Electronic Supplementary Information

Economically Sustainable Scaling of Photovoltaics to Meet Climate Targets

by David Berney Needleman *et al*.

A. Specifics on deployment scenarios

The sources of the data in **Figure 1** in the main text are shown in **Figure S1**[1–15].

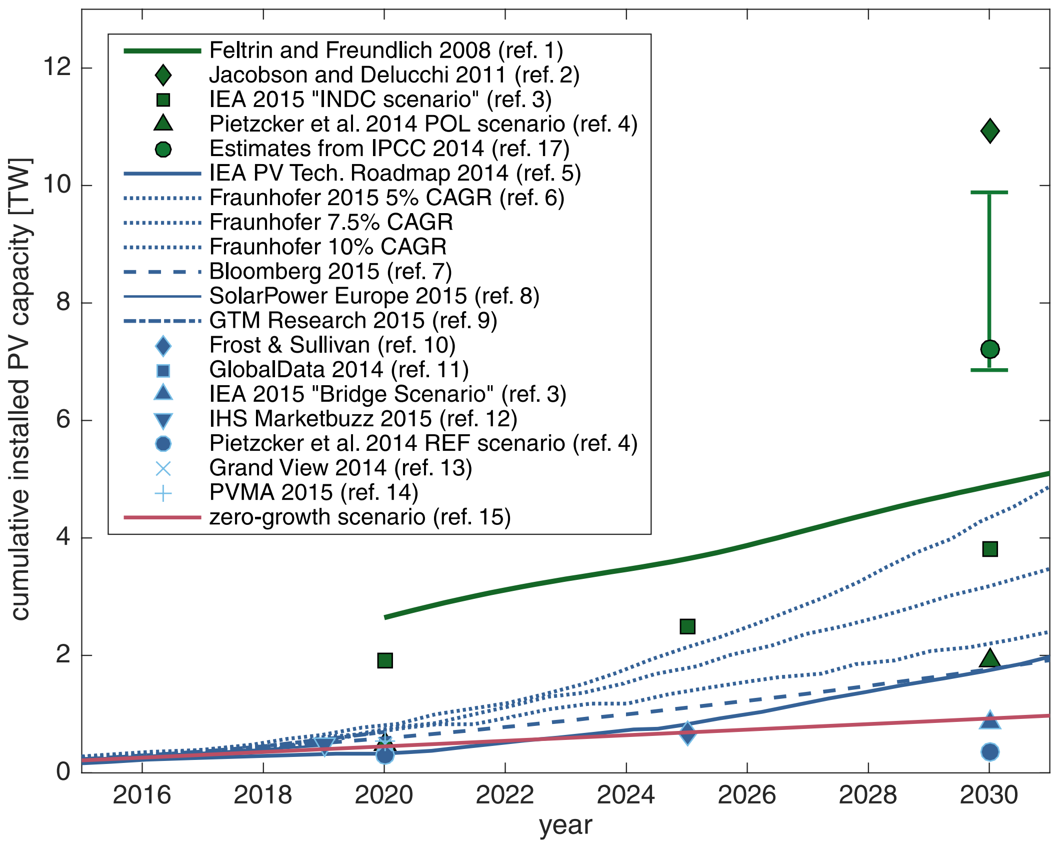

Figure S1. Reproduction of **Figure 1** in the main text with references listed for each dataset. PV deployment targets consistent with average warming less than 2°C above pre-industrial levels (green symbols and line), industry projections of PV deployment (purple symbols and lines), and upper bound of future installations with no additional manufacturing capacity (pink line). Lines represent annual data, symbols represent data with lower temporal resolution.

Jacobson and Delucchi[2,16] assume that all non-electric systems will be electrified and that all electricity will be provided by wind, hydroelectric, and solar technologies. The numbers from the IPCC 2014 Synthesis Report[17] are the interquartile range from the set of predicted scenarios consistent with 430-480 ppm CO_2-equivalent stable concentration – however, the report only includes the numbers as what percentages of primary energy demand in 2030 is met by low-carbon sources, so to show them on the plot, the primary energy demand numbers were taken from the IEA report[3] (see below) and it was assumed that 1/3 of the low-carbon share is met using PV. The two scenarios shown from the International Energy Agency's World Energy Outlook Special Report[3] are one assuming all (pre-COP21) pledges already made by countries are met on time ("INDC scenario") and one intermediate scenario ("Bridge Scenario"). Feltrin and Freundlich's[1] calculations were based on the IPCC Third Assessment report[18] and Hoffert *et al*.'s seminal paper[19] as well as the assumption that PV would satisfy the difference between projected capacities of other technologies and carbon-free electricity required to meet projected demand consistent with 450 ppm. Pietzcker *et al*.[4] predict penetration based on an economic model of the electricity market and provide a reference scenario and a scenario in which policies are enacted to cause solar to be sufficiently economically competitive to be consistent with 2° C average warming.

