Saint Martin's
UNIVERSITY

Photovoltaics Final Project

Steven Araki

Department of Mechanical Engineering, St. Martin's University
ME: 433, Photovoltaics
Mrs. Wickett, M.M.E.

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Abstract.

This report provides a detailed overview of the Photovoltaic (PV) system design, utilizing Panasonic EVERVOLT 370 Panels, string inverters, and microinverters. The customer's interest lies in a comprehensive final report, covering design steps, underlying assumptions, and maintenance requirements. The choice of Panasonic EVERVOLT 370 Panels is justified by their proven efficiency and reliability. String inverters and microinverters are selected for scalability and performance optimization. Assumptions, rooted in industry standards and empirical data, are transparently explained. The report includes maintenance procedures for longevity and efficiency, emphasizing regular inspections and troubleshooting. Financial aspects, such as project budget, costs, and potential savings, are thoroughly addressed, ensuring a holistic understanding of the proposed PV system's design, performance, and economic feasibility.

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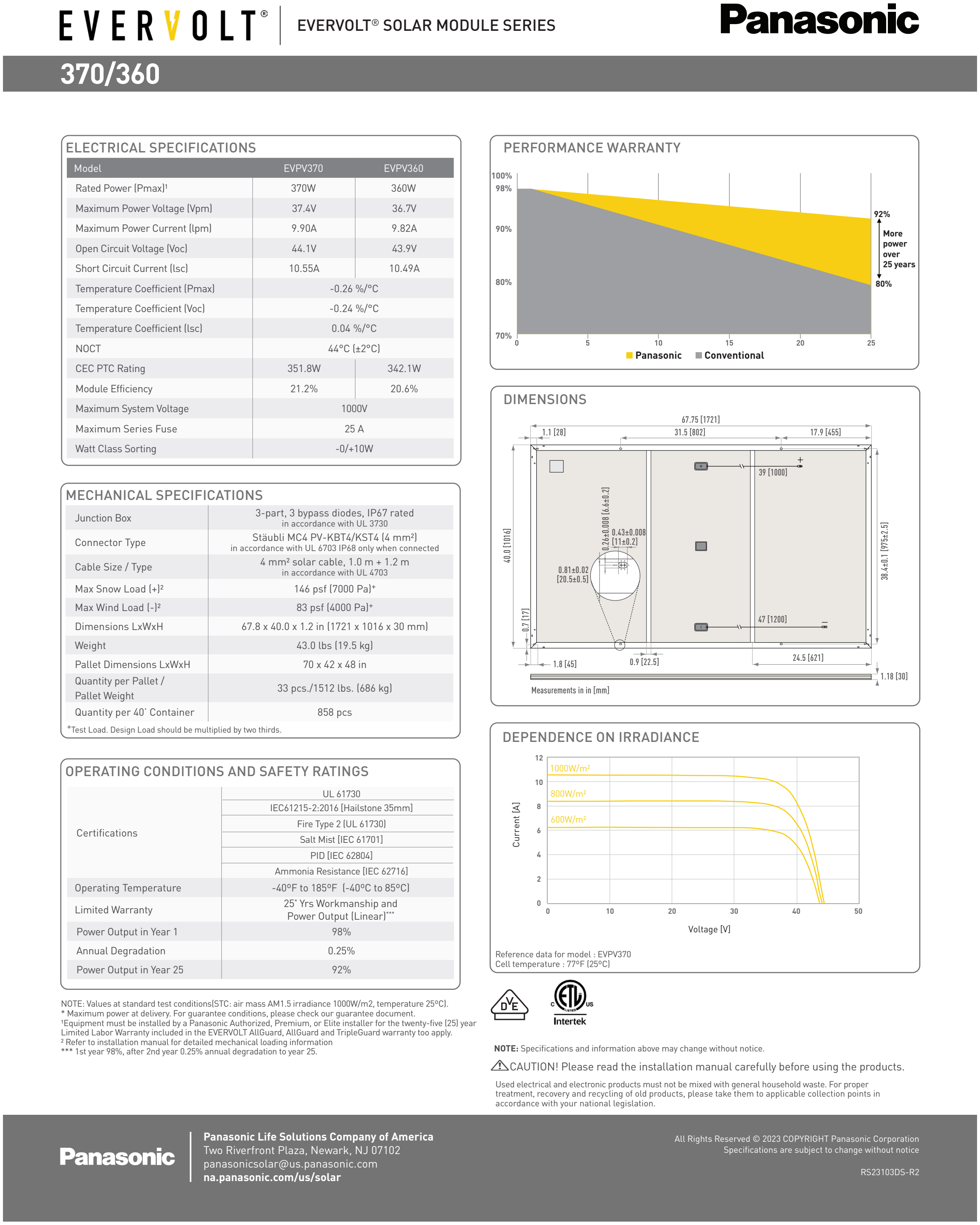
1 Introduction

