Cost-effectiveness of Residential Solar PV vs Utility-scale solar PV in California

by
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Abstract

Using cost and performance data from residential rooftop solar PV and large utility-scale solar PV "farms" in California it was found that residential solar PV costs about 6 times more than utility-scale solar PV per unit of electricity generated.

The following policy questions are raised. In its effort to increase the production of renewable energy in California why should government provide financial incentives for residential roof-top solar when utility-scale solar is so much less expensive? Could those incentives be better directed toward utility scale solar, and if so, how? One such alternative, provisionally called "remote solar", is described in a companion whitepaper.

Objective

The objective of this paper is to compare the approximate cost-effectiveness of residential rooftop solar PV with utility-scale solar farms in California. This type of comparison has apparently not been made before. What has been done is to publish and sometimes compare costs per unit of capacity as measured in $/Watt. But that omits their relative efficiencies in converting capacity into actual production in kWh over time. This whitepaper's main contribution is to include data on "capacity factors" to remedy that shortcoming.

The answer would help guide government policy-making re solar incentives, and provide those concerned about climate change know which potential policy changes to advocate.

Because this whitepaper suggests a way to generate solar power more economically and thus expand its deployment, the main stakeholders that this white-paper is directed toward are those government agencies and non-profit organizations most concerned about climate change. The government agencies in California would include: the California Environmental Protection Agency or CalEPA; California Air Resources Board or CARB; and the California Public Utilities Commission or CPUC. Owners of utility-scale solar farms may see this as a nascent business opportunity.

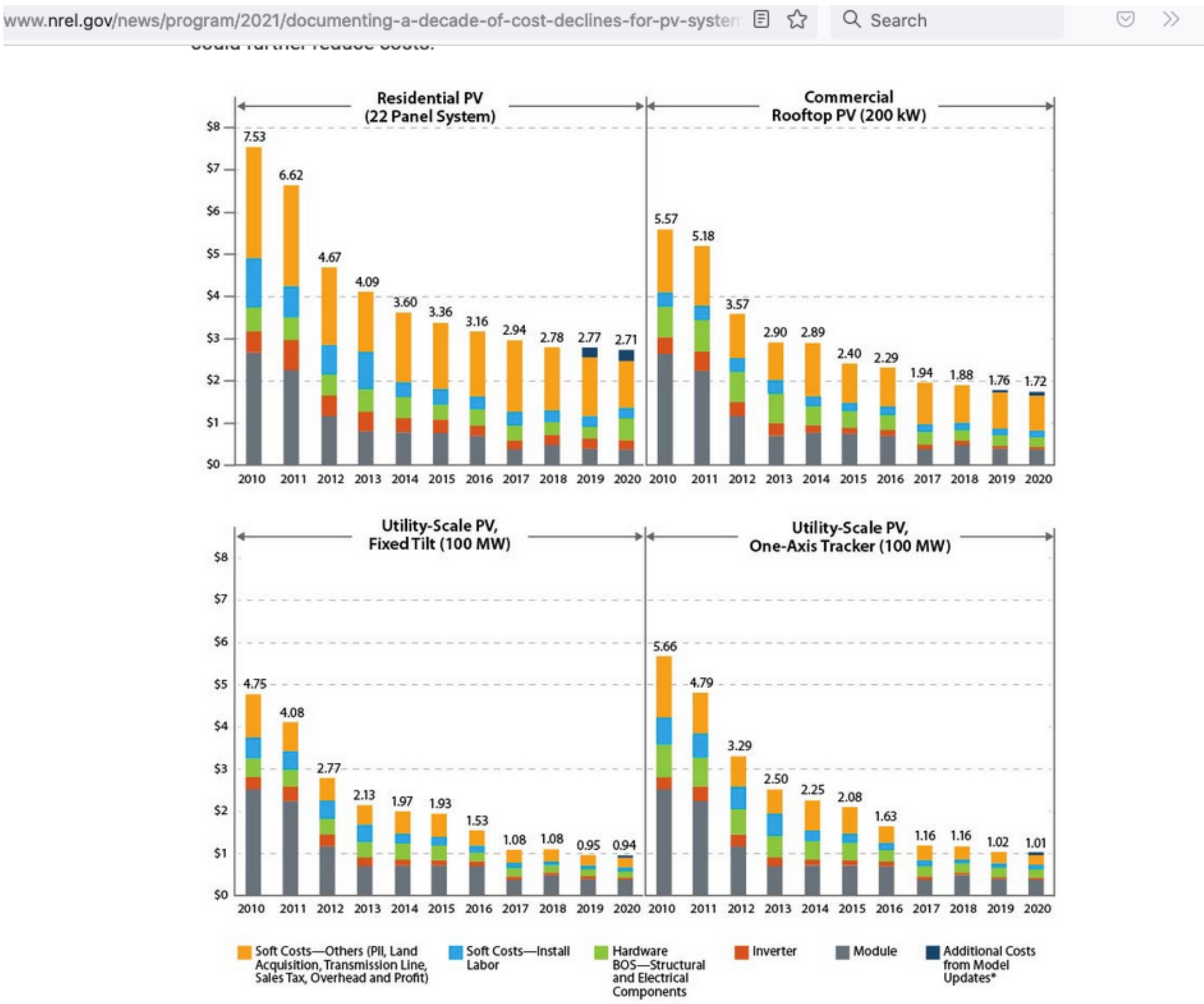
Findings

This analysis finds that utility scale solar is roughly 6 times more cost-effective than residential rooftop solar as a way to generate renewable electricity in California. In other words, society could produce about 6 times more electrical power and presumably save about 6 times more greenhouse gas by spending X dollars building utility-scale solar farms rather than spending the same amount building residential roof-top solar PV systems. This ratio is so large that any refinement of these calculations is unlikely to change the overall conclusion. Nevertheless, this analysis should be vetted and refined by others more expert than the author.