For sources that reported only energy output and not generation capacity, a very conservative capacity factor of 20% was assumed.

B. Cost and growth models

As described in detail elsewhere[20], our cost model sums the cost of all of the equipment, materials, labor, and business expenses for a typical monocrystalline silicon PV module factory. Financial decisions are affected by a discount rate (in this case equal to the weighted average cost of capital, *WACC*) for PV module manufacturers[21], depreciation of capital equipment, and amount of working capital (cash on hand to cover operational expenses for a fixed period of time, 3 months in our model, which is then reinvested). Together with price, these financial considerations enable the calculation of a discounted cash flow. The price/cost relationship implies a certain operating margin, "margin", defined here as:

$$margin = \frac{{}^{price}/_{unit} - {}^{cost}/_{unit}}{{}^{price}/_{unit}}\,. \tag{1}$$

Taxes (*T*) and interest on debt (*I*) are calculated after margin. The baseline scenario considered here is one in which the price is set such that internal rate of return (*IRR*, equivalent to interest earned on money invested in producing PV modules) calculated from the discounted cash flow equals the *WACC*. We call this price the "minimum sustainable price" (*MSP*), because it is the minimum price required for sufficient returns to investors to sustain investment[20].

Using margin, we calculate the maximum sustainable rate at which a PV module manufacturer can increase manufacturing capacity (grow), assuming that all returns on equity are reinvested in expansion (no dividends are paid) and the company maintains a constant debt-to-equity ratio, *DER*. This relationship for the maximum sustainable manufacturing growth rate (G_{M}) is defined as:

$$G_{\mathrm{M}} = \frac{(margin - I - T) \times (1 + DER)}{PPER + C}\ , \tag{2}$$

where *PPER* is the ratio of capex (*i.e.*, plant, property, and equipment) in the previous year ("*y* – 1") to gross revenue in a given year "*y*" and *C* is working capital divided by revenue[22]. In this work, growth rate always refers to growth of manufacturing capacity, G_{M}. Using this growth rate, we calculate the amount of PV capacity that can be added in a given year without changing *DER* or adding external subsidies, and thereby determine an upper bound on PV capacity and cumulative

PV installations in the future. Further information about the maximum sustainable growth rate can be found in Ref. [22].

If costs and price remain constant over time, then G_{M} is constant. This amounts to exponential growth, which provides a lower bound on the growth rate required to install a certain cumulative capacity by a certain time. G_{M} is the derivative of annual installed capacity. If $G_{\mathrm{M},C}$ is the growth rate required to reach a capacity C in a time t, then if in any year $y < t$, $G_{\mathrm{M},y} < G_{\mathrm{M},C}$, there will have to be another year $y' < t$ when $G_{\mathrm{M},y'} > G_{\mathrm{M},C}$ in order to reach capacity C by time t. Thus, $G_{\mathrm{M,C}}$ provides a lower bound on the growth rate necessary to reach capacity C by time t.

Values for the parameters used in the baseline scenario and the other scenarios in **Figure 4** are shown in **Table 1**.

Table 1: Model parameters for baseline scenario and other scenarios in **Figure 4**.

Parameter	Baseline	Line-of-sight	Increased debt	Low-variable cost advanced concept	High-efficiency advanced concept
Module efficiency	16.0%	18.0%	18.0%	18.0%	24.0%
Wafer Thickness (μm)	180	120	120	20	20
Kerf loss (μm)	130	130	130	20	20
Variable costs ($/W)	0.541	0.264	0.264	0.184	0.189
Capex ($/(W/yr))	0.676	0.345	0.345	0.139	0.104
Fixed + variable costs ($/W)	0.724	0.355	0.355	0.231	0.231
Margin	15%	15%	15%	15%	15%
DER	1:1	1:1	5:1	1:1	1:1

To define the advanced technology concepts, the thickness and kerf loss are reduced to 20 μm each with corresponding reductions in capex and variable costs. The efficiency is then increased (to 24% and 18% absolute in the high-efficiency and low-variable costs scenarios, respectively), which further reduces the capex and variable costs (per watt). The remaining capex (again in $/W/yr) is scaled by a constant factor of 0.29 for both scenarios (a 71% relative reduction). This represents making the same changes to equipment and processing for both technologies. The variable costs are then also scaled down. The variable costs in the high-efficiency scenario are scaled by 0.75 (a 25% relative reduction). The variable costs in the low-variable cost case are scaled by 0.55 (a 45% reduction), which yields the same total (fixed plus variable) costs for both scenarios.

C. Necessary conditions for novel technologies to reach 10 TW by 2030

With regard to new technologies, we note that crystalline silicon starts from a manufacturing base of more than 50 GW/year. New technologies, which traditionally take 10–15 years to commercialize[23], therefore face the additional burden of scaling to this capacity. If we assume they start from a capacity of 100 MW in 2016, have the same operating margin as assumed here for silicon, and hold the same three months of working capital, they would require about 100 times less capex than the target we identify for silicon to reach 10 TW by 2030 (about 6 times less if they have $30\%_{rel}$ higher margin). If they do not enter commercial production until 2021, they would require more than twice the margin we assume for silicon and 80 times less capex than is necessary for silicon to reach 10 TW by 2030.

