

Comparing energy payback and simple payback period for solar photovoltaic systems

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Abstract. Installing a solar photovoltaic (PV) array is both an environmental and a financial decision. The financial arguments often take priority over the environmental because installing solar is capital-intensive. The Simple Payback period (SPB) is often assessed prior to the adoption of solar PV at a residence or a business. Although it better describes the value of solar PV electricity in terms of sustainability, the Energy Payback period (EPB) is seldom used to gauge the merits of an installation. Using published estimates of embodied energies, EPB was calculated for four solar PV plants utilizing crystalline-Si technology: three being actual commercial installations located in the northeastern U.S., and a fourth installation based on a simulated 20-kilowatt roof-mounted system, in Wrocław, Poland. Simple Payback was calculated based on initial capital cost, and on the availability of avoided electricity costs based on net-metering tariffs, which at present in the U.S. are 1:1 credit ratio, and in Poland is 1:0.7 credit ratio. For all projects, the EPB time was estimated at between 1.9 and 2.6 years. In contrast, the SPB for installed systems in the northeastern U.S. ranged from 13.3 to 14.6 years, and was estimated at 13.5 years for the example system in Lower Silesia, Poland. The comparison between SPB and EPB shows a disparity between motivational time frames, in which the wait for financial return is considerably longer than the wait for net energy harvest and the start of sustainable power production.

1 Introduction

The adoption of solar photovoltaic (PV) generation at a given site is a blend of feasibility and motivations – both economic and environmental. The technical aspects can include: roof orientation and pitch, solar access, roof composition, land usage, geology, soil character, proximity to the power grid, and many others. On the other hand, financial variables include questions of access to working capital, cost of installation, and the cost of avoided electricity. The Simple Payback Period (SPB) is a commonly cited measure of the

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time in years, between initial outlay of capital on a solar installation and the return on initial investment. The Simple Payback period of a solar PV installation may be expressed:

$$SPB = (c_{\text{system}}) (Q_{\text{year}}^{-1}) (PR^{-1}) (P^{-1}) (c_{\text{elec}}^{-1}) \quad (1)$$

where c_{system} is the un-subsidized installed system cost, Q_{year} is the total annual irradiation for an optimally-inclined array at the location [1], PR is the system's annual DC to AC performance ratio [2], P is the system DC capacity in Watts, and c_{elec} is the cost of electricity that is avoided by the system's local production. The usefulness of the SPB calculation is that it is an intuitive expression of expenses and returns. However it carries a high degree of variability due the fluctuation of c_{elec} , i.e. the market electricity rate. Historically, SPB for solar PV installations has decreased, as the cost of producing PV modules and c_{system} has decreased [3, author's industry observation].

The merits of a solar PV installation as an energy investment are described with an analogous term, called Energy Payback (EPB), which may be expressed:

$$EPB = (E_M + E_{\text{INV}} + E_{\text{BOS}}) (Q_{\text{year}}^{-1}) (PR^{-1}) (P^{-1}) \quad (2)$$

where E_M , E_{INV} , and E_{BOS} represent the embodied energy of the solar modules, the DC-to-AC inverters, and Balance of System (BOS), respectively [4]. Where SPB estimates the wait time for the recoup of initial capital outlay, the EPB expresses the time required for the PV array to generate an amount of energy equivalent to its initial energy inputs, and start net energy production.

This work presents estimated EPB and SPB calculations, for three completed solar photovoltaic installations, and one typical installation based on published estimates of embodied energy and current industry and market parameters. In assessing the differences between EPB and SPB, the question arises of how best to motivate and accelerate adoption of sustainable, local PV harvest, given its comparatively short Energy Payback period.

2 Methods

Simple and Energy Payback periods were calculated for three installed systems in the northeastern U.S. including a ground-mounted array located in Thornton, NH (lat. 43.936740, long. - 71.683367), a pitched-roof array located in Franconia, NH (lat. 44.234389, long. - 71.756667), and a flat-roof array located in Concord, NH (lat. 43.218414, long. - 71.536698). For geographical comparison, payback periods were simulated for a model 20 kW DC array located in Lower Silesia Poland (lat. 51.108752, long. - 17.059876).

All SPB estimates assumed electricity escalation rates of 3% [5], a 0% discount rate, zero cash incentives, and used the electricity tariffs applicable for each customer at the time of system installation, as shown in Table 1. Mean solar production for U.S. locations was modelled using the American National Renewable Energy Laboratory's typical meteorological year data sets (TMY2, TMY3) [6]. Mean solar production for the Polish site was modelled from the Photovoltaic Solar Electricity Potential in European Countries data set [1]. The simulated SPB for the Lower Silesian PV system also assumed solar production was consumed behind the meter 50% of the time for 1:1 cost offset, and exported 50% of the time for 1:0.7 cost offset based on the recently enacted Odnawialne Źródła Energii (Renewable Energy Sources) laws. An installed cost of 7PLN per WDC was used [author's industry observation].

Energy payback period was calculated using primary energy in all instances, assuming a grid efficiency factor of 0.35, and balance of materials records from the three existing projects in the northeastern U.S. Specifically, Balance of System (E_{BOS}) was calculated as

the sum of embodied energies by mass of Aluminum, Steel, Copper, PVC, and Concrete materials used in the solar PV system, based on estimates by Frankl et al. [7]. For all four systems, embodied energy of poly-Si and mono-Si photovoltaic modules (E_M) followed from Peng et al. [4], and embodied energy of the PV inverter by AC wattage (E_{INV}) followed from estimates published by Alsema [8]. Energy payback for the simulated 20 kilowatt system referenced the same estimates of E_M [4] and E_{INV} [8]. However E_{BOS} estimates were based on a linear extrapolation from the roof-attached Franconia array, using an empirically determined E_{BOS} coefficient of 95.7 kWh/m² of array.

