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A climate rationale for research and development on photovoltaics manufacture

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Abstract

Photovoltaic (PV) power generation is critical to many climate policy goals, as PV electricity results in little or no greenhouse gas (GHG) emissions during use, utilities and governments view PV installations as a way to accelerate progress towards emissions reduction targets. However, typical analyses of the GHG implications of the PV lifecycle ignore inter-temporal effects, in which the initial GHGs emitted in PV manufacturing phase must be offset by avoided fossil-fuel combustion emissions during use. Thus, the overall climate benefits of PV are a function of both GHG efficiency of PV manufacture, and electricity generation efficiency of deployed modules during use. Improvements to PV manufacture result in immediate climate benefits, in contrast with improvements in module efficiency which may offset greater GHG emissions, albeit over decades of useful life.

This study presents a novel framework using the cumulative radiative forcing(CRF) metric to demonstrate the significant climate benefit of improving PV manufacturing processes predominantly located in GHG-intensive geographies and determines the equivalent increase in module efficiency that provide the same climate benefit. The findings show low-carbon PV manufacturing increases the life-cycle climate benefit by 20% and is equivalent to increasing the module efficiency from a baseline value of 17% to 21.7% and 16% to 18.7% for mono-Si and multi-Si modules, respectively. With commercial module efficiency having increased annually by only 0.25% over the last 12 years, the implication is that improving PV manufacturing may be more effective than module efficiency improvements for increasing the climate benefit of terawatt scale PV installations.

1 Introduction

Global photovoltaic (PV) installations are projected to exceed 1 terawatt as policy-makers strive to reduce global warming impacts of electricity production. For example, the SunShot Initiative launched by the United States Department of Energy proposes more than 630 GW of installed PV capacity by 2050 [1] and China is targeting 150 GW of installed capacity by 2020 [2]. The climate benefits of PV are determined by the displacement of non-renewable electricity sources during the use phase of the PV life-cycle, compared to the GHG emissions required to manufacture PV modules. Thus, improvements in the life-cycle GHG emissions of PV can take two forms (1) increasing module efficiencies to generate more electricity during use, and, (2) reducing GHG emissions associated with PV manufacturing processes.

To date, the dominant PV research and development (R&D) strategy is to improve life-cycle environmental and economic performance by increasing PV module efficiency [3][4]. A review and categorization of the 137 Department of Energy PV-related competitive awards from 2012 to 2016 shows that 48% of the R&D spend was allocated to increasing the module efficiency and 9% to improving the upstream PV manufacturing processes (section 11 supplementary information). Furthermore, if only silicon technologies are considered (mono-Si, multi-Si and thin film Si), the R&D spend on projects focusing on improving PV manufacturing is 4%. In response to R&D, use phase efficiencies for commercial and emerging PV technologies have increased significantly over the last 3 decades [5], albeit at irregular rates [6]. Nonetheless, the upstream silicon feedstock purification processes necessary to produce high-efficiency modules continue to be energetically expensive, accounting for 40% of the energy consumed in manufacturing crystalline silicon modules [7]. Furthermore, as PV manufacturing increasingly migrates to locations sourced by GHG-intensive electric mixes, the GHG emissions of global PV manufacture may also increase. For example, China's contribution in the worldwide module production market has increased from 5% in 2005 to 69% in 2014 [8]. Therefore, current PV R&D efforts focusing on module efficiency improvements may forgo opportunities to enhance the climate and environmental performance of PV systems through manufacturing improvements, as well as derive concomitant benefits like reduced toxicity, better human health and safety [9] and decreased reliance on materials with limited availability [10]–[12].

Reducing the climate impact of upstream processes associated with PV technologies requires understanding the technology specific trends that drove historical improvements and using this to prospectively analyze the potential for further incremental improvements as intrinsic material and manufacturing limits are approached. For example, reduction in the silicon wafer thickness which drove past manufacturing improvements, may not be a viable strategy in the future as breakage and cracking rates in wafer manufacturing operations increase below a threshold thickness [13]. Additionally, it is necessary to compare the potential of hypothetical improvements in current PV manufacturing processes to those that may be available by increases to module efficiency that could achieve the same climate benefit. Because manufacturing occurs prior to use, such a comparison must account for temporal dimensions of radiative imbalances

in the atmosphere [14]–[18]. Thus, for an equal mass of GHG emitted and offset, the climate impact of manufacturing emissions is greater than the global warming burdens avoided by the GHGs offset later in the use phase.

PV environmental studies quantify the PV manufacturing improvements using the GHG payback-time, energy payback-time or GHG intensity of PV electricity metrics. The energy payback-time is the time required by the PV module to generate the amount of energy utilized during manufacturing [7] [19]–[30]. The GHG intensity of the PV electricity is the ratio of the mass of GHG emitted during PV manufacturing and the electricity generated over the lifetime of the PV module [7] [19]–[21][24][25][29][30]. The GHG payback-time is the time required for the PV module to displace (at the deployment site) the mass of GHG emitted during PV manufacturing[24][26]. While quantifying the energy and GHG trade-off over the manufacturing and the use-phase of the PV module, the aforementioned metrics do not account for the time-sensitive climate impact of manufacturing GHGs that are emitted earlier in the PV lifecycle than the GHGs avoided subsequently post-installation[16]. Therefore, existing PV environmental studies cannot inform the PV R&D policy on the actual magnitude of the climate gains to be achieved by reducing the manufacturing energy and GHG footprint. Although there have been recent reviews and harmonization studies on the GHG intensity of PV electricity[16][17] and research on optimally locating manufacturing and deployment sites for reducing the GHG and energy impacts during rapid growth phases of global PV installations [33][34], these stopped short of analyzing the potential for future gains in time-sensitive climate benefit of improving PV manufacturing. One study presented manufacturing trends over a shorter time frame of 5 years [35], but does not quantify the climate benefit of GHG and energy reduction in PV manufacturing processes using a time sensitive metric.