D. Demand curves

As illustrated in **Figure 2** in the main text, a demand curve constrains both margin and manufacturing growth. **Figure S2a** shows demand as a function of price from Ref. [15], including historical data on cumulative installed capacity *vs*. average module selling price and projected data for demand as a function of average module selling price. From the historical data, it is clear that demand is a strong function of both the market and policy environments. Furthermore, sometimes as in the last several years, installations cannot keep up with demand at a given price.

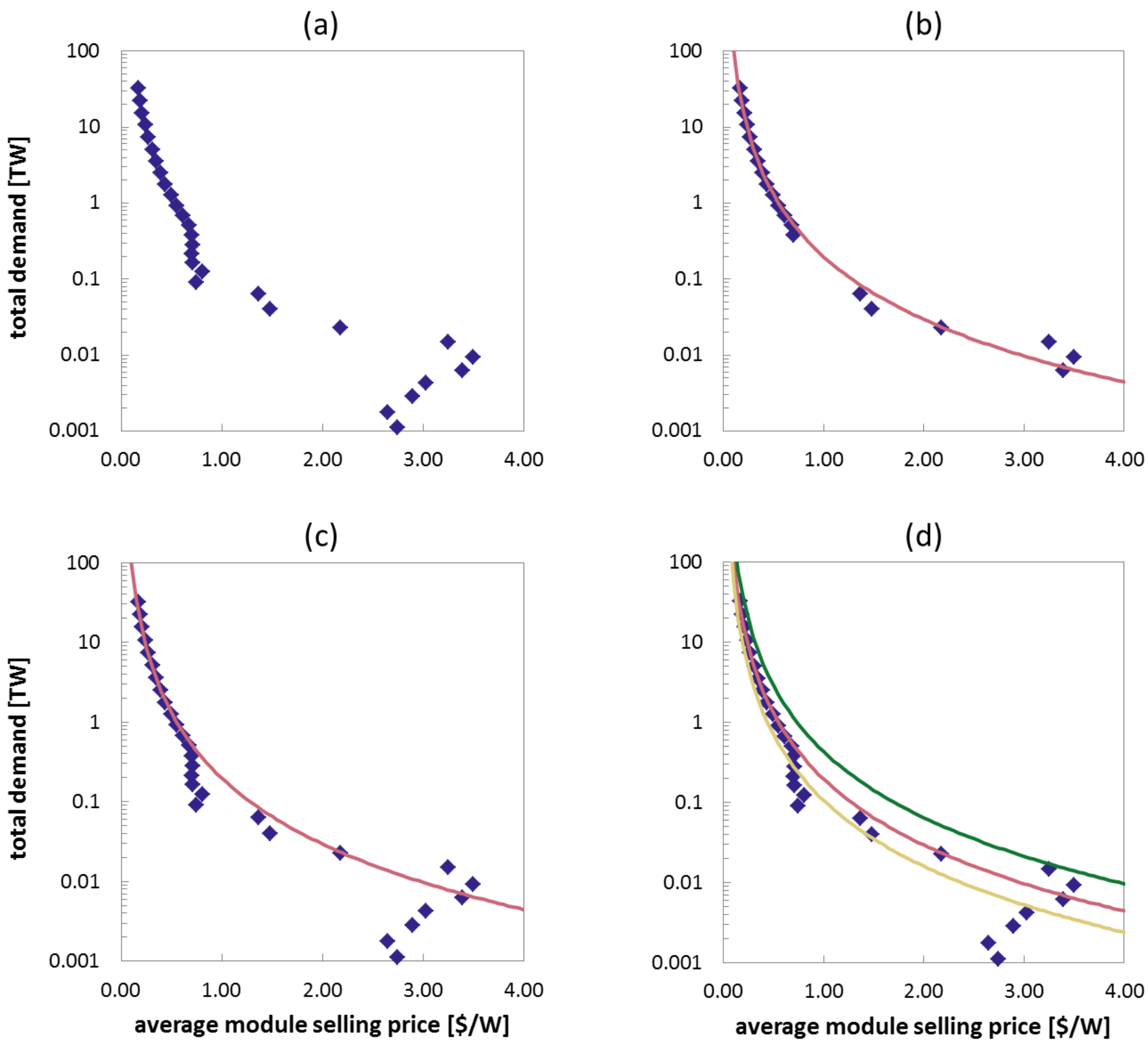

Figure S2. (a) Installed capacity (demand) as a function of selling price (historical and projected)[15]. (b) Power law fit to historical data, excluding points where installations appear to be constrained by something other than module price. (c) Power law fit from (b) with full demand curve. (d) Full demand curve with power law fit and power law shifted to account for uncertainty in the future market and policy environments.

