[e] enphase ENERGY

White Paper

PV Module "Right-Sizing" for Enphase Microinverters

Overview

This paper summarizes a discussion of the necessary choices and tradeoffs when matching PV module and microinverter power ratings. We will demonstrate examples of these tradeoffs using simulations based on real-world modules and historical weather data for three U.S. locations.

Solar Advisor Module (SAM), the NREL-developed program, was used to generate corrected irradiance levels and cell temperatures based on historical weather data. The data flow is shown in Appendix A.

If long-term energy production is a priority and real-world conditions are considered, a PV module power rating of up to 125 percent of inverter power rating is often the optimum match. In some cases, percentages of up to 140 percent can be justified. It is also clear that site installation specifics such as module tilt and local weather and soiling conditions play a significant role in appropriate inverter/module matching.

Two Theories

The correct way to pair PV modules and inverters has been debated at length. There are two basic schools of thought that apply to both microinverter and traditional string/central inverter systems; however, there are fewer variables with microinverters, and the result of those considerations is more deterministic.

Several factors should be considered. Appendix B contains a detailed list of factors, along with a brief summary and discussion of each factor. Depending on the application (e.g., a small residential system vs. a large commercial/utility PPA), the weighting of these factors varies considerably.

The two schools of thought can be summarized as follows:

1. The PV module(s) should be sized so that the inverter never limits its output power.
2. The PV module should be sized so that the inverter limits its output power frequently, possibly every clear-sky day.

The two theories represent extremes, and the appropriate course of action will almost always lie somewhere between the two. Regardless of the application, the factors listed in Appendix B will apply.

Test Cases

Our discussion will be limited to a microinverter application, and we will consider only a fixed array with a due south orientation. Several tilt angles will be considered. We will analyze a specific case in which a decision must be made between Sharp 216W and 235W modules, which will be used with an Enphase M190 Microinverter. The principles discussed here are also applicable to other module/inverter combinations. For string configurations, there are several considerations not discussed here.

Three test cases were modeled using the NREL Solar Advisor Model, along with manufacturers' data for the PV module and inverter. For the simulation, the actual AC output power limit for the inverter was 195W, which is several watts below the actual observed power limits. Irradiance profiles and temperature data were generated using actual measured data from Denver, CO; Palm Springs, CA; and Phoenix, AZ. In all cases, a five percent loss of power production was assumed for dirty modules.

Module power production was degraded by one percent per year to account for module aging. This degradation was compounded annually, and the resulting module production factor is labeled "Module Power Factor" in the data tables in appendix C, D, and E. All arrays faced due south.

Two module power ratings were used:

- The first module is rated 216W. The second module is rated at 235W. Note that these power ratings are Standard Test Condition (STC) nameplate ratings. The actual output of most modules under real-world conditions is approximately 10-12 percent less than the STC rating.
- A more realistic rating is obtained under PV-USA Test Conditions (PTC). The CEC website list of eligible modules (http://www.gosolarcalifornia.org/equipment/pvmodule.html) confirms this. The 216W and 235W modules used here are PTC rated at 190.4W and 211.7W, respectively. As a general rule, most modules have a PTC rating of 90 percent of the STC (nameplate) rating.

Table 1 shows the percentage of harvested energy based on the theoretical maximum for three locations at three different array-tilt angles for the two different module power ratings. In all cases the modules were connected to an Enphase M190 Microinverter.

TABLE 1. Twenty year lifetime — Realized energy harvest (% of possible)

		Dirty		Clean	
Module STC Power (watts)		216	235	216	235
	Roof Pitch				
Denver	3:12	99.99%	99.87%	100.00%	99.96%
	6:12	99.94%	99.67%	99.99%	99.88%
	12:12	99.87%	99.39%	99.97%	99.74%
Palm Springs	3:12	100.00%	99.99%	100.00%	100.00%
	6:12	100.00%	99.97%	100.00%	100.00%
	12:12	100.00%	99.94%	100.00%	99.99%
Phoenix	3:12	100.00%	99.94%	100.00%	99.99%
	6:12	99.99%	99.90%	100.00%	99.98%
	12:12	99.99%	99.82%	100.00%	99.96%