This paper addresses the above knowledge gap by presenting a novel framework to quantify the time-sensitive climate impact of GHGs emitted and avoided over the PV lifecycle, demonstrates the difference between using the GHG and the climate metric to inform R&D on increasing the climate benefit from PV, and analyzing if the climate benefit from PV manufacturing improvements are significant enough to motivate increased R&D on reducing the energy and material footprint of PV modules. Through analysis of significant manufacturing improvements in an environmental experience curve (Figure 1), this research quantifies the climate benefit of PV manufacturing improvements using the time sensitive cumulative radiative forcing (CRF) metric [36]. The CRF metric is a time integrated measure of the radiative forcing (in Wm^{-2}) due to an imbalance in the incoming and outgoing infrared radiation in the atmosphere induced by a GHG emission and depends on the mass and timing of the GHG emission [37]. By calculating the net CRF benefit over the PV lifecycle as the difference between the CRF impacts of PV manufacturing emissions and the CRF benefit through the GHGs subsequently offset by PV electricity generation, this research determines the time-sensitive climate benefit of GHG emission reductions through PV manufacturing improvements. Further, this approach demonstrates that the conventional GHG metrics underestimate the climate benefits of PV

manufacturing improvements (Figure 2). To accelerate the development of less climate-intensive PV manufacturing pathways for the future, this work identifies CRF hotspots in existing PV manufacturing processes (Figure 4). To demonstrate the significance of the climate benefit from manufacturing improvements, we calculate the equivalent increase in module efficiency delivering the same CRF benefit as addressing the manufacturing hotspots (Figure 3 and Figure 5) and compare this equivalent increase with the historical rate of increase in commercial module efficiency. Furthermore, based on the findings, we identify three PV manufacturing R&D strategies that can address the PV manufacturing hotspots and increase the climate gain from future PV installations that are expected to reach a terawatt scale (section 3.6).

2 Methods

2.1 Data collection, harmonization and generation of PV manufacturing experience curve

To analyze temporal trends in the manufacturing energy embodied in a PV module, data from published PV studies must be harmonized for the primary energy required to produce one peak watt of a PV module (MJ/W_p) [7], [19]–[21], [26], [35], [38]–[109]. Four commercially dominant PV technologies – mono-crystalline silicon (mono-si), multi-crystalline silicon (multi-si), cadmium telluride (CdTe) and amorphous silicon – account for around 99% of the world PV market. A broad review results in 214 data points, covering energy requirements for raw material extraction, purification, fabrication of PV cells, and PV module assembly. However, data from studies with ambiguous system boundary definitions or assumptions for the material and energy used in PV production must be eliminated. For example, we discounted a data point from a study which did not mention if frames are included in the energy required to manufacture the module [81]. To avoid duplications, data points which were repeated across multiple studies are considered only once as a part of the final analysis. For example, multiple studies[63][109] reported the same value for CdTe and we included this value only once in our analysis .

After this initial data screening, the system boundaries and assumptions for the remaining data points are examined to facilitate consistent comparisons across data from across different studies. For crystalline silicon modules, the following processes are included as a part of the system boundary: quartz processing and purification of metallurgical grade silicon, production of solar-grade silicon from metallurgical grade silicon, cell and module manufacturing, and capital equipment. For amorphous silicon and CdTe the system boundary includes cell production, module manufacturing, and capital equipment. If the reported energy values did not include energy requirements for all the steps in the system boundary, we assume values based on contemporary studies published on the same PV technology. For example, a study published in 1991[59], does not include the energy requirements for up-stream silicon purification and, therefore, we include the value reported in another study[77] which was published two years earlier. The data harmonization exercise resulted in the inclusion and rejection of 51 and 163 data points, respectively.

Based on the 51 data points collected and harmonized between 1988 and 2013, we generate a manufacturing experience curve by plotting the primary energy requirements for manufacturing 1 peak watt of the module for each PV technology as a function of time (Figure 1). The complete list of the literature surveyed, PV manufacturing energy data points, justification for the inclusion or rejection of data points, ambiguous boundary conditions and duplications is listed in section S1 of the supplementary information (SI).

2.2 Cumulative Radiative Forcing (CRF) of PV installations

The CRF impact of one kg of a GHG emission for a time period t is given by

$$CRF_{ghg} = \int_0^t [RE_{ghg} \times f(t)_{ghg}] dt \quad 1$$

In equation 1 RE , the radiative efficiency of the GHG ($Wm^{-2}kg^{-1}$), is the radiative forcing induced per unit mass of the gas in the atmosphere and $f(t)$ represents the fraction of the initial GHG emission remaining in the atmosphere after a time t . $f(t)$ for CO_2 (equation 2) and CH_4 (equation 3) is given by [36]

$$f(t)_{CO_2} = 0.217 + 0.259e^{-t/172.9} + 0.338e^{-t/18.51} + 0.186e^{-t/1.186} \quad 2$$

$$f(t)_{CH_4} = e^{-t/12} d(t) \quad 3$$

RE_{CO_2} and RE_{CH_4} have the values of 1.75×10^{-15} and $1.30 \times 10^{-13} Wm^{-2}kg^{-1}$, respectively [16]. The CRF impact of CH_4 is increased by 40% to include the indirect impacts of CH_4 emissions on stratospheric water vapor and ozone concentrations [110]. The CRF analysis in this paper considers only carbon dioxide and methane as a previous study shows that these two GHGs are responsible for 97% of the CRF impacts over the PV lifecycle [16].

The net global warming benefit (CRF_{benf_t}) in year t of the PV use-phase is given by the difference between the global warming impact avoided (CRF_{avd_t}) when PV electricity displaces fossil-fuel derived electricity, and the global warming impact of PV manufacturing GHG emissions (CRF_{mnf}).

$$CRF_{benf_t} = CRF_{avd_t} - CRF_{mnf} \quad 4$$

The avoided global warming impact, CRF_{avd_t} is given by

$$CRF_{avd_t} = \sum_{x=1}^t avd_{ghg_x} \times \int_0^x [RE_{ghg} \times f(t)_{ghg}] dt \quad 5$$

where, avd_{ghg_t} is the mass of GHG emissions avoided in year t per m^2 of the PV module and is given by

$$avd_{ghg} = depl_gGHG_kWh \times kWp_m^2 \times irr_d \times perf_rat \times (1 - perf_deg)^t \quad 6$$

where, $depl_gGHG_kWh$ is the GHG intensity of the grid electricity displaced by the PV system at the deployment location (g/kWh), kWp_m^2 is the peak wattage per m^2 of the PV module (kW), irr_d is the annual solar irradiation ($kWh\ m^{-2}\ yr^{-1}$) at the deployment location, $perf_rat$ (performance ratio) is the ratio of the AC to DC power generated by the PV system and $perf_deg$ is the annual performance degradation of the PV module (%).