Because this study considers the installation constraints imposed by PV module manufacturing, we are interested in the maximum demand at a given price. Our model also requires a single-valued function for demand at a given price. Therefore, we fit the demand curve, neglecting points that clearly indicate artificially low demand. We obtain a power law

$$demand = 197155 \times price^{-2.735} \quad , \tag{1}$$

with an R^2 value of 0.9917. The result of this fitting is shown in **Figure S2b**, and our fitted curve is shown with the full demand curve from Ref. [15] in **Figure S2c**.

As mentioned in the main text, demand is strongly dependent on the business and policy environment. Many factors can influence "willingness to pay" for PV. These include grid constraints and electricity markets, including utility tariff structures, ancillary services markets, and electric grid technology; energy and climate policy, including carbon pricing, fossil fuel subsidies, and supply- and demand-side PV subsidies like feed-in-tariffs, investment tax credits, renewable portfolio standards, low/zero-interest loans, subsidized land or equipment, *etc*.; the cost of supporting or competing technologies like fossil fuels, energy storage, PV balance-of-systems, labor for manufacturing and installation, *etc*. To account for these uncertainties, while keeping the analysis as general as possible, we shift the power law it with a constant scaling factor, so

$$demand = c \times 197155 \times price^{-2.735} \quad , \tag{2}$$

where c is a constant. We consider the cases of c = 0.54 and c = 2.19. While this appears to represent a factor of two uncertainty of demand at a given price, **Equation 2** can be rewritten as

$$demand = 197155 \times (price \times c^{-1/2.735})^{-2.735} \quad , \tag{3}$$

and one observes that these values of c only represent a factor of 0.25 uncertainty in the price at which a given cumulative PV capacity will be demanded. **Figure S2d** shows the demand curve from Ref. [15], along with the power law fit and the shifted power law curves.

E. Interactions between different technical and financial variables

Figure S3a,b,c shows the capacity achievable through simultaneous changes in only the technological variables. The relationship between capex and efficiency is monotonic, because efficiency affects cost alone and capex affects growth rate much more strongly than cost. However, there is an optimum value of variable costs at any combination of efficiency and capex because variable costs affect both cost and growth rate to a similar degree. This fact implies that while some reduction of variable costs are probably required to reach high installed capacity, continuous reductions will ultimately limit growth rate.

Figure S3d,e,f shows that by increasing margin, the optimum value of variable costs is reduced. Conversely, if margin falls, the optimum value of variable costs actually increases. This relationship is due to the fact that growth rate is driven by *PPER*. Therefore, revenue must be sufficiently high relative to factory costs to enable rapid increases in manufacturing capacity.

Figure S3g shows the relationship between debt/equity ratio and margin. Debt/equity ratio is often increased when margin decreases to enable further growth. However, in a price-constrained environment, this approach does not yield increased cumulative capacity because neither of these variables reduces cost. Ultimately, in a price-constrained environment, increased growth from increased debt/equity ratio will further reduce margin because in this situation, margin will be set by demand rather than cost, so it is not an effective long-term strategy.