As indicated in Table 1, the worst-case loss of energy harvest occurs in Denver, CO, with a 45-degree roof pitch. In this case, a 216W module will fail to produce 0.13 percent of possible energy over a 20-year period if the modules are washed frequently (e.g. once per week.) Under the same conditions, a 235W module will fail to produce 0.61 percent of potential energy. If the modules are washed only a few times per year—a far more likely scenario—these figures fall to 0.03 percent (216W module) and 0.26 percent (235W module).

Nearly all of the lost harvest occurs within the first three years for the 216W modules, and within the first seven years for the 235W modules. Lost energy harvest is also concentrated in the fall and spring seasons, when irradiance is high and temperatures are low. Test data for Denver is in Appendix C.

For Palm Springs and Phoenix, the 235W module is a perfect match for the 190W inverter. The 235W module produces 8.79 percent (235/216=1.0879) more energy than the 216W module. Over a 30-year inverter life, it is likely that a module sized up to 245W may be a good match. Appendix D includes data for Palm Springs, and the Phoenix data appears in Appendix E.

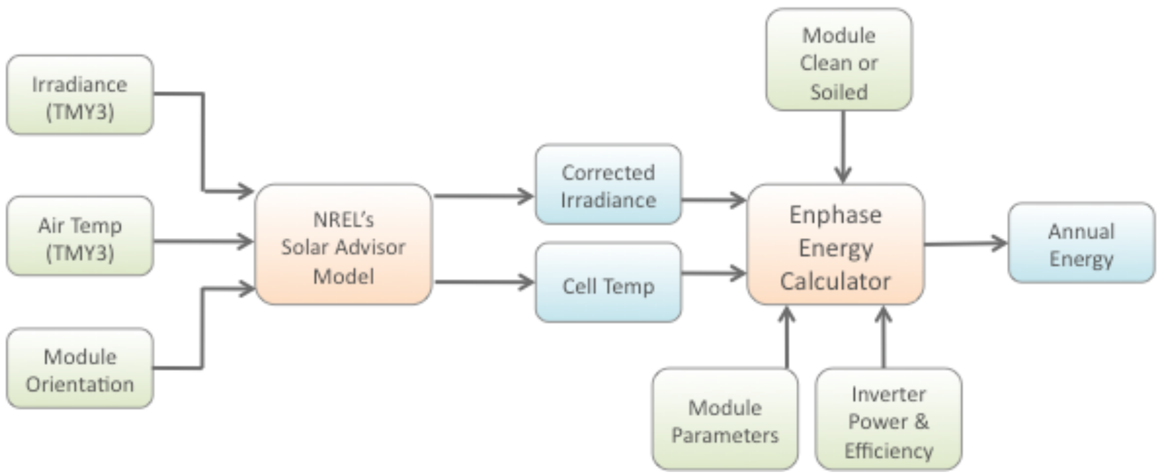
The loss of energy harvest in any of these scenarios pales in comparison to the lost energy of a string or central inverter, which suffers from inferior harvest due to module mismatch, shading, soiling, etc.

Conclusion

For a microinverter application, optimal energy harvest will generally result by selecting a module rated up to 125 percent of the maximum inverter power rating. The warmer the climate, the higher this percentage should be, assuming optimal tilt of the PV array. If the array is mounted on a horizontal surface, the module power rating will be substantially higher. In some cases, a module with an STC power rating of up to 140 percent of the inverter rating is justified. No consideration is given here to monetary factors such as annual electric rate schedules, time-of-use metering, or rebate structures.