The global warming impact of PV manufacturing GHG emissions, CRF_{mnf} , is given by

$$CRF_{mnf} = mnf_{ghg} \times \int_0^t [RE_{ghg} \times f(t)_{ghg}] dt \quad 7$$

where mnf_{ghg} , the PV manufacturing emission, is given by

$$mnf_{ghg} = (fdstk_kWh + non_fdstk_kWh) \times mnf_gGHG_kWh \quad 8$$

where $fdstk_kWh$ is the electricity required per m^2 of the module for feedstock purification processes (kWh/m^2), non_fdstk_kWh is the electricity required for non-feedstock processes per m^2 of the module (kWh/m^2), and mnf_gGHG_kWh is the GHG intensity of the electricity at the PV manufacturing location (g/kWh).

The electricity required for feedstock purification, $fdstk_kWh$, is given by

$$fdstk_kWh = kWh_Si \times Si_Wp \times Wp_m^2 \quad 9$$

where kWh_Si is the electricity required to produce one gram of solar grade silicon (kWh/g) and Si_Wp is the number of grams of silicon required to manufacture 1 peak watt of the PV module (g/Wp).

As 69% of the world's mono and multi-crystalline PV modules are manufactured in China [8], we assume the Chinese grid mix for CO_2 and CH_4 intensity of the electricity used at the PV manufacturing location.

The list of abbreviations, the assumptions for the module efficiency and the module manufacturing energy requirements for mono-Si and multi-Si and the parameters used to calculate the avoided CRF, PV manufacturing CRF and the CRF pay back time (PBT, equations 1 to 10) are tabulated in section S2 in the SI.

The CRF PBT is calculated as the year in which CRF burdens of PV manufacturing is equal to the CRF benefits of avoided GHG emissions from PV deployments and is given by

$$CRF_{avd_t} = CRF_{mnf} \quad 10$$

The CRF PBT is a short-term temporal metric as it quantifies the minimum time for the PV system to realize CRF benefits and the long-term CRF benefits are expected to accrue beyond the CRF PBT period over the 25-year lifetime of the PV system (equation 4). This study reports short-term CRF PBT in addition to long-term impacts, as rapid cumulative PV capacity additions can have short-term negative GHG and CRF burdens [16][17].

2.3 Difference between the GHG and CRF metric

To demonstrate the difference between the climate impacts as measured by the GHG and CRF metric, we plot the net GHG and CRF benefit equivalence lines for a baseline scenario representing the current state of commercial PV technology and improved PV manufacturing scenarios (Figure 2). The equivalence lines represent combinations of the GHG-intensity of PV manufacturing and the module efficiency that result in the same net GHG and CRF benefit, respectively. The net GHG benefit is the difference between the total GHG avoided over 25-year lifespan of the PV installation (avd_{ghg} in equation 6) and the GHG emission from PV manufacturing (mnf_{ghg} in equation 8). The net CRF benefit is determined from equation 4. Manufacturing improvements are simulated by decreasing the GHG intensity of PV manufacturing from the current value to a lower value representing less-GHG intensive PV manufacturing practice.

A difference in the climate benefits as measured by the GHG and the time-sensitive CRF metric is demonstrated by a difference in the (1) sensitivity of the CRF and GHG equivalence lines to the GHG intensity of PV manufacturing and (2) magnitude of benefits between the two GHG and CRF benefit equivalence lines corresponding to the baseline and improved manufacturing scenario.

2.4 Short-term equivalence between module efficiency increase and manufacturing improvements

To demonstrate the comparability of short-term climate benefits between a reduction in energy and material intensity of PV manufacturing processes and an increase in the module efficiency improvements, we generate an equivalence plot between the two strategies using the CRF payback time (CRF PBT) metric (Figure 3). The material intensity is accounted for by the mass of solar-grade silicon required to manufacture 1 m² of the PV module (kg/m²) and the energy intensity by the electricity required to purify one kg of solar-grade silicon (kWh/kg). The assumptions for material and energy intensity are based on values reported in literature (Table 3, SI). We consider solar-grade silicon as it the most energetically burdensome raw-material in a crystalline-Si PV module and accounts for 40% of the energy required to manufacture the PV module [7]. The plot (Figure 3) contains a series of CRF PBT lines which represent combinations of module efficiency and manufacturing material and energy intensity values that result in a particular CRF PBT (calculated using equations 4 to 10). Moving vertically downwards on the plot, from a higher to lower CRF PBT line, represents a decrease in CRF PBT through a reduction in manufacturing material and energy intensity. Moving horizontally towards the right, between the same pair of CRF PBT lines, represents an equivalent decrease in CRF PBT through

an increase in module efficiency. This downward or rightward movement between the same pair of lines represents an equivalence in reducing CRF PBT by decreasing the manufacturing energy and material intensity or increasing the module efficiency, respectively.

The CRF benefits of PV are dependent on the GHG intensity of the electricity avoided at the deployment location ($\text{deply_gCO}_2\text{ kWh}$ in equation 6 and CRF_{avd} in equation 4). For example, PV that displaces hydropower will result in lesser comparative climate benefits than PV that displaces coal combustion. To account for this geographical sensitivity, we will generate the CRF PBT equivalence plot based on grid emissions in Wyoming and California which are assumed to represent upper and lower extremes for grid GHG intensity, respectively ($\text{deply_gCO}_2\text{ kWh}_{\text{CA}}$ and $\text{deply_gCO}_2\text{ kWh}_{\text{WY}}$, Table 1 SI). The difference in the grid GHG intensity is a result of Wyoming's reliance on coal when compared to California's reliance on renewable sources and natural gas for electricity generation.

2.5 Climate hotspots in PV manufacturing

To maximize the long-term CRF benefits of future PV deployments, we identify the PV manufacturing hotspots by modeling the energy and flows for manufacturing 1 m² of a multi-silicon module (Figure 4). The parameters in the hotspot analysis include energy for purifying metallurgical grade silicon from quartz, energy and feedstock requirements for solar grade polysilicon production, manufacturing cells, wafers and panel and the GHG intensity of electricity at the manufacturing location. Multi-silicon technology is selected as it is the most widely installed PV technology with a 56% PV market share [8]. To investigate sensitivity, each parameter is increased and decreased by 10% from the baseline value (section S4 in the SI) while keeping other parameters fixed. The net change in the CRF benefit is calculated from equation 4. The most significant hotspots result in the highest variation in the CRF benefit resulting from the sensitivity investigation.

2.6 Climate benefits of addressing PV manufacturing hotspots

Based on the hotspots identified, this paper explores five scenarios that simulate improvements in PV manufacturing parameters that are assumed to be within the operational control of the PV manufacturer and quantify the corresponding CRF benefits (Figure 5). The scenarios simulate both: 1) incremental energy and material efficiency improvements in incumbent PV manufacturing processes, and 2) replacement of incumbent processes with novel methods that are expected to gradually gain a market share in the future.