This report will present a comprehensive analysis and recommendations for the design of a solar PV system employing a 15-panel array configuration with a string inverter utilizing three strings, as well as a microinverter-based configuration with individual microinverters for each of the 15 panels. This report aims to thoroughly understand the design steps and assumptions made in selecting and implementing these two distinct approaches.

The foundational assumptions will be established in Houghton, MI as the designated installation location of the solar systems. This will provide the premises of the local regulations and laws for the safe installation and requirements for installation. These steps in designing this system are outlined in the following sections below.

2 Panel Specification

For this system, the panels chosen will be the Panasonic EVERVOLT 370 Panel, model EVPV370PK. This panel has a higher module efficiency, which allows maximum power production and has the lowest annual degradation rate in the industry. It comes with a 25-year warranty and an 85% guarantee after the 25 years. This panel uses half-cut cell technology which minimizes electron losses maximizes conversion efficiency, and produces a higher output than conventional panels. This panel also performs better when shaded for greater energy yields and outputs (1). The specifications are shown in Figure 1



EVERVOLT® | EVERVOLT® SOLAR MODULE SERIES

Panasonic

370/360

ELECTRICAL SPECIFICATIONS

Model	EVPV370	EVPV360
Rated Power (Pmax)[1]	370W	360W
Maximum Power Voltage (Vpm)	37.4V	36.7V
Maximum Power Current (Ipm)	9.90A	9.82A
Open Circuit Voltage (Voc)	44.1V	43.9V
Short Circuit Current (Isc)	10.55A	10.49A
Temperature Coefficient (Pmax)	-0.26 %/°C	
Temperature Coefficient (Voc)	-0.24 %/°C	
Temperature Coefficient (Isc)	0.04 %/°C	
NOCT	44°C (±2°C)	
CEC PTC Rating	351.8W	342.1W
Module Efficiency	21.2%	20.6%
Maximum System Voltage	1000V	
Maximum Series Fuse	25 A	
Watt Class Sorting	-0/+10W	

MECHANICAL SPECIFICATIONS

Junction Box	3-part, 3 bypass diodes, IP67 rated in accordance with UL 3730
Connector Type	Stäubli MC4 PV-KBT4/KST4 (4 mm²) in accordance with UL 6703 IP68 only when connected
Cable Size / Type	4 mm² solar cable, 1.0 m + 1.2 m in accordance with UL 4703
Max Snow Load (+)[2]	146 psf (7000 Pa)⁺
Max Wind Load (-)[2]	83 psf (4000 Pa)⁺
Dimensions LxWxH	67.8 x 40.0 x 1.2 in (1721 x 1016 x 30 mm)
Weight	43.0 lbs (19.5 kg)
Pallet Dimensions LxWxH	70 x 42 x 48 in
Quantity per Pallet / Pallet Weight	33 pcs./1512 lbs. (686 kg)
Quantity per 40' Container	858 pcs

⁺Test Load. Design Load should be multiplied by two thirds.

OPERATING CONDITIONS AND SAFETY RATINGS

Certifications	UL 61730 IEC61215-2:2016 [Hailstone 35mm] Fire Type 2 (UL 61730) Salt Mist [IEC 61701] PID [IEC 62804] Ammonia Resistance [IEC 62716]
Operating Temperature	-40ºF to 185ºF (-40ºC to 85ºC)
Limited Warranty	25* Yrs Workmanship and Power Output (Linear)***
Power Output in Year 1	98%
Annual Degradation	0.25%
Power Output in Year 25	92%

NOTE: Values at standard test conditions(STC: air mass AM1.5 irradiance 1000W/m2, temperature 25ºC).
* Maximum power at delivery. For guarantee conditions, please check our guarantee document.
[1] Equipment must be installed by a Panasonic Authorized, Premium, or Elite installer for the twenty-five (25) year Limited Labor Warranty included in the EVERVOLT AllGuard, AllGuard and TripleGuard warranty too apply.
[2] Refer to installation manual for detailed mechanical loading information
*** 1st year 98%, after 2nd year 0.25% annual degradation to year 25.

NOTE: Specifications and information above may change without notice.