This finding about cost-effectiveness has not entered the policy making arena where it could affect the wisdom of providing tax credits and net-metering benefits to homeowners considering rooftop solar PV, or rules requiring new homes to include rooftop solar. Instead, it suggests those tax credits and net-metering benefits be redirected away from roof-top solar and into a new service concept that might be called "remote solar". Remote solar would allow homeowners (and perhaps renters) to -in effect- purchase panels in utility-scale solar farms while getting the same financial incentives as they are now getting from roof-top systems. The author has written a companion white-paper describing "remote solar" in more detail.

Motivations for this study

When writing a book about global warming the author came across the eye-catching National Renewable Energy Lab chart below. It showed that -nationwide- the up-front cost of building residential solar is roughly 3 times more than utility-scale solar per unit of capacity as measured in watts. Presumably the former are burdened by marketing and site-specific installation costs while the latter benefited from economies of scale. The cost breakdown also made clear that even if solar panels were free, the total cost of residential solar would not decline much further.



From personal observation it was also clear that many residential panels are not optimally oriented and/or are partly shaded at times, thus reducing their ability to fully utilize their nameplate capacity.

The climate crisis is so challenging that society in general, and government in particular, should spend their limited funds where they will produce the most renewable energy, and thus save the most greenhouse gas, per dollar spent. That did not appear to be residential solar. These facts motivated this effort to understand the relative cost-effectiveness of small residential roof-top PV versus large utility-scale solar. Surprisingly, the author was unable to find this information published elsewhere.

Method

Cost-effectiveness will be measured in dollars per kwh of electrical power actually produced by real-world PV systems located in California. The end results will be indicated as a ratio between the cost-effectiveness of utility scale systems and residential rooftop systems. For example, if a dollar spent building a utility-scale solar farm produced the same amount of power (as measured in kWh/year) as a dollar spent on residential solar then the cost effectiveness ratio would be one. However, if a dollar spent on utility-scale solar produced five times as much power, then the ratio would be 5 to 1.

The two key data items needed were 1) the up-front capital costs per watt of capacity ($/W) for both residential and utility-scale solar, and 2) their relative efficiencies in converting that capacity into the amount of electricity (kWh) generated over a reasonable time period, such as a year. For that we need to know their capacity factors.

Capital cost and capacity for residential systems is reported in terms of the total project cost and what's called "nameplate" capacity, usually specified in kWdc. For example: a 5-kW residential system may cost a homeowner $20,000 before tax credits. We need this data for a reasonably sized sample of real-world systems in a certain geographic area such northern California. That can be compared with the same type data for large utility-scale systems. We expect the latter should be less expensive due to economies of scale, easier installation, and lower marketing costs. See https://coldwellsolar.com/portfolio/ for video descriptions of some utility-scale solar farms.

Capacity factor is the ratio of how much electricity (in kWh) a solar system could theoretically generate over a long period (if the sun shined 24 hours per day, the panels were ideally oriented re the sun, were never shaded and so forth) versus how many kwh the system actually generated in the real world. A period of one year is adequate for our purposes. In general, the panels in utility scale solar farms can be ideally oriented, are never shaded, and have other advantages giving them a higher capacity factor.

There are several potential sources for the needed data. The capital cost of residential systems (in $/W was obtained from the "California Distributed Generation Statistics at: https://www.californiadgstats.ca.gov/downloads/ A website called "PVOutput" was the only place the author could find data needed to compute the capacity factor for residential systems. https://pvoutput.org/. Both cost and capacity factor data for utility-scale solar came from: https://emp.lbl.gov/utility-scale-solar/.

Some source data is reported in terms of AC watts while other data is reported in DC watts. Those were all converted into AC values. Some values were averages, some were weighted averages, and some were median. Care was taken to deal with these differences. In so far as practical all dollar values were for 2022.

Computation of the cost-effectiveness ratio

This ratio was computed as follows:

Cost-effectiveness Ratio = Cost per watt ratio / Capacity factor ratio

The actual numbers used were:

Cost per watt ratio: ($4.77/watt ac for residential solar) / ($1.28/watt ac for utility scale solar)= 3.73

Capacity factor ratio: (17% for residential) / (29% for utility scale) = 0.586

Cost-effectiveness ratio: 3.73/0.586 = 6.37

Conclusions

Large utility-scale solar PV systems appear to be far more cost-effective than small, residential roof-top PV systems in generating renewable electric power in California. This analysis suggests they are about 6 times more cost-effective. This multiple is so large it seems that a more accurate figure is not worth obtaining in order to merit reshaping government policies regarding residential solar and looking for opportunities for homeowners and others to take advantage of utility-scale solar in ways that benefit not only themselves, but more importantly increase the amount of solar deployed and thus the amount of GHG saved. The key issue is this: why should society spend so much on residential solar when it appears a similar investment in utility-scale solar would yield a much greater return?

This further suggests a number of other things:

1) That this whitepaper be vetted by experts and if these findings are sustained a similar paper be published by CalEPA, CARB, CPUC, NREL, EPRI, Lawrence Berkeley National Laboratory, or EERE. Policymakers may need validation from these recognized sources in the record before making policy changes.

2) If saving GHG is better accomplished by utility-scale solar than residential solar then policymakers should consider sponsoring studies to determine what unique societal benefits, if any, exist for residential solar.

3) That any unique benefits homeowners get from having solar on their roof versus obtaining renewable energy thru the grid be clearly determined; assuming they could get the same amount of "free energy", net-metering credit, and capital cost tax credit as they now get from roof top solar. (Note that most roof-top solar systems will not power the house if grid power is lost)

4) That government and environmental organizations find ways to inform the general public about this 6 to 1 ratio and its implications.