Reducing the energy intensity of the Siemens' process ("Siemen's energy reduction"): The Siemen's chemical vapor deposition process produces between 80 to 90% of the world's solar grade silicon [111][112]. Design improvements that can potentially reduce the manufacturing energy requirements of the Siemen's process include : reducing the radiative losses in the reactor by using thermal shields, capture and recycling of waste heat, increasing the reactor capacity, and optimizing deposition conditions and growth rate [112][113][114][115][116]. In this scenario, the energy requirements for the Siemen's process is reduced by 48 kWh/kg (from

baseline conditions) by increasing the number of reactor rods, improving the properties of the reactor wall and introducing thermal shields [114].

Alternatives to the Siemen's process ("FBR" and "UMG"): Two scenarios simulate the gradual market adoption of alternate solar-grade silicon production processes through either: (1) the fluidized bed reactor route which has a 6% share of the polysilicon market [111] and is currently the main, commercially significant, alternative to the Siemen's process [112], or (2) the upgraded metallurgical grade (UMG) route which is an emerging process that requires less energy but has no appreciable market share.

The energy estimates for FBR energy requirements range between 30 to 75 kWh per kg of polysilicon [112][117][118] and a middle value of 50 kWh/kg is assumed for this scenario (FBR). The energy requirements for UMG range between 18 to 55 kWh per kg of purified polysilicon [112][119][120] and this scenario (UMG) assumes a middle value of 35 kWh/kg.

Reducing kerf losses ("sawing 100 μ m wire 2 μ m abrasive" and "sawing diamond coated wire"): Around 50% of the purified and energetically intensive polysilicon is wasted as kerf loss during the wafer sawing process in the PV manufacturing industry [121]. The kerf loss in the incumbent multi-wire slurry sawing (MWSS) process is linearly related to the steel wire thickness and the diameter of the abrasive silicon carbide particles in the slurry [122]. Currently, the standard values for steel wire and abrasive particle diameters for MWSS in the industry are 120-140 μ m and 9.3 μ m diameter, respectively [121][122]. Strategies to reduce kerf loss include: reducing the abrasive particle and steel wire diameter, replacing MWSS with diamond coated wire sawing, recycling the solar grade silicon kerf from the slurry and novel kerfless sawing processes [123][124][125][126][121]. This paper models improvements in future wafer sawing process through two scenarios:

(1) "sawing 100 μ m wire 2 μ m abrasive" where the kerf loss in MWSS is decreased by reducing the steel wire diameter and silicon carbide particle size to 100 μ m and 2 μ m, respectively, and this decreases kerf loss by 50% [127], and

(2) "sawing diamond coated wire" where diamond coated wire sawing replaces MWSS which reduces kerf loss by 25% [128]. Diamond coated wire sawing has been considered to replace MWSS as it is expected to be increasingly adopted in the PV manufacturing industry, is compatible with the incumbent upstream Siemen's process, does not decrease the cell efficiency or wafer quality for downstream processes relative to the MWSS process and doesn't require slurry based sawing [129][126][130]. For these reasons, this approach avoids silicon losses in the slurry and the calculation for the reduced silicon feedstock requirement in these two scenarios is explained in section S8 of the SI.

Reducing silicon wafer thickness ("SiLayer 100 μ m"): A reduction in the silicon wafer thickness will reduce energy and material contributions from upstream silicon purification processes that represent around 40% of the silicon PV module's energetic footprint [7]. At

present, the silicon wafer is 180 μm thick and this incremental scenario assumes that the thickness can be reduced to 100 μm without a significant loss in efficiency or wafer breakage[131].

Sourcing manufacturing energy from low-carbon sources (“PV elect mnf”, “Natural gas elec mnf”): Apart from decreasing the material and energy intensity of processes, the environmental performance of PV manufacturing can be improved by utilizing electricity from less GHG intensive sources. With domestic PV deployments increasing rapidly in China [2] and natural gas expected to meet 10% of China’s total energy needs in 2020 [132], this scenario assumes that the electricity requirements for PV manufacturing in China will be sourced from PV installations and combined cycle natural gas systems. The CRF benefits will be calculated based on a GHG intensity of 51 and 450 gCO_2/kWh for electricity sourced from PV installations and combined cycle natural gas systems (section S3 in SI).

2.7 Long-term equivalence between module efficiency increase and manufacturing improvements

Addressing the PV manufacturing hotspots results in GHG improvements that could also be achieved by increasing the PV module efficiency, as both the approaches increase the CRF benefits over the PV systems life-span. We demonstrate this equivalence (Figure 5) by calculating the increase in the CRF benefit (using equation 4) for the strategies that address the PV manufacturing hotspots when compared to the baseline scenario. The manufacturing parameters are then fixed at the baseline value (Table 2 in SI) and the increase in baseline value of module efficiency required to achieve the same increase in CRF benefit over the 25-year lifetime of a PV module is determined.

3 Results and Discussion

3.1 PV manufacturing environmental experience curve

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Figure 1 PV manufacturing energy trends for mono-silicon, multi-silicon, CdTe and amorphous silicon. The lines depict a linear fit for the data points.

The results of the data harmonization of the PV manufacturing energy values (Figure 1) indicate that mono-Si, multi-Si and CdTe have shown a reduction of approximately 40, 32 and 18 MJ/Wp between 1988 and 2012, 1988 and 2012, and 1993 and 2010, respectively. These historical energetic improvements in manufacturing crystalline PV technologies were driven by the shift in feedstock from electronic grade silicon to solar grade and the reduction in the mass of silicon feedstock per m² of the module. The shift in the feedstock to solar grade silicon was driven by a worldwide shortage in the supply of electronic grade silicon [91][112]. The energy intensity of manufacturing solar grade silicon (100-150 kWh/kg [91]), produced via the modified Siemen's process, is lower by 50-100 kWh/kg than electronic grade silicon (200-250 kWh/kg [91][77][59]) due to the lower purity requirement of solar grade silicon. A reduction in wafer thickness in crystalline PV modules from 350 μm in 1999 to 270-300 μm in 2005 resulted in a 25% reduction in embodied energy [35]. For the period from 2004 to 2008, Fthenakis et al have reported a 40% reduction in manufacturing energy requirements for mono-Si cells from a reduction in cell thickness [109]. For the CdTe PV industry manufacturing energy improvements can be attributed to incremental process improvements, improved production yields and a reduction in CdTe layer thickness [133].