3 Results

The estimated SPB and EPB for installed and modelled PV systems are presented in Tables 1 and 2, respectively.

Table 1. Estimated Simple Payback periods for three actual and one simulated solar PV system.

Generator	Commissioned	System size kW DC	Solar production	Elec. Tariff \$/kWh	Simple Payback
Hubbard Brook Research Foundation Thornton, NH USA	2015	40.56	44,800 [6]	\$0.177	13.3
Gale River Motel Franconia, NH USA	2016	13.78	15,540 [6]	\$0.170	13.8
Grappone Conf. Center Concord, NH USA	2016	143.6	160,000 [6]	\$0.126	14.6
Sample roof mounted Mono-Si PV array Optimal orientation Wrocław, Poland	--	20.0	19,000 [1]	\$0.139* *[based on 3.96 PLN = 1 USD]	13.5

Table 2. Estimated Energy Payback along with estimate sources for three actual and one simulated solar PV system.

Generator	Primary energy prod. (kWh)	Estimated primary energy inputs			Total	Energy Payback years
		PV module	BOS	Inverter		
Hubbard Brook Research Foundation	128,000	213,600 [4, 10]	80,000 [7]	13,200 [8]	306,800	2.4
Gale River Motel Franconia, NH USA	44,400	71,200 [4, 10]	8,000 [7]	4,300 [8]	83,500	1.9
Grappone Conf. Center Concord, NH USA	457,100	888,800 [4, 10]	40,400 [7]	38,500 [8]	967,700	2.1
Sample roof mounted Mono-Si PV array Optimal orientation Wrocław, Poland	54,300	123,600 [4, 10]	11,000	7,800 [8]	142,400	2.6

Table 3. Balance of System summary for driven-post, ground-mounted solar system in Thornton, NH USA.

Material	Aluminum		Steel		PVC		Copper		Total
kg	1,418	Racking system	1,256	Posts	85	Conduit	37	Conductors	
	69	Fasteners	73	Channel strut	9	Misc.			
	162	Conductors	92	Misc. electrical					
			7	Fasteners					
subtotal	1,649		1,428		94		37		
kWh embodied [7]	64,900		12,700		1,700		700		80,000

Table 4. Balance of System summary for pitched-roof solar system in Franconia, NH USA.

Material	Aluminum		Steel		PVC		Copper		Total
kg	183	Racking system	12	Fasteners	1	Conduit	8	Conductors	
	12	Fasteners	8	Misc. electrical					
			4	Conduit					
subtotal	195		24		1		8		
kWh embodied [7]	7,660		213		19		152		8,000

Table 5. Balance of System summary for ballasted, flat-roof solar system in Concord, NH USA.

Material	Aluminum		Steel		Concrete		PVC		Copper		Total
kg	31	Racking system	2,524	Racking system	9,973	Ballasts	22	Conduit	149	Conductors	
	59	Conductors	26	Fasteners							
	7	Fasteners	266	Channel strut							
			286	Conduit and wireways							
			123	Misc. electrical							
subtotal	98		3,225		9,973		22		149		
kWh embodied [7]	3,840		28,700		4,520		408		2,900		40,400

Detailed balance of materials lists are shown in Tables 3, 4, and 5. For the systems in operation in the northeastern U.S., simple payback ranged from 13.3 years to 14.6 years. For the simulated system in southwest Poland, simple payback was estimated at 13.5 years. The estimated EPB for existing installations ranged from 1.9 years for a pitched-roof attached-railing system in Franconia, to 2.4 years for a pile-driven ground mount array in Thornton. The existing ballasted flat-roof system in Concord showed an EPB of 2.1 years. The simulated roof mounted PV array in Lower Silesia (Wrocław) had an EPB of 2.6 years.

4 Discussion

Between the years 1977 and 2013, the average cost of crystalline-Si photovoltaic cells dropped from 76.67 USD/W, to 0.74 USD/W [3], and this trend continues in 2017, as average PV cell prices drop below 0.30 USD/W [author's industry observation]. Nonetheless the capital investment required to purchase and install a distributed solar PV generator is great enough that out-of-pocket costs and simple payback scenarios guide customers' decision-making. Comparisons of EPB and SPB show significantly shorter wait times for the harvest and return of 100% of the energy invested in the solar equipment and the start of net energy harvest, compared to the wait for financial returns.



Fig. 1. Ground-mounted solar photovoltaic arrays at the Hubbard Brook Research Foundation. The system's estimated energy payback period of 2.4 years was significantly less than the simple payback period, 13.3 years. Note the driven-post system reaches soil depth of 2.4m, and requires no concrete to install.

Energy payback improves alongside advancements in module manufacturing, solar installation techniques, and cell efficiencies. For example, the EPB times calculated in the present study for the northeastern U.S. and Poland are significantly shorter than the EPBs surveyed for systems of similar or greater productivity that were installed between 2003 and 2006 [9]. Furthermore, the E_{BOS} estimated for the ground-mounted array at Hubbard Brook, pictured in Figure 1, was 319 kWh/m², small in comparison to previously published estimates of ground mounting balance of system embodied energies [10, 11]. However, it is unlikely that continuing technological advancement will decrease the EPB below certain physical thresholds due to constraints such as resource scarcity, transportation and mobilization costs, and labor costs of installation.

Incentivizing renewable energies by shortened SPB, or low cost loan presents a valid goal based on the physical merits of low-EPB solar generation. In mature solar markets, two policies have been successfully adopted and replicated, and may be worth long term implementation: a) Production-based incentives such as a mandated offer or a feed in tariff

guarantee, and b) Low-cost financing programs, which allow the expense of equipment and installation to be spread out over the lifetime of the solar equipment.

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