⚠CAUTION! Please read the installation manual carefully before using the products.

Used electrical and electronic products must not be mixed with general household waste. For proper treatment, recovery and recycling of old products, please take them to applicable collection points in accordance with your national legislation.

Panasonic

Panasonic Life Solutions Company of America
Two Riverfront Plaza, Newark, NJ 07102
panasonicsolar@us.panasonic.com
na.panasonic.com/us/solar

RS23103DS-R2

Figure 1: EVERVOLT Solar Module PK Black Series (1)

2.1 Panel Details

The solar panel array configuration, as depicted in Section 9 Sheet 1, adopts a landscape layout to maximize performance, particularly in mitigating shading effects, provided adequate space is available. Furthermore, the design of this array is formulated to restrict the total current flow, a crucial consideration for both safety and inverter cost efficiency. The limitation on current serves to manage the expenses associated with inverters, as higher currents are created inverters with elevated capacity are needed, thereby increasing costs. Key parameters essential for inverter selection are detailed in Figure 1, and their corresponding values are tabulated in Table 1.

Table 1: Data Specifications per Panel

Max Voltage	43.64 V
Min. Voltage	30.27 V
Normal Operating Voltage	34.7 V
Max Current	11.25 A
PV Array Power	5550 W

3 Inverter Selection

In selecting the appropriate inverter for a solar power system, careful consideration must be given to various factors to ensure optimal performance and efficiency. One crucial aspect is the choice between string inverters and microinverters. String inverters, known for their cost-effectiveness and ease of installation, are typically employed in scenarios where shading is minimal, and the solar array is uniform. They operate by converting the DC power generated by multiple solar panels connected in series into AC power. On the other hand, microinverters, which are attached to individual solar panels, offer advantages in situations with shading issues or varying panel orientations. While string inverters may be more economical for larger installations, microinverters provide increased energy harvest by mitigating the impact of partial shading and optimizing individual panel performance. The selection process should be guided by the specific characteristics of the solar array, site conditions, and the desired balance between cost efficiency and overall system productivity.