3.2 Underestimation of the climate benefit of PV manufacturing improvements as measured by GHG metrics

Figure 2 Difference in the climate benefit of improved PV manufacturing as measured by the GHG and CRF metric. A reduction in the GHG intensity of PV manufacturing from X to X' increases the net GHG benefit by only 10% (2900 to 3200 kg CO₂e) when compared to 20% increase in the net CRF benefit (4.2x10⁻¹¹ to 5.0x10⁻¹¹ Wm⁻²yr). The optimal pathway to increase the climate benefit from PV based on the CRF metric (X→C) is more sensitive to manufacturing improvements than the pathway based on the GHG metric (X→G).

To demonstrate the difference between the climate impacts as measured by the GHG and CRF metric, we use the current state of technology for commercial multi-silicon PV modules with a baseline efficiency of 16% and a manufacturing GHG intensity of 314 kg CO₂e/m² (point X, Figure 2). This corresponds to a net GHG and CRF benefit of 2900 kg CO₂e and 4.2x10⁻¹¹ Wm⁻²yr, respectively, over the 25-year lifespan of the PV module. The upper GHG (green) and CRF (orange) equivalence lines represent combinations of module efficiency and PV manufacturing GHG intensity resulting in the same net GHG and CRF benefit, respectively, as the baseline scenario. Each of the lower green and orange line represents a 10% increase in the net GHG and CRF benefit (versus the upper line), respectively, due to lowered GHG intensity of PV manufacturing. For example, reducing the GHG intensity of PV manufacturing to 17 kg CO₂e/m² (X→X' by using low GHG electricity for PV manufacturing) increases the net GHG and CRF

benefit to 3200 kg CO₂e and 5.0×10^{-11} Wm⁻²yr, respectively. The optimal pathway of achieving the same increase in GHG benefit is to move from X->G along the shortest distance between the two GHG equivalence lines. However, the optimal pathway when accounting for the climate forcing benefit of reducing the GHG intensity of PV manufacturing is X->C.

The difference in the trajectories of X->C and X->G calls attention to the fact that the CRF metric is more sensitive to the GHG intensity of PV manufacturing than the net GHG benefit metric. Improved PV manufacturing (X->X') increases the net GHG benefit by only 10% (2900 to 3200 kg CO₂e) when compared to a 20% increase (4.2×10^{-11} to 5.0×10^{-11} Wm⁻²yr) in the net CRF benefit. Similar results are observed for multi-Si and mono-Si modules manufactured in China and deployed in California and Wyoming (section S9 in SI). Manufacturing emissions avoided earlier in the PV lifecycle, by lowering the GHG intensity of PV manufacturing, have an immediate climate benefit (as measured by the CRF metric) than emissions avoided later in the use phase which are dependent on the module efficiency. Therefore, conventional time-insensitive GHG based metrics underestimate the climate benefit of PV manufacturing improvements. Policies based on GHG gas targets[134] might emphasize investments on module efficiency at the expense of manufacturing improvements. By comparison, policies based on a CRF metric will correspond better with eventual climate impacts [16].

Due to the significant difference in magnitude of impacts measured by the time-insensitive GHG metric and the CRF metric (Figure 2), this paper uses the CRF metric to quantify the short-term and long-term benefits of PV manufacturing improvements in subsequent results.

3.3 Short-term climate benefit of improved PV manufacturing

Figure 3 CRF payback time (PBT) equivalence between module efficiency improvements and reduction in feedstock energy intensity (left plot) and feedstock material intensity (right plot) for multi-Si modules. Moving vertically downwards or moving horizontally towards the right decreases the CRF PBT by reducing feedstock energy intensity (or feedstock material intensity in the right plot) or increasing the module efficiency, respectively.

Figure 3 depicts the equivalence between increasing the module efficiency and decreasing the energy and material intensity of PV manufacturing in reducing the CRF PBT for multi-Si PV modules manufactured in China and deployed in California. The slanted lines represent combinations of solar grade silicon energy intensity (kWh/kg) and module efficiencies that result in a particular CRF payback time (PBT). For example, points Q' (130 kWh/kg, 16%) and Q (150 kWh/kg, 17%) represent combinations of feedstock energy intensity and module efficiency for a CRF PBT of 3.7 years. A reduction in feedstock energy intensity and an equivalent increase in module efficiency is represented by moving down vertically and moving right horizontally, respectively, between two CRF PBT lines. As an example, reducing the feedstock energy by 20 kWh/kg (P to Q') is equivalent to increasing the module efficiency from 16 to 17% (P to Q) as both these approaches reduce the CRF PBT from 4 to 3.7 years. Similar CRF PBT equivalence plots for multi-silicon PV deployments in Wyoming and mono-Si modules manufactured in China and deployed in California and Wyoming are shown in section S5 in the SI. The results show that, for mono-Si and multi-Si modules, decreasing the feedstock energy intensity by 15-17 kWh/kg or feedstock material intensity by 0.065-0.120 kg/m² is equivalent to increasing the module efficiency by 1% when considering the resulting decrease in CRF PBT (Table 3 and Table 4, section S5 in SI).

3.4 Climate hotspots in current PV manufacturing processes

Figure 4 CRF hotspots multi-silicon PV modules manufactured in China and deployed in California. The widest bars correspond to the PV manufacturing process parameters with the highest CRF impacts.

The analysis of the climate hotspots in PV manufacturing (Figure 4) demonstrates the percentage change in the baseline CRF benefits (equation 4) when a particular PV manufacturing parameter is increased or decreased by 10% while keeping the other parameters constant at the baseline value (section S4, SI). The CRF benefit in the baseline scenario is represented by the vertical 0% line. Figure 4 suggests that sourcing electricity from less GHG intensive sources has the most potential to reduce the CRF footprint of a multi-Silicon PV module. The corresponding CRF benefit is evaluated in the “Natural gas elec mnf” and “PV elec mnf” scenario (Figure 5). Furthermore, for material and energy parameters that are within the control of a manufacturer, reducing the polysilicon feedstock per m² of the module and energy required to purify this polysilicon are two other significant CRF hotspots in the current crystalline PV manufacturing processes. Similar results are observed for multi-Si and mono- Si modules manufactured in China and deployed in California and Wyoming (section S10,SI).