5) That other options -beside rooftop solar- for individuals to invest in renewable solar power be aggressively explored; such as buying shares of utility-scale solar systems. This author has suggested one possible option, provisionally called remote solar, in a companion white-paper. By way of preview, remote solar -if approved by policy

makers- might cost the homeowner about one sixth that of roof top; receive the same benefits in terms of: 1)“free energy” for use in the house, 2) net-metering credits for exported energy, 3) capital cost tax credits; and 4) reach financial break-even in just a few years.

6) That the cost-effectiveness of intermediate size solar systems, such as are sometimes installed over parking garages or large commercial properties, be determined. This may be an appealing alternative in some cases, but the energy needed to make the heavy steel and concrete supports should be considered when estimating how much GHG would be saved.

7) That the cost-effectiveness of wind energy be evaluated in the same manner as this whitepaper has done with residential and utility-scale solar.

Data sources

The values used above came from the following sources:

Cost of utility-scale solar

The cost per watt and capacity factor of utility-scale solar were taken from the data files accompanying a detailed report done by Berkeley Lab. https://emp.lbl.gov/utility-scale-solar/

The median cost of $1.32/Wac for systems in California was taken from the data table shown below. Source: 2023 utility-scale solar data update.xlsx . It represents the total up-front cost to the owner of the utility system, but to compare it to the cost of distributed roof-top solar, which reports an average cost not a median cost, this value must be converted as best possible into an average cost.

Installed costs by state and installation year

Sources: Berkeley Lab (some data points suppressed to protect confidentiality), E

Solar COD	National	AL	AR	AZ	CA	C
2007	11.71					
2008	5.4					
2009	5.81					
2010	6.03					
2011	5.28			5.68	5.08	
2012	4.89			4.86	4.85	
2013	4.35			4.39	4.48	
2014	3.79			4.64	3.86	
2015	3.31			3.41	3.62	
2016	2.74			2.39	2.91	
2017	2.54	3.27		2.27	2.98	
2018	2.06				3.16	
2019	1.77				1.91	
2020	1.81			1.39	1.86	
2021	1.52			1.48	1.79	
2022	1.32				1.32	

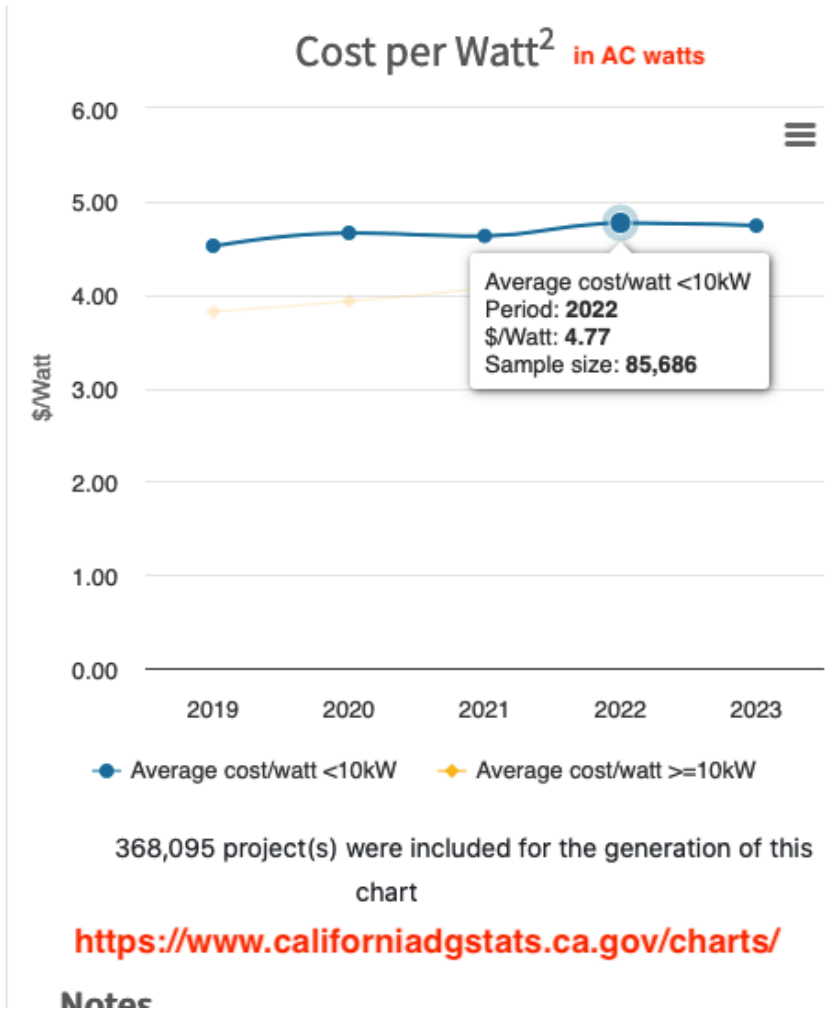
These are median costs in $/Wac in 2022$

Since the average costs for systems in Cal was not in the Berkley data file the following imperfect approach was used to convert the median cost of $1.32/W above into an approximate average cost. Per the Berkeley Lab table below the average or mean cost for all systems nationwide averaged over the years 2020, 2021 and 2022, was $1.50/W. (1.66+1.56+1.27= 4.49/3 =1.50). While the median was $1.55 (1.81+1.52+1.32= 4.65/3= 1.55). Thus the average cost is 0.97 times the median cost. Based on this ratio the median cost of $1.32/W converts to an average cost of $1.28/W (0.97 x $1.32= $1.28). <u>$1.28/W is the value used to compute the relative cost of utility solar vs residential solar.</u>