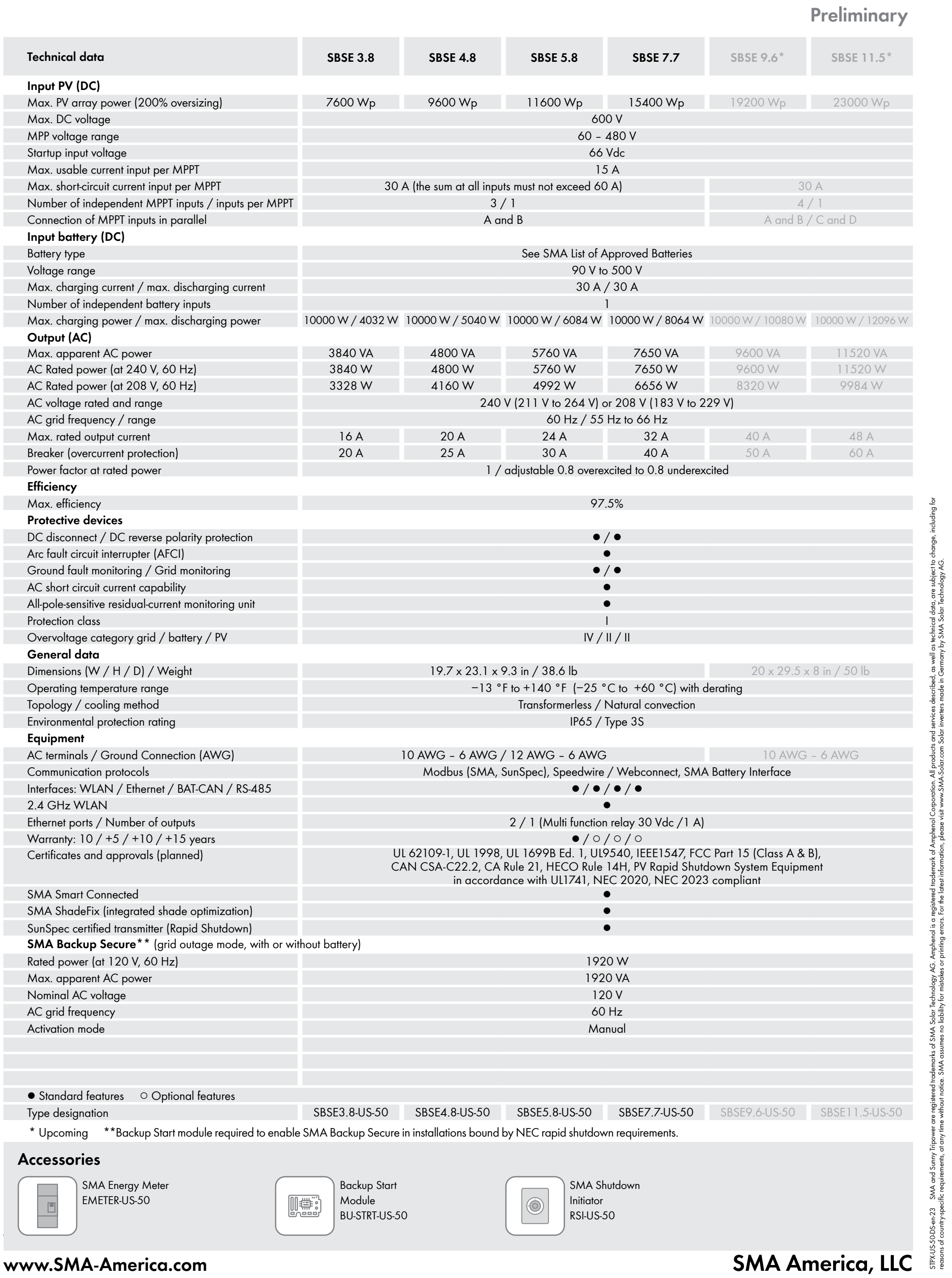
3.1 String Inverter

The configuration detailed in Section 9, where panels are interconnected in series, gives rise to a 3-string array. The maximum voltage for each string is determined by multiplying the maximum voltage by the number of panels in the series. In this instance, with five panels in series, this value is derived from the maximum voltage found in Table 1. The minimum voltage for the string follows a similar process but involves one less panel; thus, it is obtained by multiplying the maximum voltage by the number of panels in series (four in this case). The maximum normal operating voltage aligns with the process used to find the maximum voltage of the string, as explained earlier. As the panels are in series, the current remains constant throughout the string. The data resulting from this configuration is outlined in Table 2.

Table 2: Single String Electrical Data

Max Voltage	218.2 V
Min. Voltage	121.08 V
Normal Operating Voltage	173.5 V
Max Current	11.25 A
PV Array Power	5550 W

The data provided, the string inverter selected is the Sunny Boy Smart Energy-US 4.8, model SBSE4.8. This has a 200% DC/AC design, a 3 Maximum Power Point Tracking system for optimizing channels, a 10-year warranty, and is within tolerance of the data from Table 2. The data is outlined below in Figure 2.