APPENDIX A. Data Flow

Solar Advisor Module, the NREL-developed program, was used to generate corrected irradiance levels and cell temperatures based on historical weather data. The data flow is shown below:



APPENDIX B. Detailed List of Factors

1. Inverter power rating
2. Inverter power limit (actual)
3. Inverter efficiency
4. PV module actual vs. specified power output
5. PV module aging characteristics
6. PV module pricing
7. Site latitude
8. Site elevation
9. Site annual irradiance profile
10. Site annual temperature extremes and profiles
11. Site soiling conditions
12. Tracking vs. fixed array
13. If tracking – single or dual axis tracking
14. If fixed – tilt of array
15. If fixed – azimuth
16. Site maintenance practices
17. Financial rebate structure
18. Metering type – net metered vs. TOU
19. For string – module mismatch
20. For string – differential soiling
21. For string – module shading
22. Wind

First we will generalize the effects of the factors mentioned above and discuss some interrelationships. No inference is made as to the importance of any factor in a particular situation.

Items 1-4 above are related. The inverter power rating is a rating only. UL1741, the standard for Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources, requires that inverter output power be limited to within 10 percent of the nameplate rating. However, inverters that qualify for the California Incentive Program have been tested in addition to UL1741 certification to meet a guaranteed minimum output power.

The CEC-rated power refers to the lowest output power during a three-hour test, or the nameplate rating, whichever is less. This power rating is used in calculating rebate dollars. For this reason, most inverters limit their output power to some value just above the nameplate rating. Similarly, a CEC conversion efficiency test is performed and the weighted average efficiency is used in the rebate calculation. Modules are also tested for their actual power output. Unlike most inverters, most modules are CEC-rated at a lower power level than their nameplate rating.

For this analysis we used the Sharp 216 (ND-U216C1) and 235 (NU-U235F1) modules. The nameplate ratings are 216W and 235W, respectively; however the PTC ratings on the CEC module list are 190.4W (88.15 percent of nameplate) and 211.7W (90.08 percent of nameplate), respectively.

Inverter efficiencies vary, but they are generally around 95 percent efficient. We assumed 95 percent. Obviously, the higher the efficiency of the inverter, the greater the amount of energy delivered to the utility over the life of the system.

Item 5: PV Module aging. PV module power output degrades over time. Several mechanisms contribute to degradation, and degree of degradation varies between module technologies. Also, the rate of degradation changes over time. It is beyond the scope of this paper to discuss factors impacting power output degradation. We assume one percent degradation per year; a value commonly used in the PV industry.

Item 6: PV Module pricing. While financial considerations will almost certainly drive final decisions regarding module/inverter pairing, we leave it to the reader to apply their financial requirements to their particular situation.

Item 7: Site latitude. Latitude and longitude determine many of the other factors that must be considered. Elevation, irradiance, temperature, soiling, tilt, and shading are all location specific. For our discussion, we chose three locations with dissimilar environmental factors; Denver, CO; Palm Springs, CA; and Phoenix, AZ.

Item 8: Site elevation. Elevation affects several other aspects of the site. Higher elevations can be subject to greater swings in temperature, and they often receive higher levels of peak irradiance.

Item 9: Irradiance profile. Irradiance, the amount of light in Watts/Meter^2 impinging on a surface, determines PV power production. Assuming all other factors are stable, power output increases linearly with increased irradiance once the irradiance exceeds approximately 100 Watts/Meter^2. Instantaneous irradiance is important, but the word “profile” was used here because it is important to recognize that a given irradiance will produce varying power levels depending on the simultaneous values of other factors such as temperature and wind.

Item 10: Temperature. Temperature plays a significant role in PV power production. Ambient temperature, wind speed and direction, array orientation, irradiance, and sun angle all contribute to PV cell temperature. Modules are rated at STC conditions of 1000W/Meter^2 and 25^{O}C. The following is useful as a general rule: Every 1^{O}C increase in cell temperature will result in a 0.5 percent decrease in power output. It is not uncommon for cell temperatures to reach 90^{O}C in some environments, which would result in a power output reduction of 32.5 percent. Hence, the module would produce only 67.5 percent of its rated power.

Item 11: Soiling conditions. Soiling is generally defined as normal atmospheric contamination that adheres to the module surface (e.g., dust, pollen, and ash) and reduces power output. Regular module cleaning is recommended for maximum energy harvest. Many experts recommend cleaning PV modules at least four times per year. Depending on site-specific conditions, power production can be increased 6 percent or more by cleaning the module surface.