23	*Sources: Berkeley Lab, Energy Information Administration*				
24	*Note:* **Berkeley data sheet tab "CapEx by Mount Type" for**				
25	**systems nationwide.**				
26	Commercial Operation Year	All Count	All Capacity (MW_{AC})	All Capacity-weighted Mean	All Median
27	2007	2	19	11.64	11.71
28	2008	1	10	5.40	5.4
29	2009	2	46	5.98	5.81
30	2010	10	175	5.57	6.03
31	2011	29	428	5.26	5.28
32	2012	41	930	4.30	4.89
33	2013	38	1,344	4.65	4.35
34	2014	65	3,184	4.49	3.79
35	2015	87	2,870	3.69	3.31
36	2016	146	7,389	2.74	2.74
37	2017	163	4,046	2.58	2.54
38	2018	94	3,951	2.18	2.06
39	2019	103	4,533	1.86	1.77
40	2020	158	9,442	1.66	1.81
41	2021	128	11,228	**1.50** 1.56	**1.55** 1.52
42	2022	59	4,622	1.27	1.32
43	**Total**	**1126**	**54,215**	**Mean = 1.50/1.55 Median**	
44					

Cost of residential solar PV

The value of $4.77/watt ac is from the following chart reporting the costs for all systems in the data base that are interconnected to the California grid. Most residential systems are under 10-kw in size. This data is apparently reported by system installers and is accessible at: https://www.californiadgstats.ca.gov/charts/ and https://www.californiadgstats.ca.gov/downloads/#_nem_cids. The value of $4.77/watt ac represents the total cost to the homeowner of his or her roof-top system before any tax credits are applies. For example, at $4.77/W a typical 8 kW system would cost the homeowner $38,160 up-front, before the federal tax credit was applied.



The SEIA chart below shows the different cost elements that comprise the total system cost. This breakdown helps explain why residential solar is so much more expensive than utility-scale solar. The totals in this chart are average costs (in $/Wdc) for systems nationwide. The NREL publishes similar charts.

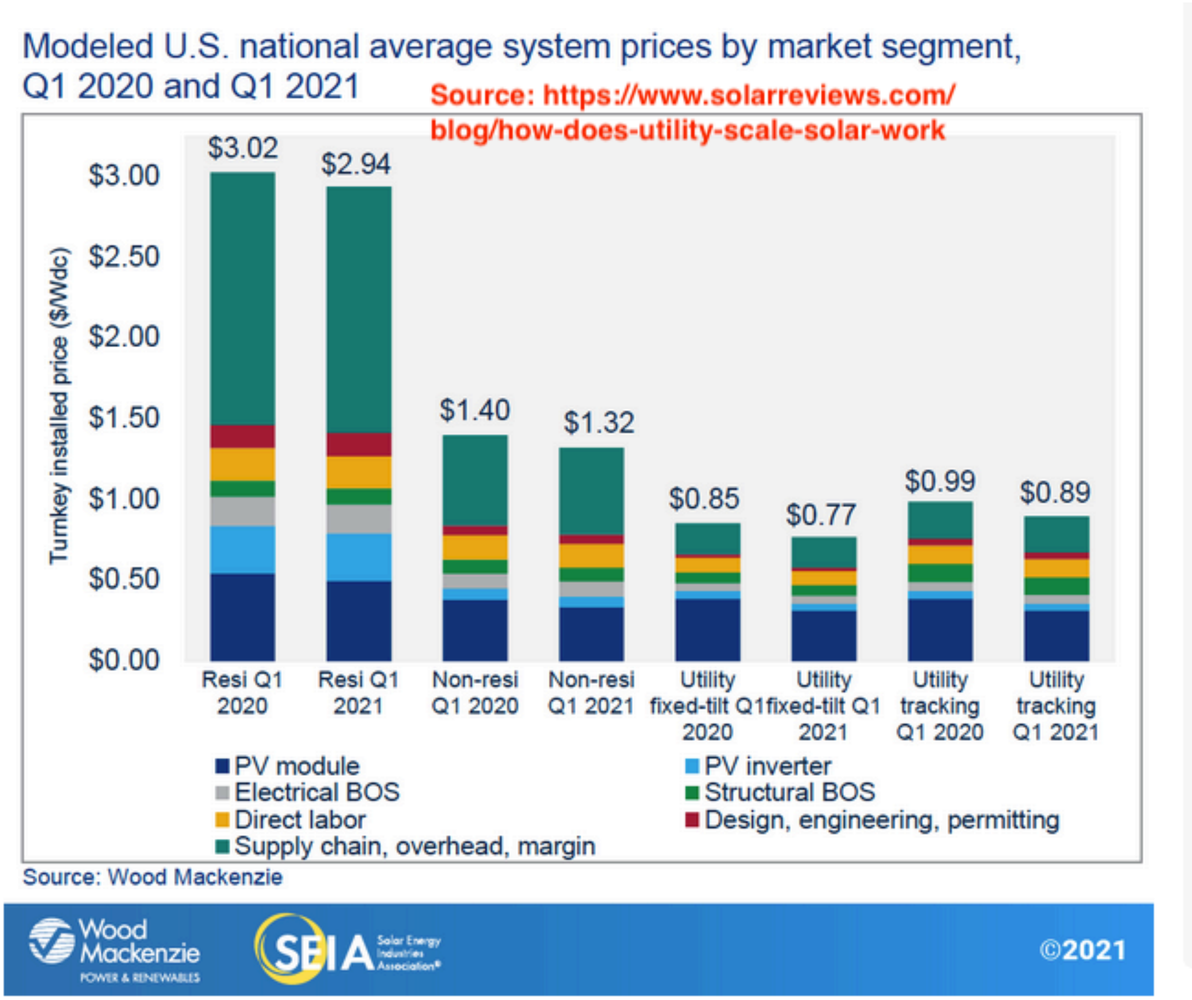
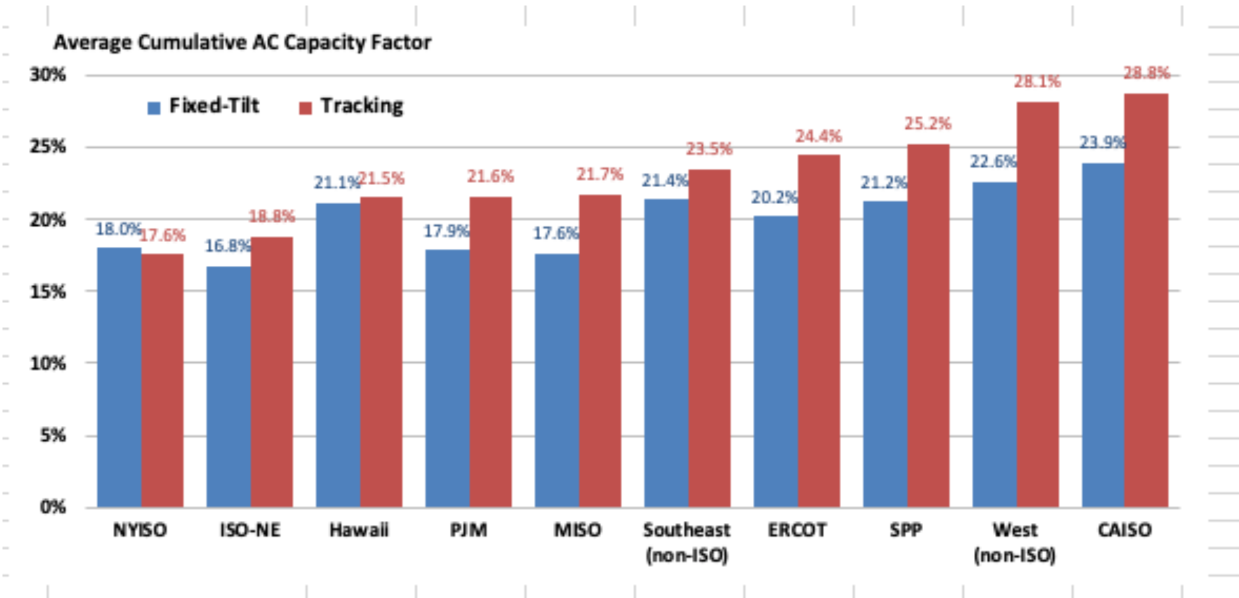