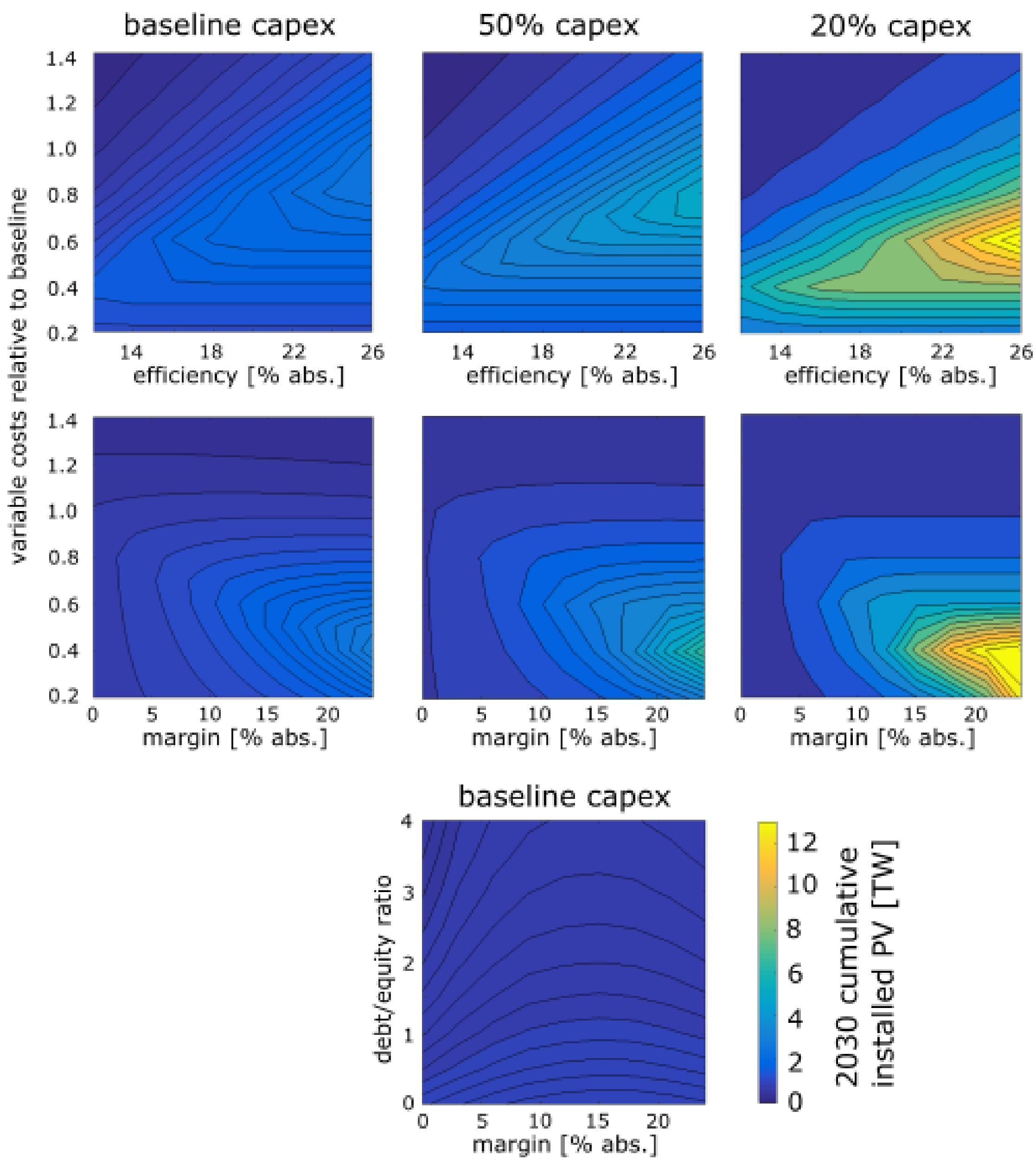

Figure S3: Contour plots of installed capacity in 2030 *vs.*relative changes in pairs of variables for (a) efficiency and variable costs at baseline capex, (b) efficiency and variable costs with a capex reduction of 50% from baseline, (c) efficiency and variable costs with a capex reduction of 80% from baseline, (d) margin and variable costs at baseline capex, (e) margin and variable costs with a capex reduction of 50% from baseline, (f) efficiency and variable costs with a capex reduction of 80% from baseline, (g) operating margin and debt/equity ratio with baseline capex.