Preliminary

Technical data	SBSE 3.8	SBSE 4.8	SBSE 5.8	SBSE 7.7	SBSE 9.6*	SBSE 11.5*
Input PV (DC)						
Max. PV array power (200% oversizing)	7600 Wp	9600 Wp	11600 Wp	15400 Wp	19200 Wp	23000 Wp
Max. DC voltage	600 V					
MPP voltage range	60 – 480 V					
Startup input voltage	66 Vdc					
Max. usable current input per MPPT	15 A					
Max. short-circuit current input per MPPT	30 A (the sum at all inputs must not exceed 60 A)				30 A	
Number of independent MPPT inputs / inputs per MPPT	3 / 1				4 / 1	
Connection of MPPT inputs in parallel	A and B				A and B / C and D	
Input battery (DC)						
Battery type	See SMA List of Approved Batteries					
Voltage range	90 V to 500 V					
Max. charging current / max. discharging current	30 A / 30 A					
Number of independent battery inputs	1					
Max. charging power / max. discharging power	10000 W / 4032 W	10000 W / 5040 W	10000 W / 6084 W	10000 W / 8064 W	10000 W / 10080 W	10000 W / 12096 W
Output (AC)						
Max. apparent AC power	3840 VA	4800 VA	5760 VA	7650 VA	9600 VA	11520 VA
AC Rated power (at 240 V, 60 Hz)	3840 W	4800 W	5760 W	7650 W	9600 W	11520 W
AC Rated power (at 208 V, 60 Hz)	3328 W	4160 W	4992 W	6656 W	8320 W	9984 W
AC voltage rated and range	240 V (211 V to 264 V) or 208 V (183 V to 229 V)					
AC grid frequency / range	60 Hz / 55 Hz to 66 Hz					
Max. rated output current	16 A	20 A	24 A	32 A	40 A	48 A
Breaker (overcurrent protection)	20 A	25 A	30 A	40 A	50 A	60 A
Power factor at rated power	1 / adjustable 0.8 overexcited to 0.8 underexcited					
Efficiency						
Max. efficiency	97.5%					
Protective devices						
DC disconnect / DC reverse polarity protection	● / ●					
Arc fault circuit interrupter (AFCI)	●					
Ground fault monitoring / Grid monitoring	● / ●					
AC short circuit current capability	●					
All-pole-sensitive residual-current monitoring unit	●					
Protection class	I					
Overvoltage category grid / battery / PV	IV / II / II					
General data						
Dimensions (W / H / D) / Weight	19.7 x 23.1 x 9.3 in / 38.6 lb				20 x 29.5 x 8 in / 50 lb	
Operating temperature range	−13 °F to +140 °F (−25 °C to +60 °C) with derating					
Topology / cooling method	Transformerless / Natural convection					
Environmental protection rating	IP65 / Type 3S					
Equipment						
AC terminals / Ground Connection (AWG)	10 AWG – 6 AWG / 12 AWG – 6 AWG				10 AWG – 6 AWG	
Communication protocols	Modbus (SMA, SunSpec), Speedwire / Webconnect, SMA Battery Interface					
Interfaces: WLAN / Ethernet / BAT-CAN / RS-485	● / ● / ● / ●					
2.4 GHz WLAN	●					
Ethernet ports / Number of outputs	2 / 1 (Multi function relay 30 Vdc /1 A)					
Warranty: 10 / +5 / +10 / +15 years	● / ○ / ○ / ○					
Certificates and approvals (planned)	UL 62109-1, UL 1998, UL 1699B Ed. 1, UL9540, IEEE1547, FCC Part 15 (Class A & B), CAN CSA-C22.2, CA Rule 21, HECO Rule 14H, PV Rapid Shutdown System Equipment in accordance with UL1741, NEC 2020, NEC 2023 compliant					
SMA Smart Connected	●					
SMA ShadeFix (integrated shade optimization)	●					
SunSpec certified transmitter (Rapid Shutdown)	●					
SMA Backup Secure** (grid outage mode, with or without battery)						
Rated power (at 120 V, 60 Hz)	1920 W					
Max. apparent AC power	1920 VA					
Nominal AC voltage	120 V					
AC grid frequency	60 Hz					
Activation mode	Manual					
● Standard features ○ Optional features						
Type designation	SBSE3.8-US-50	SBSE4.8-US-50	SBSE5.8-US-50	SBSE7.7-US-50	SBSE9.6-US-50	SBSE11.5-US-50

* Upcoming **Backup Start module required to enable SMA Backup Secure in installations bound by NEC rapid shutdown requirements.