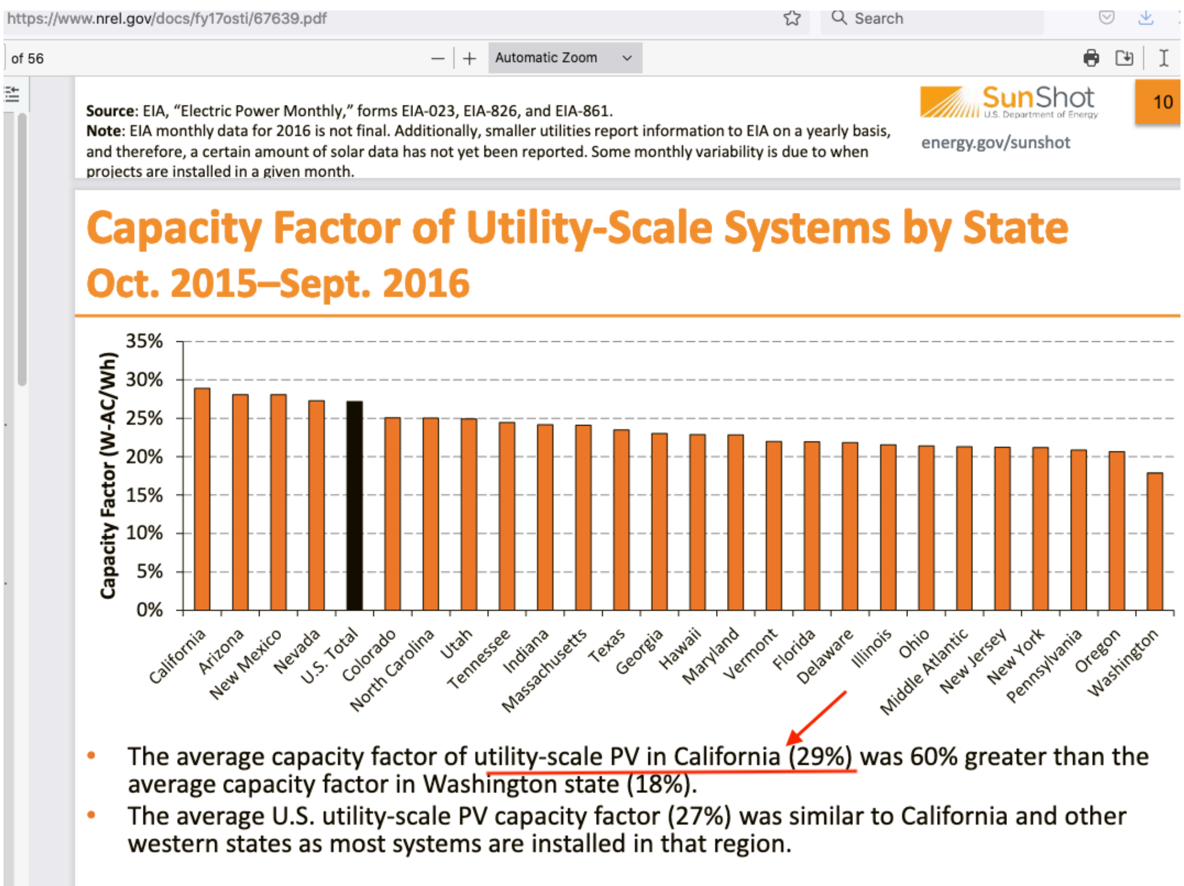
Image source: ***SEIA Solar Market Report Q2 2021***