F. Effects of new technology based on year deployed

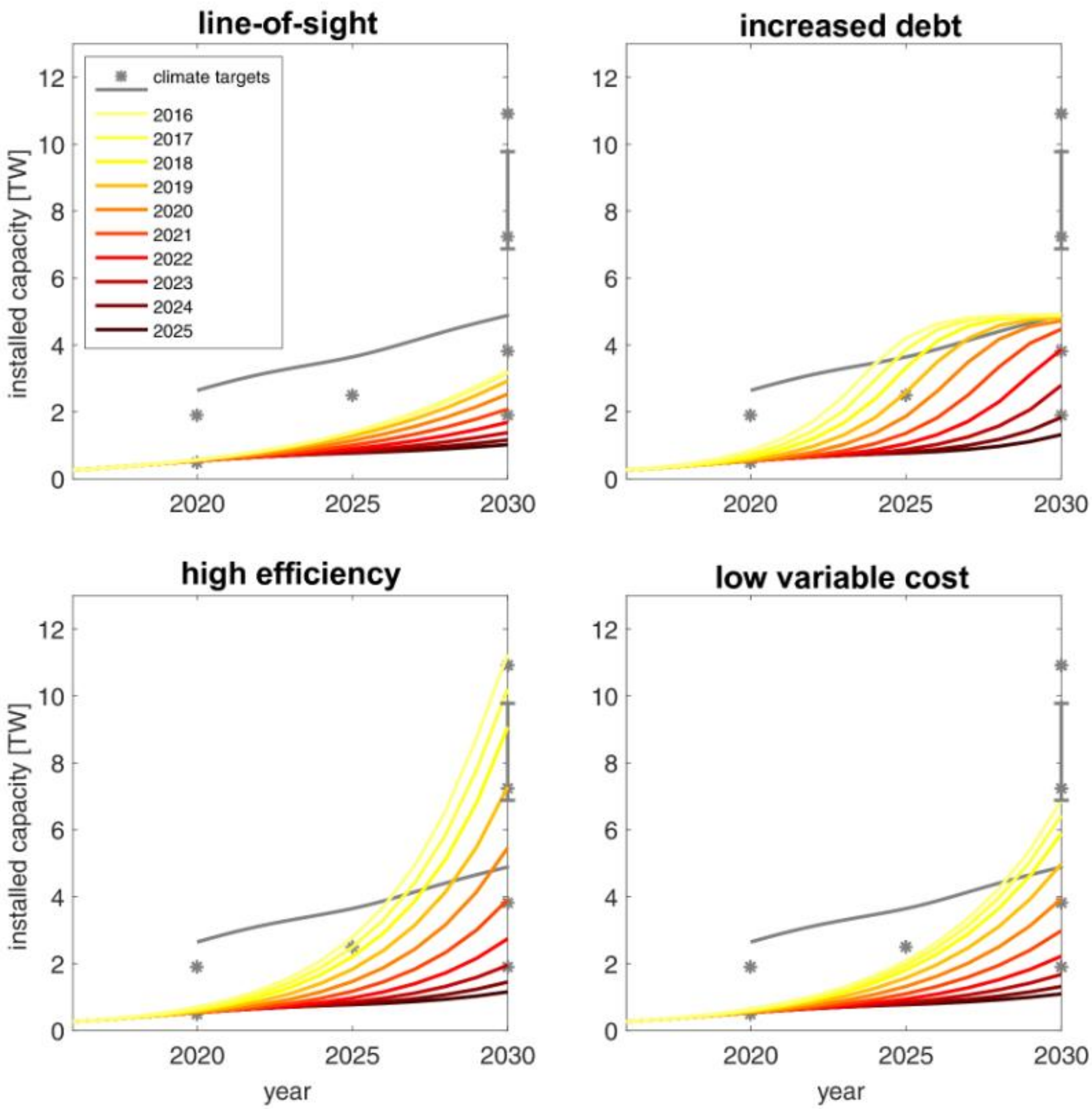

Figure S4: Climate targets (gray line and symbols) along with our projections for installed capacity in each year for: (a) line-of-sight technology improvements, (b) line-of-sight technology improvements with a debt/equity ratio of 5:1, (c) the high-efficiency advanced technology concept, and (d) the low-variable cost advanced technology concept. Each curve indicates an adoption of the technology in a different year (darker curves are later and lighter curves are earlier). Installations proceed according to the baseline scenario until the new technology is adopted.

In **Figure 4** of the main text, we assume all new technology is deployed in 2016. This represents an upper limit on the installed capacity that can be achieved with this technology. However, when new technology is developed and adopted is crucial in the impact it can have on future PV deployment. **Figure S4** shows this effect for (a) line-of-sight technology, (b) line-of-sight technology with increased debt, (c) the high-efficiency advanced technology concept, and (d) the low-variable cost advanced technology concept. The importance of developing and rolling out new technology as quickly as possible is clear. Furthermore, the potential for debt to maintain high growth rates while lower capex technology is developed is shown in the comparison between **Figure S4a and S4b**.

G. Effect of increased interest rate on high-debt scenario

Figure S5 shows the effect of increased interest rate on PV deployment in the high-debt scenario. As in **Figure 4** in the main text, the colored line indicates the installed PV capacity as a function of time for the baseline demand assumptions, and the shaded area indicates the range of installed capacity when demand is increased and decreased by 25%. The red curve indicates the installed capacity for line-of-sight technology with a debt/equity ratio of 1:1 and an interest rate on debt of 5%. The tan curve shows installed capacity for line-of-sight technology with a debt/equity ratio of 5:1 and an interest rate on debt of 5%. The brown curve shows installed capacity for line-of-sight technology with a debt/equity ratio of 5:1 and an interest rate of 10%. A higher interest rate significantly reduce the efficacy of increased debt on increasing installed capacity.