Accessories

SMA Energy Meter
EMETER-US-50

Backup Start
Module
BU-STRT-US-50

SMA Shutdown
Initiator
RSI-US-50

www.SMA-America.com **SMA America, LLC**

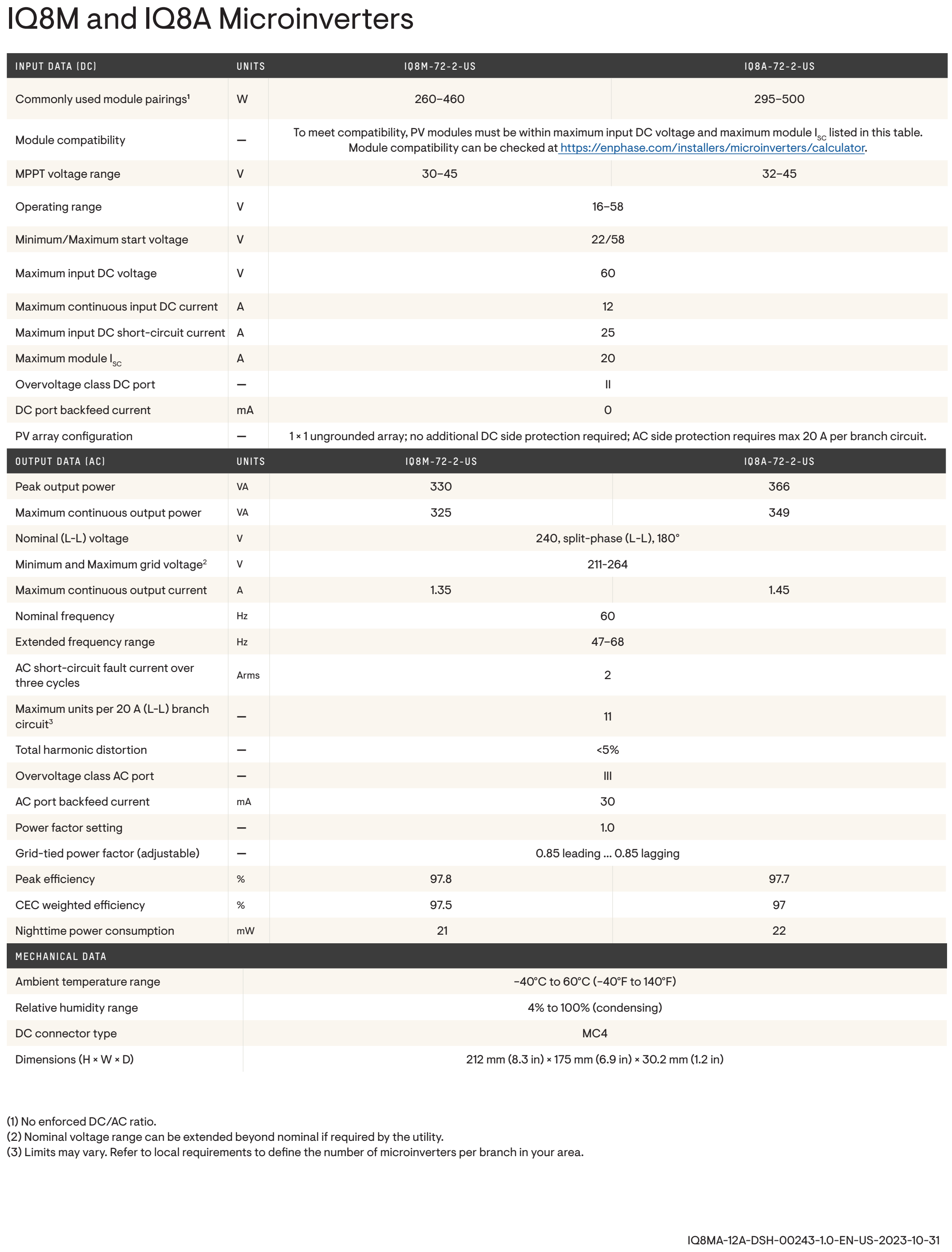
Figure 2: Sunny Boy Smart Energy-US 3.8 (2)

To ensure that the phenomenon of clipping, where the peak capacity of a string inverter limits its AC power output despite surplus power availability from solar modules, does not impede system performance, validation was executed utilizing the National Renewable Energy Laboratory PVWatts Calculator (3). The input data from Table 1 and Table 2 yielded a clipping value of 0%, indicating unhindered power output capacity for the inverter.

Although the considered string inverter is equipped with Wi-Fi smart connect capability, its utilization is presently deferred. The option to implement this feature remains available for potential system upgrades at the customer's discretion. Extensive investigation into alternative, smaller inverters revealed potential cost-effectiveness but raised concerns about clipping issues. In the context of optimizing the PV system, the current selection stands out as the most suitable choice.

3.2 Microinverter

The choice of a microinverter depends solely on the electrical specifications of each solar panel, detailed in Table 1. For this particular system, the microinverter of choice is the ENPHASE IQ8M, specifically the model IQ8M-72-2-US. Distinguished by its split-phase power conversion capability, this microinverter enhances the efficiency of converting DC power to AC power. It features Power Line Communication for seamless component interaction, a Class II double-insulated enclosure, and adherence to the latest advancements in grid support technology. It is accompanied by a 25-year warranty provided by the manufacturer. Detailed specifications can be found in Figure 3 below.