Capacity factor of utility-scale solar

The capacity factor of 29% for utility scale solar was taken from the CASIO tracking bar in the chart below. (CASIO is mostly California) The tracking bar was selected for this analysis due to the following quote from Berkeley Lab: "Fixed-tilt projects are increasingly only being built on particularly challenging sites (e.g., due to terrain or wind loading) or in the least-sunny regions in the northeast." From slide 11 at https://emp.lbl.gov/sites/default/files/utility_scale_solar_2023_edition_slides.pdf



The EIA chart below is another source for capacity factors.



Capacity factor of residential solar PV systems:
The data to calculate the capacity factor for residential solar came from the web site "PV Output" at: https://pvoutput.org/ The author has not been able to find any other source for such data.

PVOutput reports the actual performance of PV systems that their owners choose to register with PVOutput. Their database includes systems all over the world. The screenshot below shows the location of registered systems near and east of the SF Bay. Unable to locate any other published information on the capacity factor for residential solar the author selected a sample of systems in California from this map to compute the average capacity factor of small residential solar systems in northern California. Next are some charts to better explain the type of data obtained from PVOutput and how it was used.

One display offered by PVOutput appears below.

https://pvoutput.org/map.jsp?country=244&region=California 90% Sear

PVOutput

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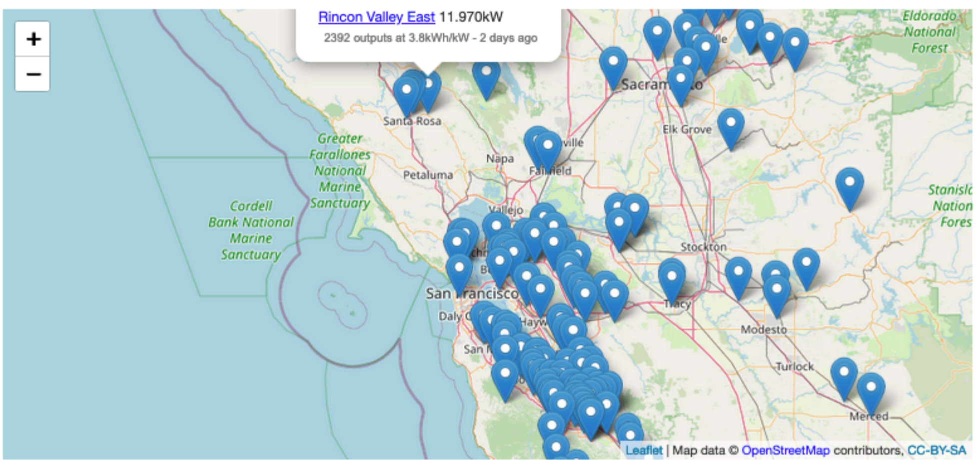

Prev 1 2 3 4 5 6 7 8 9 10 11 Next

California 21.001MW Find: Tips

Rank	Name	Location	System Size	Generation▾	Efficiency	Average	Outputs
1	RRW-Lakeside	92040	289.140kW	3,508.164MWh	4.274kWh/kW	1,235.704kWh	2,839 Days
2	MCC-SunnyBoy	92040	24.150kW	500.054MWh	4.396kWh/kW	106.169kWh	4,710 Days
3	Reel EFX	91601	100.000kW	406.994MWh	1.554kWh/kW	155.282kWh	2,621 Days
4	Goddard School SD by CM Solar	92056	26.280kW	255.093MWh	4.195kWh/kW	110.334kWh	2,312 Days
5	Kahng Home	93010	10.725kW	227.997MWh	7.769kWh/kW	83.332kWh	2,736 Days
6	Turborick	93551	24.600kW	206.136MWh	4.935kWh/kW	67.255kWh	3,065 Days
7	KKC Ground Mount PV array	93614	20.800kW	196.819MWh	4.396kWh/kW	91.459kWh	2,152 Days
8	Chula Vista, CA by the Lakes	91914	18.000kW	195.356MWh	4.281kWh/kW	77.522kWh	2,520 Days
9	La Honda Hilltop	94062	9.408kW	177.182MWh	4.732kWh/kW	44.440kWh	3,987 Days
10	Poway 12kW	92064	12.000kW	175.716MWh	5.284kWh/kW	62.244kWh	2,823 Days
11	madbrain	95127	20.690kW	165.664MWh	3.919kWh/kW	37.312kWh	4,440 Days
12	OfficeSaid	94513	26.000kW	163.120MWh	3.729kWh/kW	96.807kWh	1,685 Days
13	14KW PV System	92065	14.000kW	161.443MWh	3.992kWh/kW	55.882kWh	2,889 Days
14	Gold Country Auburn CA	95602	13.440kW	156.563MWh	4.391kWh/kW	58.903kWh	2,658 Days

By way of example, clicking one of the icons on this map reveals considerable information on including the chart below. This example shows the system size (in kw dc) and power generated (in kwh) by year for the Rincon Valley East system in Santa Rosa, Sonoma County. On-site inspection showed this roof-top system was oriented almost directly south and has no shade. In 2021 this 11.97 kw system generated 16.576 megawatt hours of ac electricity. Had it produced at this rate for 24 hours per day 365 days per year it would have produced 104.857 megawatt hours of ac electricity. The capacity factor is thus 16.58/104.86 or 16%. (Capacity factor can only be obtained after output is monitored over a year or more. The year 2021 was chosen.