Items 12 and 13: Tracking vs. fixed and single vs. dual axis. Trackers can increase energy harvest substantially. For the purposes of this discussion, we will assume a fixed array.

Item 14: Tilt. This refers to the angle of the module relative to a horizontal surface, with the angle measured along the azimuth line.

Item 15: Azimuth. This is the orientation of the array relative to true north. In the Northern Hemisphere, a true south azimuth is generally preferred, but other orientations may be preferable due to factors such as time-of-use rebate structures and local load time-of-day profiles.

Item 16: Maintenance. For the purpose of this discussion, only cleaning of modules is considered.

Item 17: Financial rebates. We do not consider rebates as part of this discussion, but the end user will obviously consider them. For example, some rebates are limited based on the module and inverter ratings. In the past, some rebates were calculated based on module STC ratings. Today, many rebates use the more practical PTC rating.

Item 18: Metering type. This refers to the rate schedule, typically chosen by the system owner. Electric services are usually “net metered” or have a feed-in tariff. For net-metered accounts, the PV system owner can usually choose between time-of-use and non-time-of-use.

Items 19, 20, and 21: Module mismatch, differential soiling, and shading. These factors apply primarily to string/central inverter configurations and are not considered here.

Item 22: Wind. Wind speed and direction can impact PV module power production significantly. Wind cools the module, and the cooler the module, the greater the power produced.

APPENDIX C. Module Power Factor, Denver, CO

State: CO													
Latitude: 39.833 Longitude: -104.650													
Elevation: 1650m													
		Modules cleaned a few times per year. 5% degradation in power production.											
		3:12 array tilt				6:12 array tilt				12:12 array tilt			
	Module	216	216	235	235	216	216	235	235	216	216	235	235
year	Power Factor	unclipped	195	unclipped	195	unclipped	195	unclipped	195	unclipped	195	unclipped	195
1	1	351,254	351,213	382,152	381,481	369,863	369,604	402,397	400,571	373,009	372,349	405,820	402,254
2	0.99	347,742	347,717	378,330	377,801	366,165	365,983	398,373	396,836	369,279	368,772	401,762	398,733
3	0.98	344,265	344,253	374,547	374,136	362,503	362,382	394,390	393,106	365,587	365,208	397,745	395,192
4	0.97	340,822	340,819	370,802	370,490	358,878	358,800	390,446	389,389	361,931	361,659	393,767	391,634
5	0.961	337,414	337,413	367,094	366,865	355,289	355,240	386,541	385,682	358,311	358,122	389,830	388,060
6	0.951	334,040	334,040	363,423	363,258	351,736	351,706	382,676	381,987	354,728	354,606	385,931	384,484
7	0.941	330,699	330,699	359,788	359,672	348,219	348,202	378,849	378,312	351,181	351,114	382,072	380,911
8	0.932	327,392	327,392	356,191	356,110	344,737	344,728	375,061	374,656	347,669	347,637	378,251	377,327
9	0.923	324,118	324,118	352,629	352,579	341,289	341,287	371,310	371,014	344,193	344,180	374,469	373,741
10	0.914	320,877	320,877	349,102	349,071	337,876	337,876	367,597	367,388	340,751	340,747	370,724	370,159
11	0.904	317,668	317,668	345,611	345,595	334,498	334,498	363,921	363,779	337,343	337,342	367,017	366,592
12	0.895	314,492	314,492	342,155	342,149	331,153	331,153	360,282	360,190	333,970	333,970	363,347	363,036
13	0.886	311,347	311,347	338,734	338,732	327,841	327,841	356,679	356,620	330,630	330,630	359,713	359,495
14	0.878	308,233	308,233	335,346	335,346	324,563	324,563	353,112	353,076	327,324	327,324	356,116	355,969
15	0.869	305,151	305,151	331,993	331,993	321,317	321,317	349,581	349,560	324,050	324,050	352,555	352,469
16	0.86	302,099	302,099	328,673	328,673	318,104	318,104	346,085	346,074	320,810	320,810	349,029	348,985
17	0.851	299,078	299,078	325,386	325,386	314,923	314,923	342,624	342,620	317,602	317,602	345,539	345,521
18	0.843	296,088	296,088	322,132	322,132	311,774	311,774	339,198	339,197	314,426	314,426	342,084	342,077
19	0.835	293,127	293,127	318,911	318,911	308,656	308,656	335,806	335,806	311,282	311,282	338,663	338,661
20	0.826	290,195	290,195	315,722	315,722	305,569	305,569	332,448	332,448	308,169	308,169	335,276	335,276
		6,396,101	6,396,019	6,958,721	6,956,102	6,734,953	6,734,206	7,327,376	7,318,311	6,792,245	6,789,999	7,389,710	7,370,576
Total Lost Energy (Wh)			82		2,619		747		9,065		2,246		19,134
235W module gain over 216W module					8.76%				8.67%				8.55%