IQ8M and IQ8A Microinverters

INPUT DATA (DC)	UNITS	IQ8M-72-2-US	IQ8A-72-2-US
Commonly used module pairings¹	W	260–460	295–500
Module compatibility	—	To meet compatibility, PV modules must be within maximum input DC voltage and maximum module I_{SC} listed in this table. Module compatibility can be checked at https://enphase.com/installers/microinverters/calculator.	
MPPT voltage range	V	30–45	32–45
Operating range	V	16–58	
Minimum/Maximum start voltage	V	22/58	
Maximum input DC voltage	V	60	
Maximum continuous input DC current	A	12	
Maximum input DC short-circuit current	A	25	
Maximum module I_{SC}	A	20	
Overvoltage class DC port	—	II	
DC port backfeed current	mA	0	
PV array configuration	—	1 × 1 ungrounded array; no additional DC side protection required; AC side protection requires max 20 A per branch circuit.	
OUTPUT DATA (AC)	**UNITS**	**IQ8M-72-2-US**	**IQ8A-72-2-US**
Peak output power	VA	330	366
Maximum continuous output power	VA	325	349
Nominal (L-L) voltage	V	240, split-phase (L-L), 180°	
Minimum and Maximum grid voltage²	V	211-264	
Maximum continuous output current	A	1.35	1.45
Nominal frequency	Hz	60	
Extended frequency range	Hz	47–68	
AC short-circuit fault current over three cycles	Arms	2	
Maximum units per 20 A (L-L) branch circuit³	—	11	
Total harmonic distortion	—	<5%	
Overvoltage class AC port	—	III	
AC port backfeed current	mA	30	
Power factor setting	—	1.0	
Grid-tied power factor (adjustable)	—	0.85 leading ... 0.85 lagging	
Peak efficiency	%	97.8	97.7
CEC weighted efficiency	%	97.5	97
Nighttime power consumption	mW	21	22
MECHANICAL DATA			
Ambient temperature range		-40°C to 60°C (-40°F to 140°F)	
Relative humidity range		4% to 100% (condensing)	
DC connector type		MC4	
Dimensions (H × W × D)		212 mm (8.3 in) × 175 mm (6.9 in) × 30.2 mm (1.2 in)	

(1) No enforced DC/AC ratio.
(2) Nominal voltage range can be extended beyond nominal if required by the utility.
(3) Limits may vary. Refer to local requirements to define the number of microinverters per branch in your area.

IQ8MA-12A-DSH-00243-1.0-EN-US-2023-10-31

Figure 3: ENPHASE IQ8M Microinverter (4)

Upon further evaluation using PVWatts, it is noteworthy that the microinverter exhibits an impressive 0% clipping rate. This indicates an optimal performance scenario where the AC power output is not restricted, ensuring that the system harnesses the full potential of the solar modules. Additionally, it is crucial to highlight that the microinverter complies rigorously with all regulatory laws governing its operation. This commitment to regulatory compliance underscores the reliability and adherence to industry standards, assuring the microinverter's safety, efficiency, and conformity to legal requirements.

4 System Advisor Modeling (SAM), Performance

The inclusion of the System Advisor Model (SAM) in our report is essential to harness its powerful techno-economic modeling capabilities. SAM serves as a valuable decision-support tool for evaluating various renewable energy systems, ranging from photovoltaic and wind power to concentrated solar power and beyond. Its versatility caters to a wide audience, including project managers, engineers, and policy analysts, providing a comprehensive understanding of the economic feasibility and performance potential of different renewable energy technologies. SAM's ability to model financial aspects for diverse project types, such as residential, commercial, and Power Purchase Agreement (PPA) projects, ensures a robust analysis of economic viability and potential revenue streams. By incorporating SAM into our report, we enhance the depth and accuracy of our assessments, facilitating informed decision-making and contributing to a more comprehensive and insightful evaluation of renewable energy solutions (5).

Utilizing the specifications of both string and microinverters outlined in Section 3 and the panel details presented in Section 2.1, we can derive key performance metrics for Year 1. These metrics include Annual AC energy, DC capacity factor, Energy yield, Performance ratio, Levelized Cost of Energy (LCOE) in both nominal and real terms, as well as the Electricity bill without the system (Year 1), Electricity bill with the system (Year 1), and Net savings with the system (Year 1). This comprehensive set of metrics serves as a crucial indicator, demonstrating the energy production in Houghton, MI, and illustrating the significant energy savings achieved both with and without the system in place.

4.1 Performance Metrics for String Inverter System

The evaluation of the string inverter system involves an in-depth analysis of critical performance metrics derived from the specifications outlined in Section 3 and the corresponding panel details presented in Section 2.1. The comprehensive summary, depicted in Table 3, provides an intricate overview, allowing for a detailed and technical assessment of the system's energy production efficiency in Houghton, MI. This examination underscores the nuanced impact on energy savings when the system is operational, offering a precise understanding of the overall performance of the string inverter system.

Table 3: Performance Metrics, String Inverter

Annual AC energy in Year 1	6,176 kWh
Energy yield in Year 1	1,112 kWh/kW
Electricity bill without system (year 1)	$2,418
Electricity bill with system (year 1)	$895
Net savings with system (year 1)	$1,523

The detailed evaluation of the string inverter system, considering critical performance metrics and financial parameters as presented in Table 3, provides valuable insights into the system's performance in the specific context of Houghton, MI. The Annual AC energy output of 5,856 kWh in Year 1, coupled with an impressive Energy yield of 1,054 kWh/kW, underscores the system's efficiency in converting sunlight into usable electrical energy.

