The Energy Balance of the PV industry:

High EROI is essential for rapidly growing industries to provide net energy

Dr. Michael Dale, Prof. Sally Benson

Global Climate and Energy Project, Stanford University, CA. T: (650) 725-8579; e: mikdale@stanford.edu

GCEP Global Climate & Energy Project STANFORD UNIVERSITY

Introduction:

This research is motivated by concerns over the net energy yield of a growing photovoltaic (PV) industry, though it applies equally to any rapidly growing industry within the energy sector.

Our aim is to demonstrate the benefits of energy technologies with low embodied energy and to promote the use of net energy analysis (NEA) in energy modeling and technology development priorities.

Theory:

Grimmer [1] defines a relationship between the fractional re-investment, f [%/yr], from an energy system composed of devices with energy payback time (EPBT), t_{pb} [yrs], growing at rate, r [%/yr], as:

$$r = \frac{f}{t_{pb}} \quad (1)$$

Energy-return-on-investment (EROI):

Energy investments into an energy conversion device are made in three stages (see Figure 1):

1. **Construction** – energy, E_c, is invested indirectly in the form of materials and directly in installation
2. **Operation** – the device produces energy, E_g, whilst generating operating costs, E_{op}.
3. **Decommission** – the device requires energy input, E_d, towards decommission.

EROI is defined as the energy produced by an energy conversion device divided by the energy required to construct, operate and dispose of the device (2). There are a number of 'levers' on which technology and deployment can focus, including both technological (green) and geographical (blue) factors.

The capacity factor may vary from 10% up to 23% depending on site insolation[3]. Air pollution may decrease irradiance [W/m²/nm] by more than 20% at peak wavelengths ~550 nm [4].

$$\text{EROI} = \frac{\text{PV Efficiency} \times \text{Operating Lifetime} \times \text{Capacity Factor } (\textit{location})}{\text{Embodied Energy}} \quad (2)$$

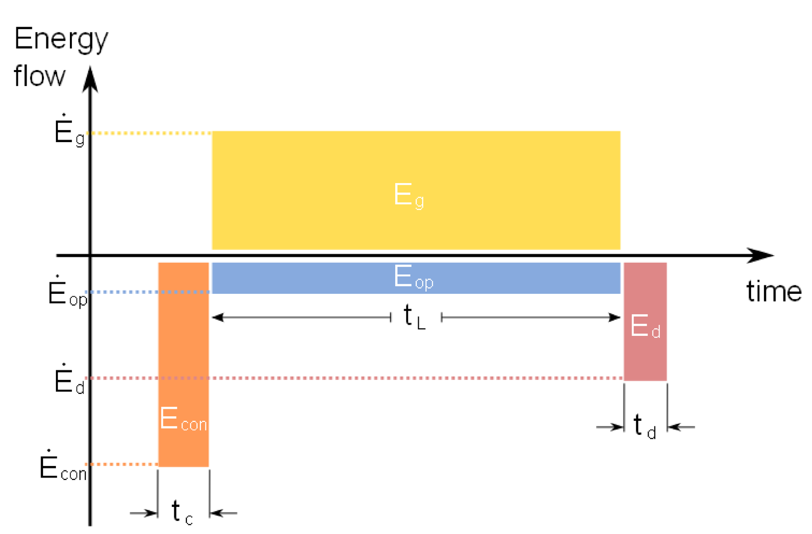

Figure 1. Energy inputs and production over the lifetime of an energy conversion device [2].