APPENDIX D. Module Power Factor, Palm Springs, CA

State: CA
Latitude: 33.633 Longitude: -116.167
Elevation: -34m

						Modules cleaned a few times per year. 5% degradation in power production.							
	Module		3:12 array tilt				6:12 array tilt				12:12 array tilt		
	Power	216	216	235	235	216	216	235	235	216	216	235	235
year	Factor	unclipped	195	unclipped	195	unclipped	195	unclipped	195	unclipped	195	unclipped	195
1	1	400,015	400,015	435,201	435,191	414,797	414,797	451,284	451,214	409,000	409,000	444,977	444,767
2	0.99	396,015	396,015	430,849	430,843	410,649	410,649	446,771	446,736	404,910	404,910	440,527	440,393
3	0.98	392,055	392,055	426,541	426,539	406,542	406,542	442,303	442,288	400,861	400,861	436,121	436,044
4	0.97	388,134	388,134	422,275	422,275	402,477	402,477	437,880	437,876	396,852	396,852	431,760	431,714
5	0.961	384,253	384,253	418,053	418,053	398,452	398,452	433,501	433,501	392,883	392,883	427,443	427,417
6	0.951	380,410	380,410	413,872	413,872	394,468	394,468	429,166	429,166	388,955	388,955	423,168	423,157
7	0.941	376,606	376,606	409,733	409,733	390,523	390,523	424,875	424,875	385,065	385,065	418,937	418,932
8	0.932	372,840	372,840	405,636	405,636	386,618	386,618	420,626	420,626	381,214	381,214	414,747	414,744
9	0.923	369,112	369,112	401,580	401,580	382,752	382,752	416,420	416,420	377,402	377,402	410,600	410,599
10	0.914	365,420	365,420	397,564	397,564	378,924	378,924	412,255	412,255	373,628	373,628	406,494	406,494
11	0.904	361,766	361,766	393,588	393,588	375,135	375,135	408,133	408,133	369,892	369,892	402,429	402,429
12	0.895	358,149	358,149	389,652	389,652	371,384	371,384	404,052	404,052	366,193	366,193	398,404	398,404
13	0.886	354,567	354,567	385,756	385,756	367,670	367,670	400,011	400,011	362,531	362,531	394,420	394,420
14	0.878	351,021	351,021	381,898	381,898	363,993	363,993	396,011	396,011	358,906	358,906	390,476	390,476
15	0.869	347,511	347,511	378,079	378,079	360,353	360,353	392,051	392,051	355,317	355,317	386,571	386,571
16	0.86	344,036	344,036	374,299	374,299	356,750	356,750	388,130	388,130	351,764	351,764	382,706	382,706
17	0.851	340,596	340,596	370,556	370,556	353,182	353,182	384,249	384,249	348,246	348,246	378,879	378,879
18	0.843	337,190	337,190	366,850	366,850	349,650	349,650	380,406	380,406	344,764	344,764	375,090	375,090
19	0.835	333,818	333,818	363,181	363,181	346,154	346,154	376,602	376,602	341,316	341,316	371,339	371,339
20	0.826	330,480	330,480	359,550	359,550	342,692	342,692	372,836	372,836	337,903	337,903	367,626	367,626
		7,283,994	7,283,994	7,924,713	7,924,695	7,553,165	7,553,165	8,217,562	8,217,438	7,447,602	7,447,602	8,102,714	8,102,201
Total Lost Energy (Wh)			0		18		0		124		0		513
235W module gain over 216W module					8.80%				8.79%				8.79%