3.5 Equivalence between manufacturing and module efficiency improvements

Figure 5 The equivalent increase in module efficiency for mono-Si and multi-Si modules realized by addressing hotspots in PV manufacturing (Figure 4). The equivalent increase in module efficiency is determined by projecting the difference between the CRF benefit equivalence lines of the baseline and the improved manufacturing scenario to the x-axis.

The CRF benefit equivalence line of each scenario (Figure 5) represents a combination of PV manufacturing GHG intensity and module efficiency resulting in the same net CRF benefit over the 25-year life span of a PV module. The PV manufacturing improvement in a particular scenario is quantified by starting the net CRF benefit equivalence line from a point that is lower than the baseline scenario on the y-axis. For example, the manufacturing improvement between the baseline and the “PV elec mnf” scenario for mono-Si modules (upper plot) is a reduction in the PV manufacturing GHG intensity from 563 to 30 CO₂e kg/m² and the corresponding CRF benefit increases from 3.80×10^{-11} to 5.31×10^{-11} Wm⁻²yr (black and pink lines).

As the GHG intensity of electricity used in the PV manufacturing process is the most significant CRF hotspot (Figure 4), using electricity from less GHG-intensive sources like PV at the manufacturing location (PV elec mnf) offers the greatest CRF benefit. While reducing manufacturing emissions receives lower PV R&D focus compared to increasing use-phase efficiency, the analysis shows it is equivalent to increasing the mono-Si and multi-Si module efficiency from the baseline value of 17% to 21.7% and 16% to 18.6%, respectively. Alternate solar grade silicon refining processes like UMG and FBR also offer a significant CRF benefit equivalent to increasing the baseline efficiency to a value between 18.4 and 18.7% for mono-Si modules and 16.7 and 16.85% for multi-Si modules.

The incremental strategies of improving existing manufacturing processes by reducing the silicon layer thickness to 100μm, decreasing the energy footprint of the Siemen’s process, reducing the wire thickness and abrasive particle diameters in the MWSS process and using the diamond coated wire sawing process yield lower CRF benefits that provide an equivalent module efficiency gain between 17.3% to 17.9% for mono-Si modules and, 16.2% and 16.5% for multi-Si modules. The equivalent increase in module efficiency from short and long-term CRF benefits of PV manufacturing improvements (Figure 3 and Figure 5) is significant as commercial multi-silicon PV modules have shown an average year on year efficiency increase of only 0.25% from 2004 to 2016 (section S7 in SI). It is important to note that the equivalent improvement in module efficiency is independent for each scenario and implementing multiple manufacturing process improvements would yield an additive CRF benefit and a corresponding module efficiency gain. Further, the Siemen’s energy reduction, UMG and the FBR scenarios are mutually exclusive as they represent alternate solar-grade silicon refining processes.

For modules manufactured in China and deployed in Wyoming, the CRF benefit of using PV electricity for manufacturing (PV elec mnf) is equivalent to increasing the module efficiency from 17 to 20% for mono-Si and 16 to 17.7% for multi-Si modules, respectively (section S6 in SI). Wyoming has a higher GHG intensity of grid electricity than California and, therefore, the net CRF benefit (CRF_{bmf} in equation 4) is more sensitive to the CRF impact of GHGs avoided per unit of PV electricity generated (CRF_{avd}) than CRF impacts of lowered PV manufacturing emissions (CRF_{mnf} in equation 4). Thus, the equivalent increase in module efficiency is lower in Wyoming than California.

The results demonstrate that shifting to low-carbon electricity sources for PV manufacturing in GHG intensive geographies like China results in the greatest increase in the climate benefit of PV systems. Thus, prospective CRF benefits of possible manufacturing improvements demonstrate the climate case for complementing the dominant strategy of increasing the module efficiency with PV R&D on manufacturing improvements to increase the climate benefit of a terawatt scale of PV installations.

3.6 PV manufacturing R&D priorities to improve the climate performance of future installations

As a first step, R&D focusing on the PV manufacturing should identify and address operational bottlenecks that prevent large scale solar-grade silicon manufacturers in the US and other locations from utilizing carbon-efficient sources of electricity. A transition to carbon-efficient electricity sources will not require any changes in the capital equipment and downstream processes that produce solar-grade silicon. Recent reports show that commercial PV electricity in China will reach grid parity in the next five years [135][136][137] and, therefore, this transition to low-carbon electricity at manufacturing sites is economically favorable and may not impact module prices. Natural gas electricity, with a cost comparable to coal electricity in China [135], is a potential intermediate source that can enable a transition to a less carbon intensive electricity sources (like PV) in the future for PV manufacturing. The climate benefit from this transition is also significant as this is equivalent to increasing the efficiency of multi-Si and mono-Si modules from 16 to 17.5% and 17 to 19.6%, respectively. Further, sourcing electricity from these low-carbon sources will not impact PV manufacturing costs significantly as energy contributes to less than 2% of the wafer, cell and module costs in China [138].

As a second step, manufacturing R&D can accelerate incremental manufacturing improvements that can increase the equivalent module efficiency gain from 17 to 17.9% for mono-Si modules and 16 to 16.5% for multi-Si modules (Figure 5). Specifically, further research is required to enable a transition to thinner wafers by analyzing the physical limits and resolving potential issues that downstream PV manufacturing processes will face with incremental improvements like reducing the thickness of the silicon absorber layer. Past studies have indicated that at values below 100 μm , current manufacturing processes will require changes to avoid an increase in breakage in the robotic handling and transfer steps, manage increased flexibility, lower temperature soldering, kerf-free wafer processes, advanced light trapping methods and improved surface passivation methods to reduce surface recombination [139][140][141].

As a third step, R&D can identify possible strategies to accelerate the adoption of emerging, less energy intensive, solar-grade silicon refining technologies like UMG and FBR which that can increase the equivalent module efficiency gain from 17 to 18.7% for mono-Si modules and 16 to 16.9% for multi-Si modules (Figure 5). A large scale transition to these processes will have to overcome the advantages of the incumbent Siemen's process including market dominance, the economic gains realized from scale and the cumulative technical experience of manufacturers over the last 60 years [111][142]. Specifically, increasing the economic and environmental

attractiveness of FBR refining methods requires decreasing silicon losses due to reverse reactions in trichlorosilane (TCS) based FBR reactors [143] and the formation of fine particles and consequent contamination of silicon in silane based FBR reactors [144]. Market adoption of UMG silicon can be accelerated through focused research on reducing light induced degradation due to boron-oxygen clusters [145], improving defect gettering in UMG silicon feedstock [146], increasing efficiencies through novel cell fabrication processes [147], and reducing carbon, boron and phosphorus impurity levels [148][149] to avoid cell performance issues in downstream PV processing activities.