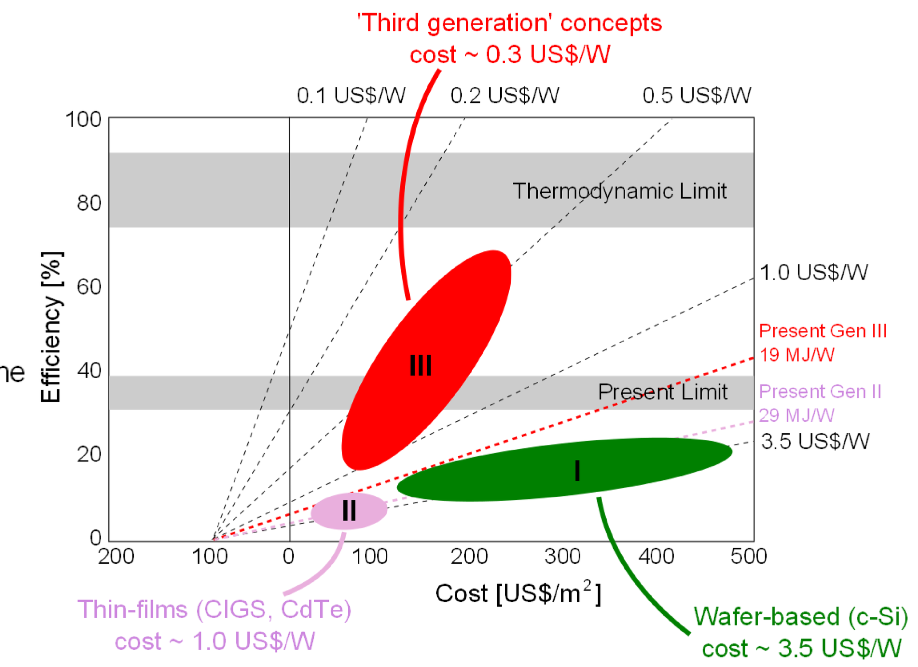

Figure 2. Efficiency vs. cost for three generations of solar panel [5]

Embodied energy in PV technology:

Green [5] categorized PV panels into three generations with corresponding, efficiency [%], per-unit area [US$/m²] and per-unit capacity [US$/W] cost projections (see Figure 2). Sherwani et al. [6] review a number of estimates of energy embodied in installed PV capacity [MJ/W] (see Figure 3a) and lifetime greenhouse gas (GHG) emissions [g-CO_2/kWh$_e$] (see Figure 3b) ranging from 9.4 to 217 g-CO_2/kWh$_e$. This compares with emissions from coal, natural gas and nuclear of 900, 420 and 30 g-CO_2/kWh$_e$ respectively [7]. As shown in Figure 3b, there is in inverse (exponential) relationship between GHG emissions and embodied energy. The data provided in Figure 3a were used to define levels of energy embodied in each of the three generations of PV technology:

Gen I – 45 MJ/W **Gen II** – 13 MJ/W **Gen III** – 4.3 MJ/W

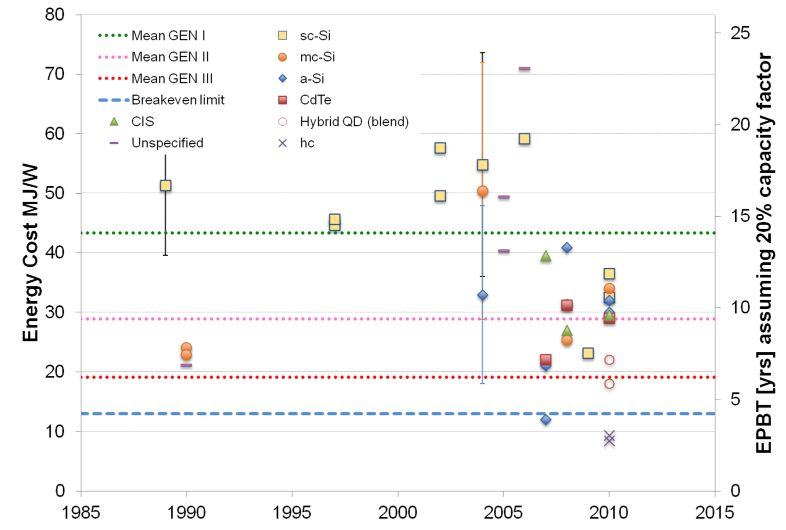

Figure 3a. Energy costs of a number of PV technologies [MJ/W] including balance of system (BOS) energy costs [6].

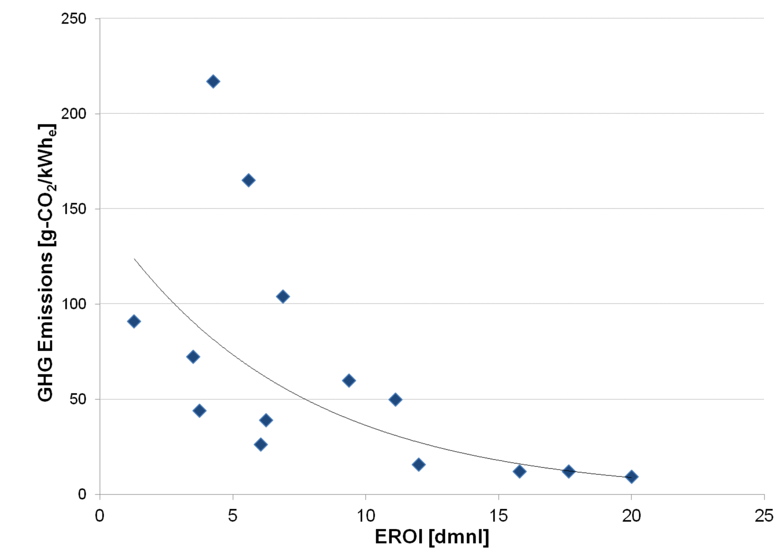

Figure 3b. GHG emissions [g-CO_2/kWh$_e$] as a function of PV EROI [6].