APPENDIX E. Module Power Factor, Phoenix, AZ

State: AZ
Latitude: 33.450 Longitude: -111.983
Elevation: 337m

						Modules cleaned a few times per year. 5% degradation in power production.							
	Module		3:12 array tilt				6:12 array tilt				12:12 array tilt		
	Power	216	216	235	235	216	216	235	235	216	216	235	235
year	Factor	unclipped	195	unclipped	195	unclipped	195	unclipped	195	unclipped	195	unclipped	195
1	1	401,228	401,227	436,521	436,270	415,438	415,420	451,981	451,445	409,356	409,346	445,364	444,355
2	0.99	397,216	397,216	432,156	431,978	411,284	411,273	447,461	447,085	405,263	405,258	440,911	440,180
3	0.98	393,244	393,244	427,834	427,712	407,171	407,166	442,987	442,730	401,210	401,209	436,501	435,987
4	0.97	389,311	389,311	423,556	423,478	403,099	403,098	438,557	438,383	397,198	397,198	432,136	431,793
5	0.961	385,418	385,418	419,320	419,274	399,068	399,068	434,171	434,053	393,226	393,226	427,815	427,595
6	0.951	381,564	381,564	415,127	415,102	395,077	395,077	429,829	429,750	389,294	389,294	423,537	423,406
7	0.941	377,748	377,748	410,976	410,962	391,127	391,127	425,531	425,478	385,401	385,401	419,302	419,226
8	0.932	373,971	373,971	406,866	406,860	387,215	387,215	421,276	421,240	381,547	381,547	415,109	415,071
9	0.923	370,231	370,231	402,798	402,795	383,343	383,343	417,063	417,041	377,731	377,731	410,957	410,944
10	0.914	366,529	366,529	398,770	398,770	379,510	379,510	412,892	412,880	373,954	373,954	406,848	406,841
11	0.904	362,863	362,863	394,782	394,782	375,715	375,715	408,764	408,757	370,214	370,214	402,779	402,777
12	0.895	359,235	359,235	390,834	390,834	371,957	371,957	404,676	404,673	366,512	366,512	398,752	398,752
13	0.886	355,642	355,642	386,926	386,926	368,238	368,238	400,629	400,629	362,847	362,847	394,764	394,764
14	0.878	352,086	352,086	383,056	383,056	364,555	364,555	396,623	396,623	359,219	359,219	390,816	390,816
15	0.869	348,565	348,565	379,226	379,226	360,910	360,910	392,657	392,657	355,626	355,626	386,908	386,908
16	0.86	345,079	345,079	375,434	375,434	357,301	357,301	388,730	388,730	352,070	352,070	383,039	383,039
17	0.851	341,629	341,629	371,679	371,679	353,728	353,728	384,843	384,843	348,549	348,549	379,209	379,209
18	0.843	338,212	338,212	367,963	367,963	350,191	350,191	380,994	380,994	345,064	345,064	375,417	375,417
19	0.835	334,830	334,830	364,283	364,283	346,689	346,689	377,184	377,184	341,613	341,613	371,663	371,663
20	0.826	331,482	331,482	360,640	360,640	343,222	343,222	373,413	373,413	338,197	338,197	367,946	367,946
		7,306,083	7,306,082	7,948,747	7,948,024	7,564,838	7,564,803	8,230,261	8,228,588	7,454,091	7,454,075	8,109,773	8,106,689
Total Lost Energy (Wh)			1		723		35		1,673		16		3,084
235W module gain over 216W module					8.79%				8.77%				8.76%