4 Conclusion

The current practice of using GHG metrics underestimates the climate benefit of addressing PV manufacturing hotspots (Figure 2) that can be realized through PV R&D focusing on upstream PV manufacturing processes. The PV manufacturing experience curve generated by harmonizing PV manufacturing data from the last three decades (Figure 1) shows that reducing the thickness of the silicon wafer and replacing electronic grade silicon with less energetically intensive solar grade silicon historically drove PV manufacturing energy improvements. Further improvements are suggested by a hotspot analysis for the current crystalline silicon module manufacturing processes (Figure 4), which identifies the GHG intensity of the electricity used for manufacturing processes and the material and energy intensity of solar-grade silicon feedstock as the most significant opportunities to improve the climate benefit from PV manufacturing and deployment. Based on the short-term CRF payback time analysis (Figure 3), reducing solar-grade silicon's energy intensity by 15-17 kWh/kg or the solar-grade silicon material intensity by 0.065-0.120 kg/m² is equivalent to a 1% increase in the baseline efficiency for mono-Si or multi-Si modules. Furthermore, by using low-carbon electricity sources like PV for manufacturing, the climate benefit realized over the 25-year lifetime of a PV module is equivalent to increasing the efficiency of multi-Si and mono-Si modules from 16% to 18.7% and 17% to 21.7%, respectively (Figure 5). These potential efficiency gains that can be realized by pursuing PV manufacturing improvements are significant as the commercial crystalline silicon module efficiencies have increased annually by only 0.25% over the last 12 years.

Thus, prospective CRF benefits of manufacturing improvements demonstrate the climate case for complementing the dominant strategy of increasing the module efficiency with PV R&D on manufacturing improvements to increase the climate benefit of a terawatt scale of PV installations. In specific, this should include - identifying and resolving challenges that prevent large scale solar-grade silicon manufacturers from utilizing carbon-efficient sources of electricity, incremental improvements in existing manufacturing processes that reduce the solar-grade silicon feedstock required to manufacture modules, and accelerating the market adoption of emerging silicon refining technologies like UMG and FBR that environmentally outperform the incumbent Siemen's process.

The CRF framework presented in this paper is applicable to other renewable energy technologies (e.g. PV thermal, concentrated PV, wind) that require a significant upfront manufacturing GHG

emission to realize the climate benefits from avoiding GHGs subsequently after installation. This will require data on the GHG emissions during the manufacturing and the GHG avoided at the deployment site post-installation. Manufacturing oriented R&D will improve the climate performance of these technologies if the CRF analysis shows that manufacturing improvements yield a significant climate benefit when compared to module efficiency improvements in the use-phase.

The calculation of the equivalent increase in module efficiency (Figure 5) is based on a conservative assumption of typical solar insolation and weather conditions after the PV system is installed. We have not included unfavorable weather conditions and parameters like dust and soiling which reduce the renewable electricity generated by the PV system [150], [151] and decreases the avoided GHGs and the corresponding CRF benefit after installation. This increases the relative significance of the climate benefit from manufacturing improvements when compared to module efficiency improvements and further strengthens the case for increased R&D focus on PV manufacturing improvements.

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Figure 6 CRF payback time (PBT) equivalence between module efficiency improvements and reduction in solar-grade energy intensity for poly-silicon modules manufactured in China and installed in California.

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The dotted horizontal line and the y-axis intersect the CRF PBT equivalence lines at multiples module efficiency and feedstock energy intensity values (Figure 1). As explained in the main paper, the CRF PBT can be reduced from 4 to 3.7 years by decreasing the feedstock energy intensity from 147 to 127 kWh kg⁻¹ or increasing the module efficiency from 16 to 16.89%. This corresponds to an equivalence ratio of 22.47 kWh kg⁻¹ per unit percentage increase in module efficiency (20 kWh kg⁻¹/0.89%). Similar equivalence ratios between the feedstock energy intensity and the module efficiency values are calculated by moving horizontally and vertically between pairs of CRF PBT lines. The mean of all the calculated equivalence ratios is 16.93 kWh kg⁻¹ per unit increase in module efficiency percentage. Similar equivalence values are calculated for mono-Si and multi-Si modules manufactured in China and deployed in Wyoming and California (Table 1 and Table 2).

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Table 1 Equivalence between solar-grade silicon energy intensity (kWh/kg) and unit increase in module efficiency (%) for mono and poly-Si modules manufactured in China and installed in California and Wyoming

Scenario	Equivalence between energy intensity (kWh/kg) and unit increase in module efficiency (%)	Reference Figure
multi-Si manufactured in China, Installed in California	16.93	Figure 6
multi-Si manufactured in China, Installed in Wyoming	16.02	Figure 8
mono-Si manufactured in China, Installed in California	17.19	Figure 10
mono-Si manufactured in China, Installed in Wyoming	15.59	Figure 12

Table 2 Equivalence between solar-grade silicon feedstock intensity (kg/m²) and a unit increase in module efficiency (%) for mono and poly-Si modules manufactured in China and installed in California and Wyoming

Scenario	Equivalence between feedstock intensity (kg m ⁻²) and unit increase in module efficiency (%)	Reference figure
multi-Si manufactured in China, Installed in California	0.065	Figure 7
multi-Si manufactured in China, Installed in Wyoming	0.069	Figure 9
mono-Si manufactured in China, Installed in California	0.128	Figure 11
mono-Si manufactured in China, Installed in Wyoming	0.119	Figure 13

Figure 7 CRF payback time (PBT) equivalence between an increase in module efficiency and reduction in solar-grade feedstock intensity for poly-silicon modules manufactured in China and installed in California.

Figure 8 CRF payback time (PBT) equivalence between an increase in module efficiency and reduction in solar-grade energy intensity for poly-silicon modules manufactured in China and installed in Wyoming.

Figure 9 CRF payback time (PBT) equivalence between an increase in module efficiency and reduction in solar-grade feedstock intensity for poly-silicon modules manufactured in China and installed in Wyoming.

Figure 10 CRF payback time (PBT) equivalence between an increase in module efficiency and reduction in solar-grade energy intensity for mono-silicon modules manufactured in China and installed in California.

Figure 11 CRF payback time (PBT) equivalence between an increase in module efficiency and reduction in solar-grade feedstock intensity for mono-silicon modules manufactured in China and installed in California.