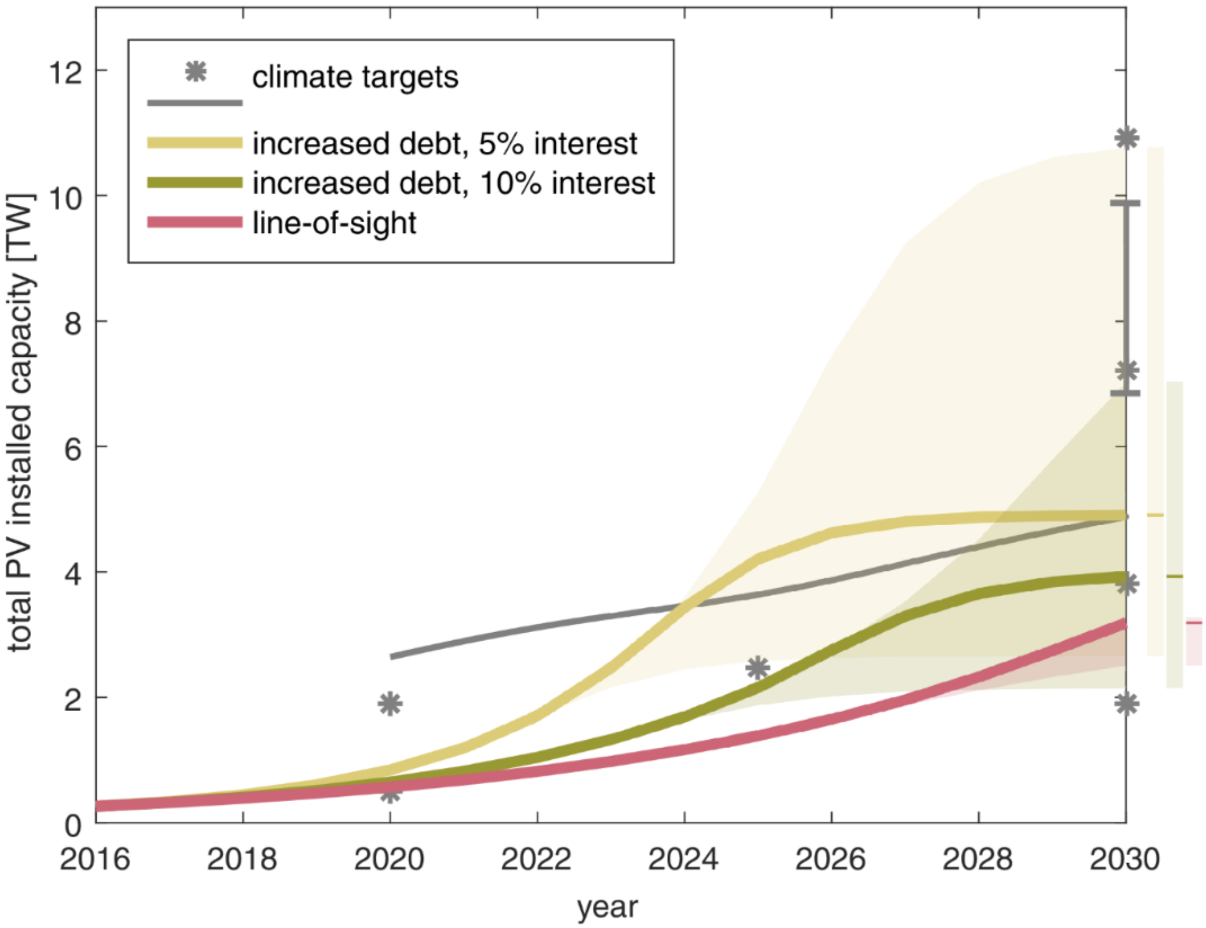

Figure S5: Climate targets (gray line and symbols) along with our projections for: line-of-sight technology improvements (red), line-of-sight technology improvements with a debt/equity ratio of 5:1 and an interest rate on debt of 5% (tan), and line-of-sight technology improvements with a debt/equity ratio of 5:1 and an interest rate on debt of 10% (brown). The shaded area indicates the range obtained in with increased and decreased demand. Colored lines indicate projection for power law fit to projected demand curve from Ref. [15].

H. Plant, property, and equipment ratio to revenue

PPER can vary based on local factors and how vertically integrated a company is (how much of the value chain they have in house). To estimate a maximum growth rate with current technology, we take a capex value corresponding to a *PPER* of 0.8. This value is on the low end of *PPER* estimated by bottom-up cost modeling and reported in Refs. [20,22]. Cost models suggest this *PPER* represents the capex of a U.S.-based monocrystalline panel manufacturer buying polysilicon feedstock or a Chinese multicrystalline panel manufacturer producing their own feedstock. This baseline *PPER* is also consistent with the values reported by top ten panel manufacturers over the last ten years, as shown in **Figure S6**. **Figure S6** shows (a) a histogram and (b) a cumulative distribution function of the *PPER* of top ten solar manufacturers from 2005 – 2014. Each company in each year represents one data point.