Note: dc kw was not converted to ac kw (by multiplying by 0.96) when these two images were made. However, that correction was made when calculating the capacity factor for the systems in the spreadsheet below. When so corrected the capacity factor for Rincon Valley East still rounded to 0.16.

https://pvoutput.org/aggregate.jsp?id=50236&sid=45710&v=0&t=y

PVOutput **11.97kw x 24 x 365 = 104857 kwh**

Welcome, PVOutput is a free service for sharing and comparing PV output data. **2021 CF is 16.58/ 104.8 = 15.8 %**
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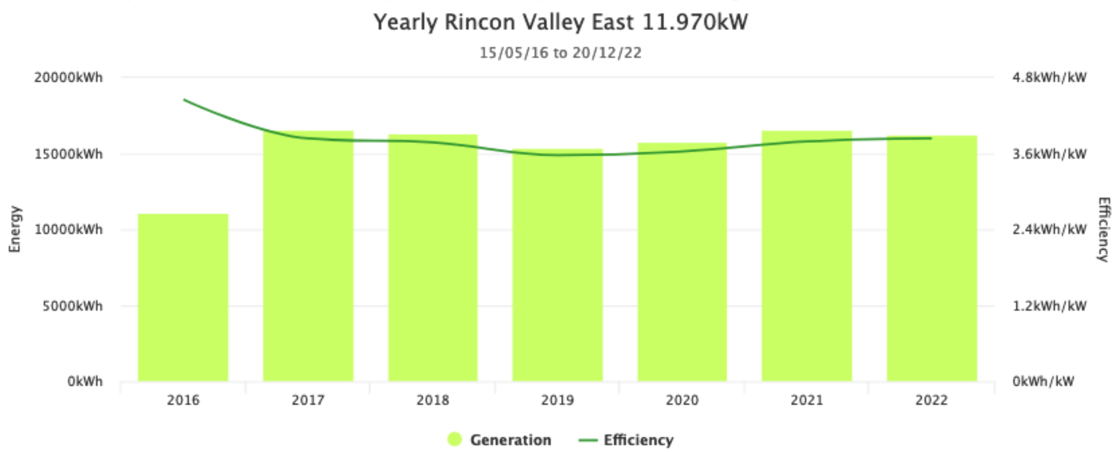

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Generation 909 of 46252 · 3 Followers · 1 Following · 1 Team · 108.0 MWh · 115.6 T CO_2

Target 128% $23,891.54▲ · 108,052 kWh

Rincon Valley East 11.970kW Compare: Tips

Year▾	Generated	Efficiency	Exported	FIT Credit	Low	High	Average	Comments
2022	16.289MWh	3.844kWh/kW	16.289MWh	$3,757.92	4.812kWh	76.535kWh	46.013kWh	Partial Year (354 days)
2021	16.576MWh	3.794kWh/kW	16.576MWh	$3,816.31	1.133kWh	77.711kWh	45.413kWh	
2020	15.755MWh	3.636kWh/kW	15.755MWh	$3,620.27	3.448kWh	80.910kWh	43.521kWh	Partial Year (362 days)
2019	15.374MWh	3.578kWh/kW	15.374MWh	$3,519.07	1.520kWh	78.472kWh	42.825kWh	Partial Year (359 days)
2018	16.326MWh	3.778kWh/kW	16.326MWh	$3,731.20	1.023kWh	78.397kWh	45.224kWh	Partial Year (361 days)
2017	16.594MWh	3.840kWh/kW	16.594MWh	$3,781.65	1.010kWh	81.360kWh	45.966kWh	Partial Year (361 days)
2016	11.138MWh	4.457kWh/kW	7.050MWh	$1,665.12	1.293kWh	82.997kWh	48.217kWh	Partial Year (231 days)

Its notable that a few systems sampled in the central valley produced similar capacity factors even though a higher one might be expected. For example, the next image is for the Harris system in Merced, which had a capacity factor of 16.7%.

https://pvoutput.org/aggregate.jsp?id=60303&sid=53680&v=0&t=y

PVOutput

6.96kw x 24 x 365 = 60970 kwh

2021 CF = 10.2 / 60.97 = 16.7 %

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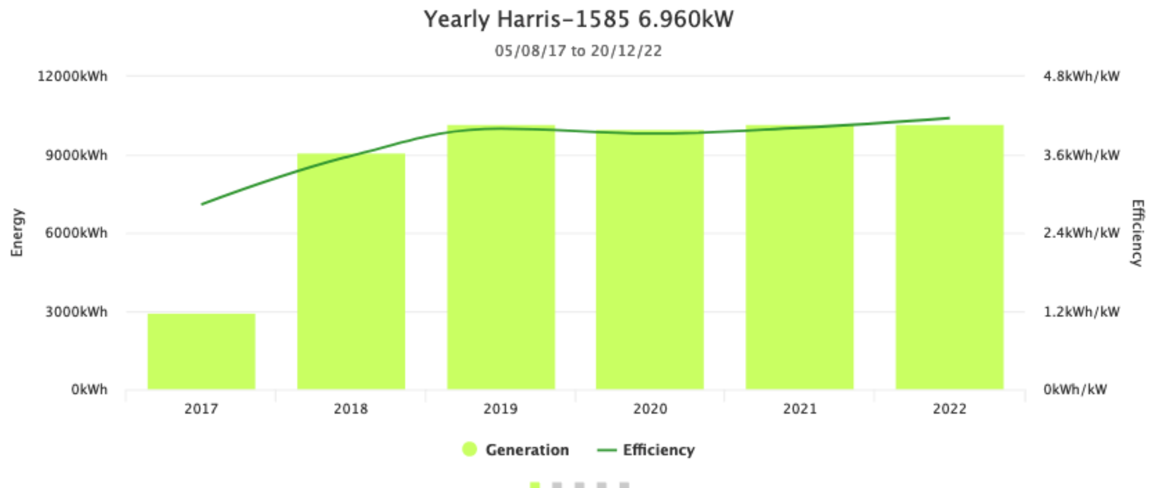