Figure 12 CRF payback time (PBT) equivalence between an increase in module efficiency and reduction in solar-grade energy intensity for mono-silicon modules manufactured in China and installed in Wyoming.

Figure 13 CRF payback time (PBT) equivalence between an increase in module efficiency and reduction in solar-grade feedstock intensity for mono-silicon modules manufactured in China and installed in Wyoming.

S1. Equivalent increase in module efficiency by addressing CRF hotspots in manufacturing processes

Figure 14 The equivalence in the CRF benefits between addressing PV manufacturing hotspots (Figure 4) and an increase in module efficiency for mono-Si (upper plot) and multi-Si (lower plot) modules manufactured in China and deployed in Wyoming. The manufacturing improvement that addresses the hotspot is accounted for by lowering the manufacturing GHG intensity (y-axis). The equivalent increase in module efficiency is

determined by projecting the difference between the CRF benefit equivalence lines of the improved manufacturing and baseline scenario on to the x-axis.

S2. Growth in commercial multi-silicon module efficiency

The commercial module efficiency in 2004 was 13.2% (10) and has increased to 16.7% in 2016 (4)(5). This corresponds to an annual increment of 0.25% per year from 2004 to 2016.

S3. Kerf loss and silicon feedstock requirement

The solar-grade silicon feedstock in 1m² of a multi-silicon PV wafer is 0.625 kg (8). The typical thickness of the silicon wafer is 180 μm and the volume is 180x10⁻⁶ m³ (8). Based on the density of silicon (2330 kg/m³), the mass of solar-grade silicon contained in 180 x10⁻⁶ m³ of the multi-silicon wafer is 0.41 kg and, therefore, the kerf-loss is 0.2 kg/m² (0.625-0.41) or 33%.

If the kerf loss is decreased by 50% (“mwss_wire_abrasive_reduced_diameter” scenario in the main paper) or by 25% (“diamond_coated_wire_saw” scenario in the main paper), the new feedstock requirement will be 0.52 kg or 0.57 kg per m² respectively.

S4. Difference between GHG and CRF metrics

Figure 15 Difference in the climate benefit of improved PV manufacturing as measured by the net GHG and net CRF benefits for multi-Si modules manufactured in China and deployed in Wyoming. The green and orange lines represent combinations of PV manufacturing GHG intensity and module efficiency that result in the same net GHG and net CRF benefit over the 25-year lifespan of a module, respectively. A reduction in the GHG intensity of PV manufacturing from 314 to 17 kg CO₂e/m² increases the net GHG benefit by only 6% (4700 to 5000 kg CO₂e) when compared to 11% increase in the net CRF benefit (7.2x10⁻¹¹ to 8.0x10⁻¹¹ Wm⁻²yr)

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1108 **Figure 16 Difference in the climate benefit of improved PV manufacturing as measured by**
 1109 **the net GHG and net CRF benefits for mono-Si modules manufactured in China and**
 1110 **deployed in California. The green and orange lines represent combinations of PV**
 1111 **manufacturing GHG intensity and module efficiency that result in the same net GHG and**
 1112 **net CRF benefit over the 25-year lifespan of a module, respectively. A reduction in the**
 1113 **GHG intensity of PV manufacturing from 563 (current state of manufacturing) to 30 kg**
 1114 **CO₂e/m² (using PV electricity for PV manufacturing) increases the net GHG benefit by**
 1115 **only 18% (2800 to 3300 kg CO₂e) when compared to 39% increase in the net CRF benefit**
 1116 **(3.8x10⁻¹¹ to 5.3x10⁻¹¹ Wm⁻²yr)**

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Figure 17 Difference in the climate benefit of improved PV manufacturing as measured by the net GHG and net CRF benefits for mono-Si modules manufactured in China and deployed in Wyoming. The green and orange lines represent combinations of PV manufacturing GHG intensity and module efficiency that result in the same net GHG and net CRF benefit over the 25-year lifespan of a module, respectively. A reduction in the GHG intensity of PV manufacturing from 563 (current state of manufacturing) to 30 kg CO₂e/m² (using PV electricity for PV manufacturing) increases the net GHG benefit by only 13% (4700 to 5300 kg CO₂e) when compared to 21% increase in the net CRF benefit (7.0x10⁻¹¹ to 8.5x10⁻¹¹ Wm⁻²yr)

1128 **S5. CRF Hotspot analysis**

1129 **Figure 18 CRF hotspots multi-silicon PV modules manufactured in China and deployed in**
1130 **Wyoming. The width of the bars indicate the percentage change in the CRF benefit of the**
1131 **baseline scenario when a parameter in the manufacturing process is incremented and**
1132 **decremented by 10%. The widest bars correspond to the PV manufacturing process**
1133 **parameters with the highest CRF impacts.**
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1135 **Figure 19 CRF hotspots mono-silicon PV modules manufactured in China and deployed in**
1136 **California. The width of the bars indicate the percentage change in the CRF benefit of the**
1137 **baseline scenario when a parameter in the manufacturing process is incremented and**
1138 **decremented by 10%. The widest bars correspond to the PV manufacturing process**
1139 **parameters with the highest CRF impacts.**
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Figure 20 CRF hotspots mono-silicon PV modules manufactured in China and deployed in Wyoming. The width of the bars indicate the percentage change in the CRF benefit of the baseline scenario when a parameter in the manufacturing process is incremented and decremented by 10%. The widest bars correspond to the PV manufacturing process parameters with the highest CRF impacts.

S6. Break-up of the PV R&D spends

A total of 137 PV R&D projects funded by the Department of Energy from 2011 to 2016 were categorized by the areas of research focus with a break-up of the corresponding funding (Figure 21). The categorization of the projects is available on the following URL <http://ow.ly/O92v306kfoi>

Figure 21 Break-up of the DOE funding for PV projects from 2011 to 2016 according to the research focus

Projects on decreasing the material and energy requirements and earth-limited raw materials are categorized as “Manufacturing Improvement”. Projects focusing on both manufacturing and module efficiency improvements are also included in the “Manufacturing Improvement” category (e.g SI no 70 in excel). Projects on modeling, theoretical and analytical approaches to advance understanding on underlying physical processes in PV cells are categorized as “Methods/Tools”. Projects working on technologies apart from mono and multi silicon and CdTe are categorized as “Novel Technology”. Projects that focused on increasing the module efficiency, increasing module efficiency and education, and increasing module efficiency and reliability are categorized as “Module Efficiency Improvement”. Projects focusing on education, characterization, system integration and related technologies (e.g. PV microinverters) are categorized as “Others”.

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