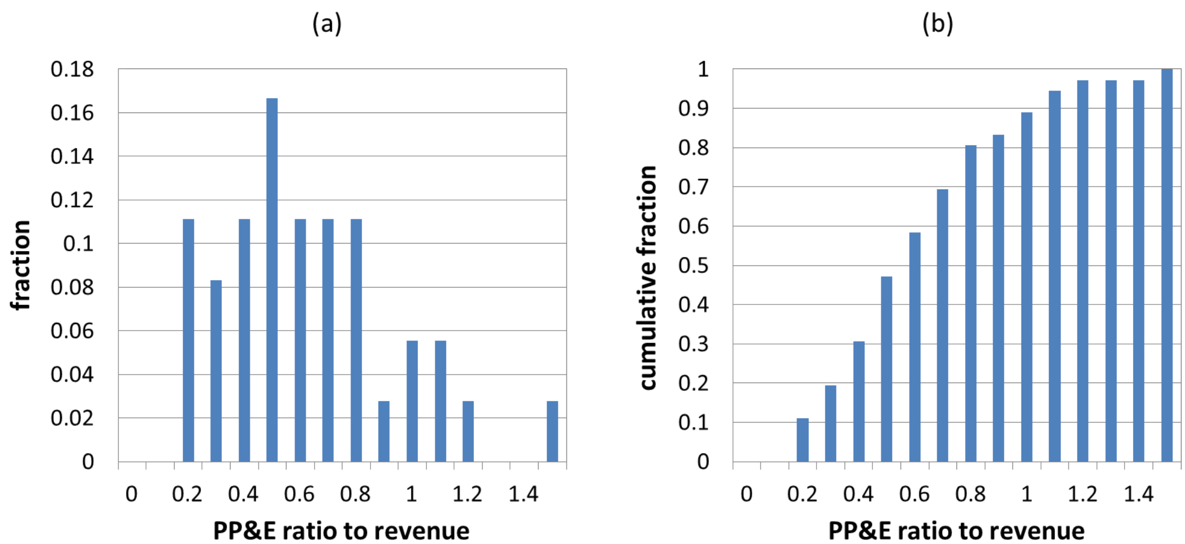

Figure S6. (a) Histogram and (b) cumulative distribution function of PP&E ratios of top ten solar manufacturers from 2005 to 2014.

I. Debt to equity ratio

Debt/equity ratios of solar companies vary dramatically between firms and over time. **Figure S7** shows (a) a histogram and (b) a cumulative distribution function of the debt/equity ratios of top ten solar manufacturers from 2005 – 2014. Each company in each year represents one data point. We use a value of 1:1 as our baseline to match Ref. [22] and because it is near the 50% point of the cumulative distribution function shown in **Figure S7b**.

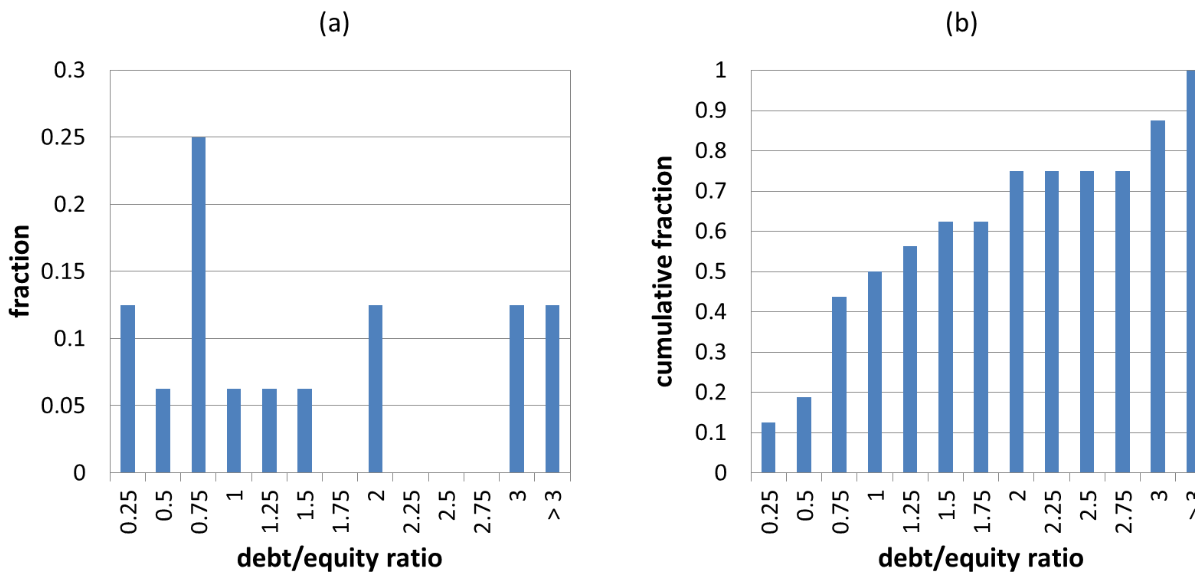

Figure S7. (a) Histogram and (b) cumulative distribution function of debt/equity ratios of top ten solar manufacturers from 2005 to 2014.

J. Life-cycle assessment and energy payback benefits

Reducing capex and increasing efficiency have the added benefits of reducing energy and CO_2 payback time for silicon PV modules, which have already come down by almost two orders of magnitude in the last forty years[24]. Life-cycle assessments (LCA) of silicon PV[25–27] have shown that over 60% of the embodied energy and carbon in PV modules is in the silicon wafer and about 10% is the module frame. Reducing the amount of silicon by an order of magnitude and eliminating the frame, as we propose for capex reduction, therefore substantially reduce the energy required to produce a module. Increasing the efficiency increases the energy yield of a system, which is inversely proportional to energy and CO_2 payback times. One prospective LCA of a technology similar to the high-efficiency advanced concept we propose suggests that energy payback times for a frameless, high-efficiency module with thin kerfless silicon wafers could be less than four months[27]. These effects may be particularly important if the annual manufacturing for PV grows to more than 1 TW/year, which may be required to reach 10 TW by 2030. In this case, the energy required to produce PV modules would be a significant new energy load[28].

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