Live | Daily | Weekly | Monthly | Summary | Map | Statistics | Weather | Seasonal | Record Dates | Customise | Minimise

Generation 4101 of 46252 ▼2 · 0 Followers · 0 Following · 52.6 MWh · 56.3 T CO_2

Target 138% $0.00▲ · 52,624 kWh

Harris-1585 6.960kW Compare: Tips

Year▾	Generated	Efficiency	Exported	FIT Credit	Low	High	Average	Comments
2022	10.202MWh	4.164kWh/kW	-	$0.00	2.149kWh	49.560kWh	28.983kWh	Partial Year (352 days)
2021	10.201MWh	4.015kWh/kW	-	$0.00	1.180kWh	51.356kWh	27.947kWh	
2020	10.005MWh	3.927kWh/kW	-	$0.00	2.511kWh	51.400kWh	27.334kWh	
2019	10.168MWh	4.003kWh/kW	-	$0.00	2.020kWh	52.561kWh	27.858kWh	
2018	9.105MWh	3.584kWh/kW	-	$0.00	1.504kWh	44.207kWh	24.944kWh	
2017	2.943MWh	2.838kWh/kW	-	$0.00	2.800kWh	38.187kWh	19.753kWh	Partial Year (149 days)

Given the background above, the spreadsheet below captures the data for about 30 systems selected by the author. It then computes the capacity factors for each system, and for the entire sample. The CF formula appears at the top of the chart. To be selected a system had to be operational at least a year and have generated power for all of 2021. As shown in the lower right cell the average capacity factor for these small systems was 0.17 or 17%. Thus a value of 17% was used when comparing the cost-effectiveness of roof top residential solar with utility-scale solar.

I35 =($F35*1000)/($E35*0.96*8760)

	A	B	C	D	E	F	G	H	I
1		system name	zip	system size kw dc	system size kw dc	MWh(ac) generated in 2021	life		Capacity factor
2									
3									
4	811	29th and Moraga SF	94122	5.940kW	5.94	9.34	1,760 Days		0.19
5	813	ghorn Terrace	94131	3.420kW	3.42	5.32	2,370 Days		0.18
6	820	ckSolar	94401	6.600kW	6.6	10.90	767 Days		0.20
7	821	schwatoo Home	94401	4.290kW	4.29	7.32	860 Days		0.20
8	825	ywood	94402	5.985kW	5.985	9.11	1,937 Days		0.18
9	827	licon Valley	94403	4.880kW	4.88	5.23	1,649 Days		0.13
10	828	Hollys Home	94403	4.745kW	4.745	10.69	620 Days		0.27
11	831	Leo's FC Solar	94404	4.800kW	4.8	7.02	2,214 Days		0.17
12	834	RaT House	94501	7.020kW	7.02	9.27	1,214 Days		0.16
13	844	rewPG&E	94506	5.520kW	5.52	7.09	2,543 Days		0.15
14	845	EnglishOak	94506	11.175kW	11.175	13.55	3,161 Days		0.14
15	847	Werle B - Alamo, CA	94507	7.560kW	7.56	11.70	2,360 Days		0.18
16	851	Brentwood South Facing S	94513	5.040kW	5.04	8.08	2,547 Days		0.19
17	852	Shadowcliff	94513	8.450kW	8.45	12.5	1,177 Days		0.18
18	853	Home578	94513	10.530kW	10.53	15.96	1,690 Days		0.18
19	856	afrmthabay S/W/E syster	94513	7.590kW	7.59	10.767	1,923 Days		0.17
20	858	Brentwood System NorCa	94513	7.560kW	7.56	10.358	2,538 Days		0.16
21	866	ygar-A	94523	7.500kW	7.5	11.582	1,735 Days		0.18
22	869	ygar-V	94523	6.300kW	6.3	7.64	1,680 Days		0.14
23	870	JR's Roof	94523	9.240kW	9.24	13.12	1,928 Days		0.17
24	1201	MariposaHouse	95338	5.880kW	5.88	9.433	2,545 Days		0.19
25	1202	SolarEdge 8.16	95340	8.160kW	8.16	13.751	564 Days		0.20
26	1203	Harris-1585	95340	6.960kW	6.96	10.20	1,972 Days		0.17
27	1206	Modesto (Village One)	95355	11.400kW	11.4	15.62	2,371 Days		0.16
28	1211	Fairway Oaks	95366	12.190kW	12.19	12.39	2,615 Days		0.12
29	1215	W Tracy	95377	3.200kW	3.2	5.02	6,200 Days		0.19
30	1221	ome4757	95405	4.480kW	4.48	6.40	2,383 Days		0.17
31	1225	Rincon Valley East	95409	11.970kW	11.97	16.57	2,403 Days		0.16
32	1227	Vine Hill Road	95472	7.200kW	7.2	10.791	796 Days		0.18
33	1228	Sol-noma	95476	6.960kW	6.96	9.188	1,458 Days		0.16
34									
35				Total for selected systems	212.545	305.89			0.17
36									
37									

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