Net energy yield from growing energy systems:

Figure 4 plots equation (1), the relationship between system growth rate, r [%/yr], and the embodied energy [MJ/W] (top axis) or the EPBT [yrs] (bottom axis) for a variety of fractional re-investment rates, f [%]. The ranges of embodied energy of a various PV technologies are plotted on the right. The PV industry is currently growing at ~ 40 %/yr (red dashed line). Continuing at this rate, although highly unlikely, the installed capacity would surpass the current total primary energy supply (~ 15 TW) by 2030. Given an embodied energy of 45 MJ/W, a system growing at this rate requires a fractional re-investment of 300 % (yellow bullseye), 3 times more energy than it produces. While PV is still a small portion of the global energy system, these growth rates are possible. As PV penetration grows, sustained growth will require devices with lower EROI.

Method:

Two logistic growth scenarios for installed capacity [MW] were modeled assuming a panel capacity factor of 20%:

Year	IEA [3]	WGBU [8]
2020	200 GW	2500 GW
2030	900 GW	40,500 GW
2040	2000 GW	105,000 GW
2050	3000 GW	155,000 GW
2100	-	164,000 GW

Each growth scenario was modeled assuming deployment of 1st, 2nd and 3rd generation panels as well as deployment of panels of decreasing embodied energy (e.g. SunShot targets [9]).

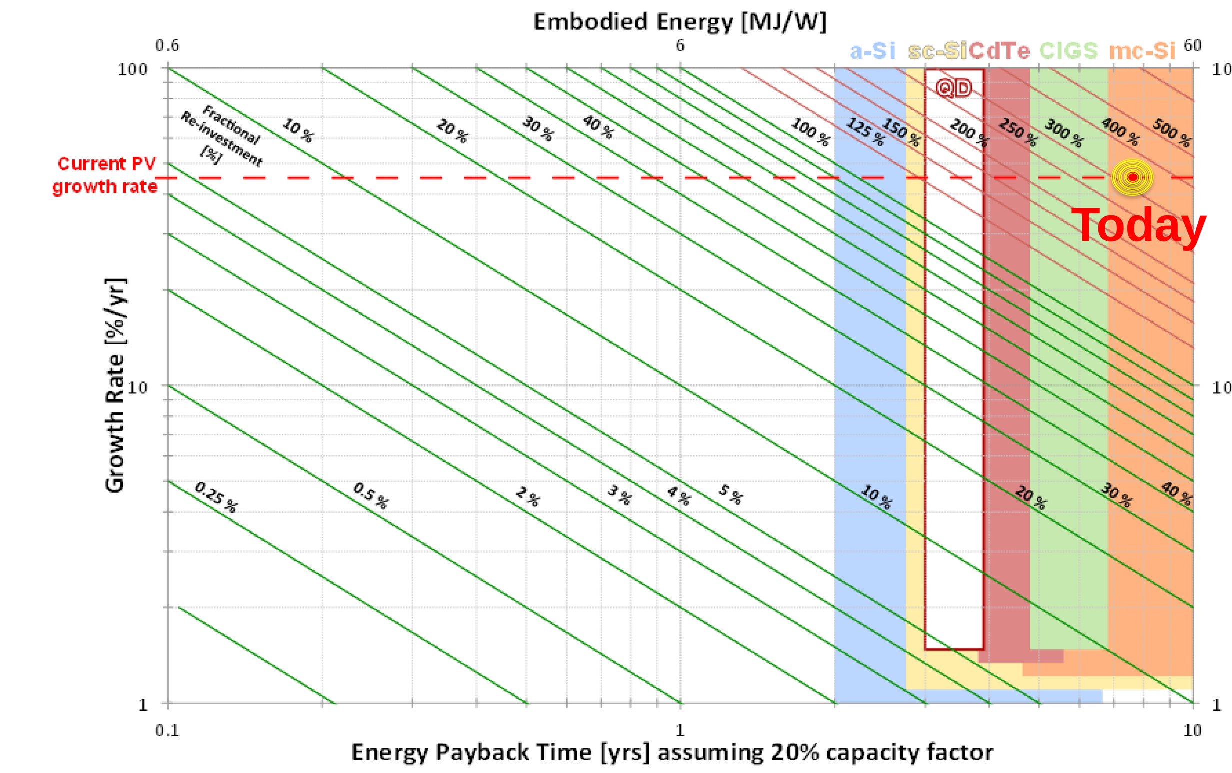

Figure 4. System growth rate [%/yr] as a function of embodied energy [MJ/W] (top axis) and energy-payback-time (EPBT) [yrs] (bottom axis)

Results:

Figures 5a and 5b show the net energy yield [EJ/yr] for Gen I (green line), Gen II (pink line) and Gen III (red line) PV and the decreasing embodied energy case (orange line) for both the IEA and WGBU growth scenarios. Rapid deployment of 1st generation PV results in a negative net energy yield until 2030. Lower embodied energy technologies offer greater net energy yields and a quicker return on investment.

