricity (EROI = 4–11, EROI = 12–35), and the EROI of CdTe, which has the lowest energetic requirements for system manufacture and deployment of all PV technologies, is within the range of coal-fired electricity (EROI = 12–25, EROI = 41–82).35 While the device level EROI shows that over its lifetime a PV system will produce between 19 and 38 times the electrical energy equivalents needed to produce it, this metric does not consider the implications of having over 90% of the energetic cost “paid up front”. A breakdown of cost inputs into different stages in the multicrystalline silicon (mc-Si) PV system production process indicates that one-third of financial costs occur in the last stage involving manufacture of the balance of system (BOS) components and system installation.22 This stage accounts for only 13% of energy inputs. The majority of energetic costs (57%) involve the extraction and purification of poly silicon and the production of PV wafers,23 as illustrated in Figure S2. This indicates that not all financial cost reduction will result in commensurate energetic cost reductions.

A number of such energy analyses have determined the CED for the materials, manufacturing, and installation of PV modules and installed PV systems, including BOS costs.7,11,23–49 These studies were compared in a meta-analysis to allow comparison between studies (see SI Section Meta-analysis for methodological details). We convert all inputs to PV system manufacture into equivalents of electricity (discussed in SI section Meta-analysis) to determine the cumulative electricity demand (CED) \([\text{kWh}/\text{W}_p]\) which allows direct comparison of energy inputs into the PV system with electrical output from the system.

Distribution of estimates for CED of the six PV technologies that make up over 99% of the global PV installed capacity are shown in Figure 4. Underlying data are presented in SI PV CED.xlsx. Wafer technologies (sc-Si and mc-Si) have CED between 2 and 16 kWh/W\(_p\). In general thin film technologies (a-Si, ribbon, CdTe and CIGS) have lower CED, ranging between 1 and 7 kWh/W\(_p\).

Learning curves have been used extensively to track financial costs in a variety of energy technologies.50 We present here an analogous model tracking CED of PV system manufacturing and installation. A number of alternative models were evaluated and are discussed in SI Section Alternative models of decreasing CED. The CED of the production of PV modules (left column) and systems (right column), per unit of peak capacity as a function of cumulative installed capacity \([\text{MW}_p]\), is shown on a log–log plot in Figure 5 for sc-Si, mc-Si, a-Si, and for CdTe. The curves demonstrate a clear reduction in the CED of PV system manufacture and installation. Rates of decrease are comparable to those for financial costs within the PV industry.

Cumulative Electricity Demand and Growth of the PV Industry. The CED can be used to determine the electricity payback time (E,PBT) for a PV system. E,PBT for a system is proportional to the CED of that system assuming a fixed capacity factor. Using national data for PV installed capacity and electricity generation between 2005 and 2008,2,3 we have calculated the distribution in capacity factor for the global PV industry, shown in Figure 6. The median for the EIA data (dark blue) is 11.5%, and the median for the UN data (light blue) is 12.5%. Average values are highly weighted toward the capacity factor of Germany, which makes up nearly 40% of global installed capacity.

We combine rates of decrease in CED from Figure 5 with E,PBT and technology specific growth rates shown in Figure 1 to determine the historical electricity balance of each of the PV technologies between 2000 and 2010. The growth trajectories of the PV technologies are depicted on a biannual basis in Figure 7, based on an average capacity factor of 11.5% for global PV deployments as a whole. Sizes of circles represent the installed capacity of each of the PV technologies.

At the global average growth rate between 2000 and 2010 of 40%, for the PV industry as a whole to be a positive net electricity provider, the E,PBT must be below 2.5 yrs, which is equivalent to a CED of 2.5 kWh/W\(_p\). All of the PV technologies started at or below the breakeven threshold in the year 2000. As their rates of growth increased over time, they
and installed new capacity. We assume a system lifetime of 25 years and zero operation and maintenance and decommissioning electricity costs. In reality, operation, maintenance, and decommissioning costs account for less than 5% of total lifecycle electrical energy costs for PV systems. As such, electrical energy inputs due to O&M activity will be less than 1% of total annual electricity inputs to the PV industry, since they are spread over the full 25 year lifetime of the PV system. Decommissioning electrical energy inputs lag construction inputs by the lifetime of the system, so remain negligible over the modeled time period. This assumption is discussed in more detail in SI Section O&M and disposal costs.

We also assume that the PV industry received until the year 2000 a total electricity subsidy of 10 TWh from the existing electricity system. We carried out a Monte Carlo analysis (full details of which can be found in SI Section: Monte Carlo simulation) to test the sensitivity of the model outputs to varying technology growth rates, CE<sub>eD</sub> and capacity factor of PV installations. We assume a continuation of growth rates from the period 2005–2010 and historical rates of reduction of CE<sub>eD</sub>.

### RESULTS AND DISCUSSION

Figure 8 shows the estimated gross and net annual power [TWh/yr] (top) and cumulative electricity [TWh] (bottom) output of the PV industry in both absolute terms (left axis) and annual output as a fraction of the 2010 global annual electricity production of 20,000 TWh/yr (right axis). Historical gross power output [TWh/yr] is plotted as blue circles. The gross output (green line) represents the median value from the sensitivity analysis. The net output is plotted in different shades for both 50% and 100% confidence intervals about the median (dark red line).

There is a 50% probability that the PV industry stopped being a net consumer of electricity by 2011. Figure 8 (top) shows that, in the ‘worst case’ scenario, the PV industry does not become a net electricity producer until 2015. Figure 8 shows that the payback year has a 50% likelihood of occurring between 2012 and 2015 with the probability increasing to almost certainty by 2020. Thus, the PV industry should “pay back” electricity consumed in its early growth only by the end of this decade.

The CE<sub>eD</sub> of PV system production and installation has decreased since the year 2000. With further reduced CE<sub>eD</sub>, the PV industry could achieve even greater net electricity yields and shows that deployment of most PV technologies was operating at a net electricity loss for most of the decade 2000–2010. As of 2010 — the latest year of historical data — the only technology producing a positive net electricity yield was ribbon silicon. The fractional reinvestment of CdTe in 2010 was similar to that of sc-Si at around 150%, despite CdTe having a much higher growth rate (160% compared with 63%). This highlights the obvious benefit of technologies with lower CE<sub>eD</sub>. This perspective does not incorporate the distribution in capacity factor nor any uncertainty in the CE<sub>eD</sub>. To incorporate these factors, we undertook an analysis using a system dynamics model outlined in SI Section Model Structure.

The installed capacity of PV in the year 2000 was 1.4 GW, rising to 22.9 GW in 2010. Using historical installed capacity (Figure 1) and projecting average growth rates from 2005 to 2010 to estimate installed capacity beyond 2010, coupled with the curves tracking reduction in CE<sub>eD</sub> (Figure 5), we modeled the net electricity production of the PV industry to 2020, after accounting for electricity to construct and install new capacity.

Our analysis found that the PV industry was a net electricity consumer as recently as 2010, and in 2008 the PV industry consumed 75% more electricity than it produced. Figure 7 all moved into the negative net electricity domain, with the exception of ribbon silicon, despite reduction in their CE<sub>eD</sub>.
thus have the potential to offset more GHG emissions. If the PV industry continues at its current growth rate, by 2020 production could reach 3300 TWh/yr (approximately 17% of current global annual electricity production). If no decrease in CE$_D$ occurs, this would entail an electrical energy input of around 2937 TWh/yr, representative of a fractional reinvestment of 89%. If, however, the PV industry continues the historical rate of decreasing CE$_D$, the input would be 264 TWh/yr, a fractional reinvestment of 8%, corresponding to an industry-wide, mean CE$_D$ of some existing polymer PV systems. Consequently, it is important to continue to track and reduce the CE$_D$ of the PV industry.

A number of factors could decrease the fractional reinvestment rate: reducing the growth rate of the PV industry, reducing the CE$_D$ or increasing the capacity factor of PV system deployment. If the goal is a rapid transition to a sustainable, low-carbon energy sector, then maintaining high PV industry growth rates is beneficial. Consequently, the PV industry will benefit from further reductions in the CE$_D$ and deployment in areas with higher capacity factors.

Technology development can reduce the CE$_D$ of PV by decreasing the material requirements per unit of capacity [kg/$W_p$] (or alternatively increasing the device efficiency per unit of material used [$W_p$/kg]) and by decreasing the energy required to process the materials. R&D can decrease the amount and purity of materials required in order to maximize the utilization of a given material feedstock (e.g., silicon). There are fundamental thermodynamic limits to our ability to reduce the CE$_D$, such as the minimum chemical exergy that must be provided in order to purify a material from its usual ore state, for example obtaining pure silicon from silica. It is therefore important to simultaneously increase net energy production by also increasing system efficiency and durability. A number of nascent technologies exist to boost PV efficiency beyond the Shockley-Queisser limit (which defines the maximum theoretical efficiency of a single p-n junction solar cell at 34%) such as multijunction and multiple-exciton cells, hot-carrier cells, up-conversion, or thermophotonics.51

The other major factor in how well the PV industry performs going forward is the capacity factor that new installations can achieve. Doubling the capacity factor, ceteris paribus, halves the E$_{PBT}$. Deployment of PV in regions with high insolation and capacity factors provides greater overall benefits for the energy system. As such, policies aimed solely at rapid deployment in areas with low insolation, without increasing net electricity yield (by either decreasing CE$_D$ or improving PV performance), might not be beneficial for the energy sector as a whole.

In summary, a model has been developed to track the evolution of electrical energy inputs to PV system deployment,
more specifically the change in CE,D as a function of cumulative installed capacity of PV. The benefits of this model have been demonstrated by modeling both historic evolution of the PV industry between 2000 and 2010 and also by forecasting PV industry performance out to 2020.

Judging the impact of a GHG emissions reduction strategy should be based on the actual GHG emissions reduction achieved by PV deployment considering the full life-cycle of emissions. Electrical energy inputs to and electricity production by the PV industry should be monitored to judge the success of such a strategy. This requires supplementing economic and market analyses with energy and material flow analysis. The importance of reducing CE,D and increasing net energy should also be recognized as explicit goals in their own right.

The electricity balance of the PV industry is critical to the success of any GHG emissions reduction strategy based on PV deployment. This analysis is, however, not limited to the PV industry but applies equally to any rapidly growing alternative energy industry (e.g., wind, solar thermal energy conversion or energy storage) as well as energy conservation strategies (e.g., insulation, low-energy buildings, or fuel-efficient vehicles) that require large, up-front investment.

**ASSOCIATED CONTENT**

* Supporting Information
  Tables S1–S3, Figures S1–S3, and text. This material is available free of charge via the Internet at http://pubs.acs.org.

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**Notes**

The authors declare no competing financial interest.

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**REFERENCES**

(6) Sijm, J. The performance of feed-in tariffs to promote renewable electricity in European countries; Energy Research Centre of the Netherlands ECN, 2002.
(41) Raugei, M.; Bargigl, S.; Ugliati, S. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. Energy 2007, 32, 1310−1318.
(49) Held, M.; Ilg, R. Update of environmental indicators and energy payback time of CdTe PV systems in Europe. Prog. Photovoltaics 2011, 19, 614−626.