Note: Vertical scales are different

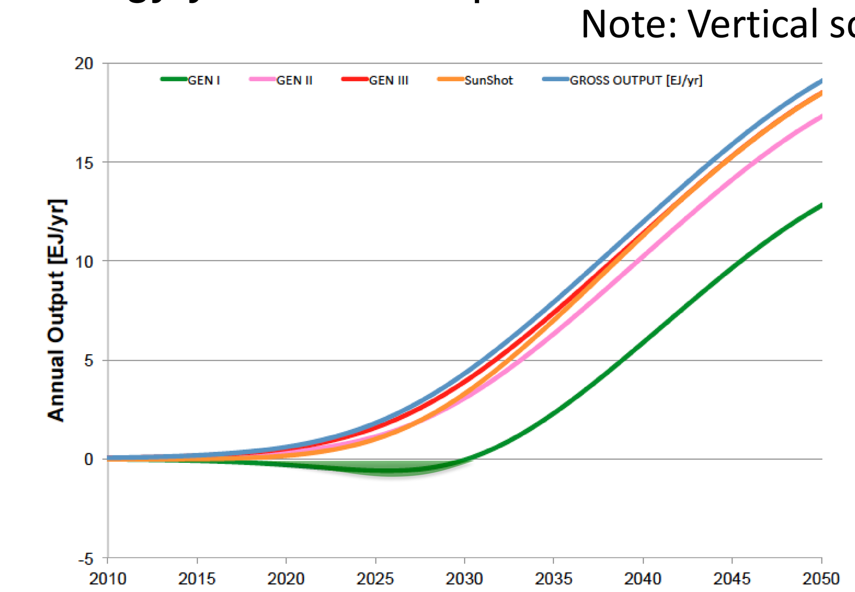

Figure 5a. Annual gross and net energy yield from the PV industry under the IEA Technology Roadmap scenario.

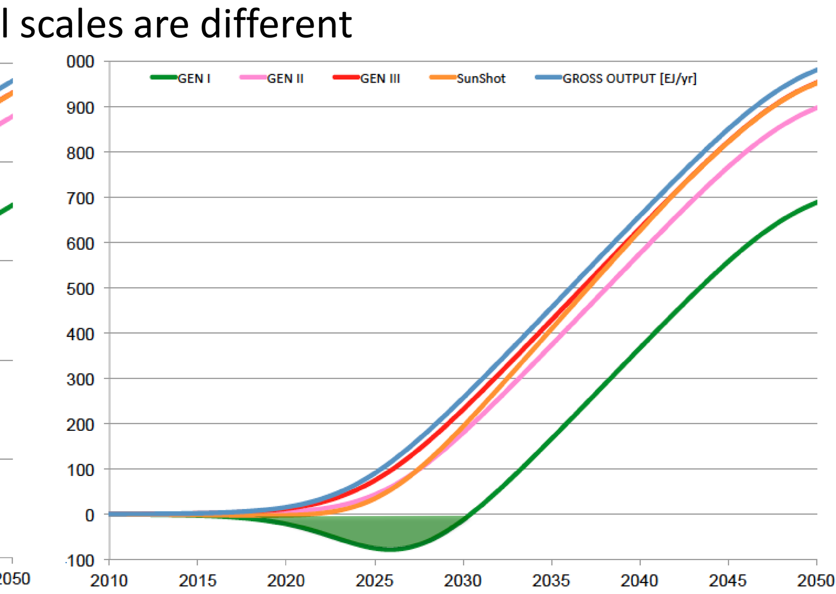

Figure 5b. Annual gross and net energy yield from the PV industry under the WGBU scenario.

Findings:

We have shown that there are significant benefits to the whole energy system in reducing the energy cost of PV production. We believe that our analysis also highlights some other important implications:

1. Economic analysis should be supplemented with energy analysis.
2. EROI is a function of both geographical and technological factors (2).
3. EROI of energy technologies may constrain rapid growth of low GHG emission energy technologies.
4. There is an inverse relationship between EROI and environmental impacts, in particular GHG emissions.
5. Low embodied energy costs of energy production devices should be a fundamental concern for technology development.
6. Policies aimed solely at rapid deployment, without raising EROI, may not be beneficial for the energy system as a whole.
7. Deployment of PV in regions with high insolation and capacity factors provide greater overall benefits for the energy system.

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