The substantial reduction in the Electricity bill with the system, from $1,784 to $743 in Year 1, manifests the tangible economic benefits of implementing the string inverter system. Notably, the Net savings with the system amounting to $1,042 in the same period further emphasizes the financial advantages, affirming the system's viability and potential return on investment.

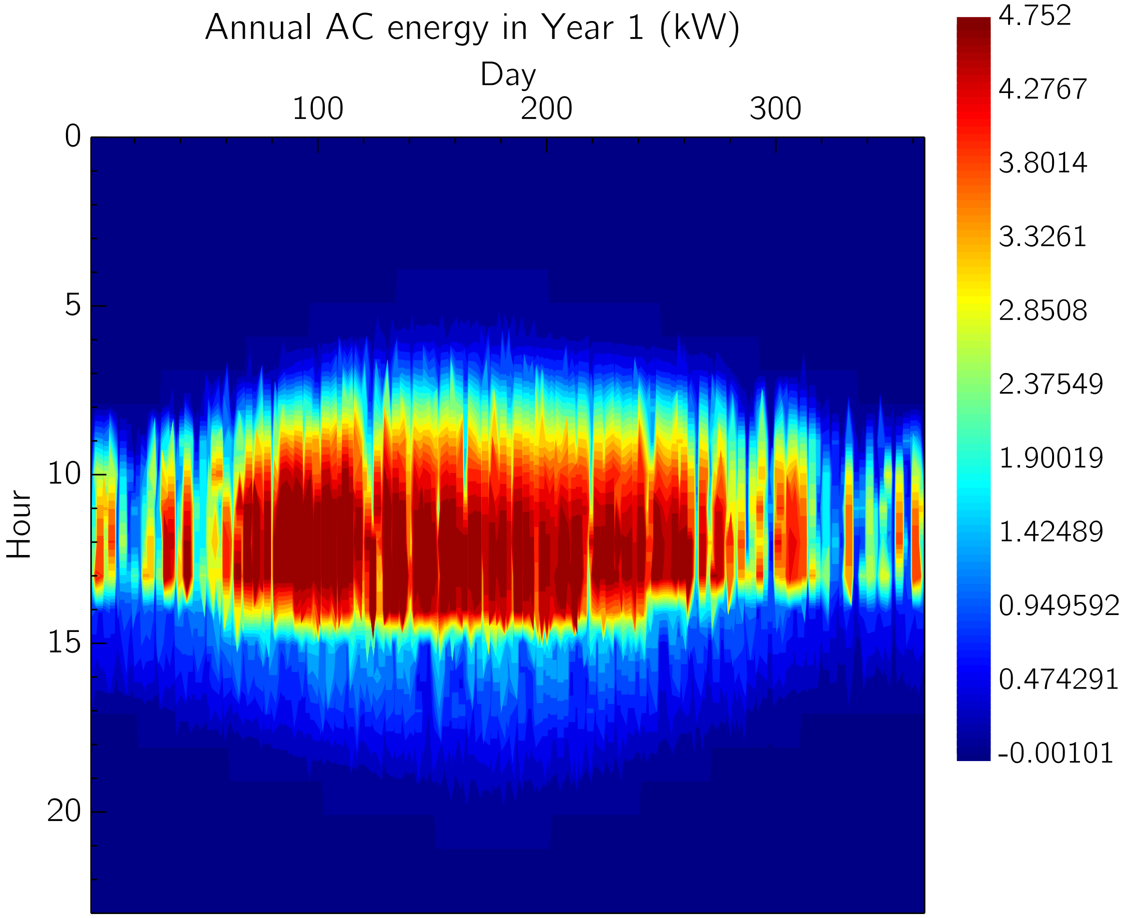


Figure 4: Annual AC energy in Year 1 (kW), String Inverter (5)

In the graphical representation presented in Figure 4, the annual AC energy is visualized across hours and days of the year. This visualization highlights a notable trend where the highest production of annual AC energy occurs during the summer months, particularly around noon. This observed peak aligns with expectations, considering the geographical location in Michigan. During the summer, the days are longer, and sunlight is more abundant, resulting in increased energy production. In contrast, the winter months, characterized by cloudier skies and shorter days, exhibit a decrease in energy production. The graph provides a clear understanding of the seasonal variations in AC energy generation, offering valuable insights into the system's performance dynamics influenced by the unique climatic conditions in Michigan.

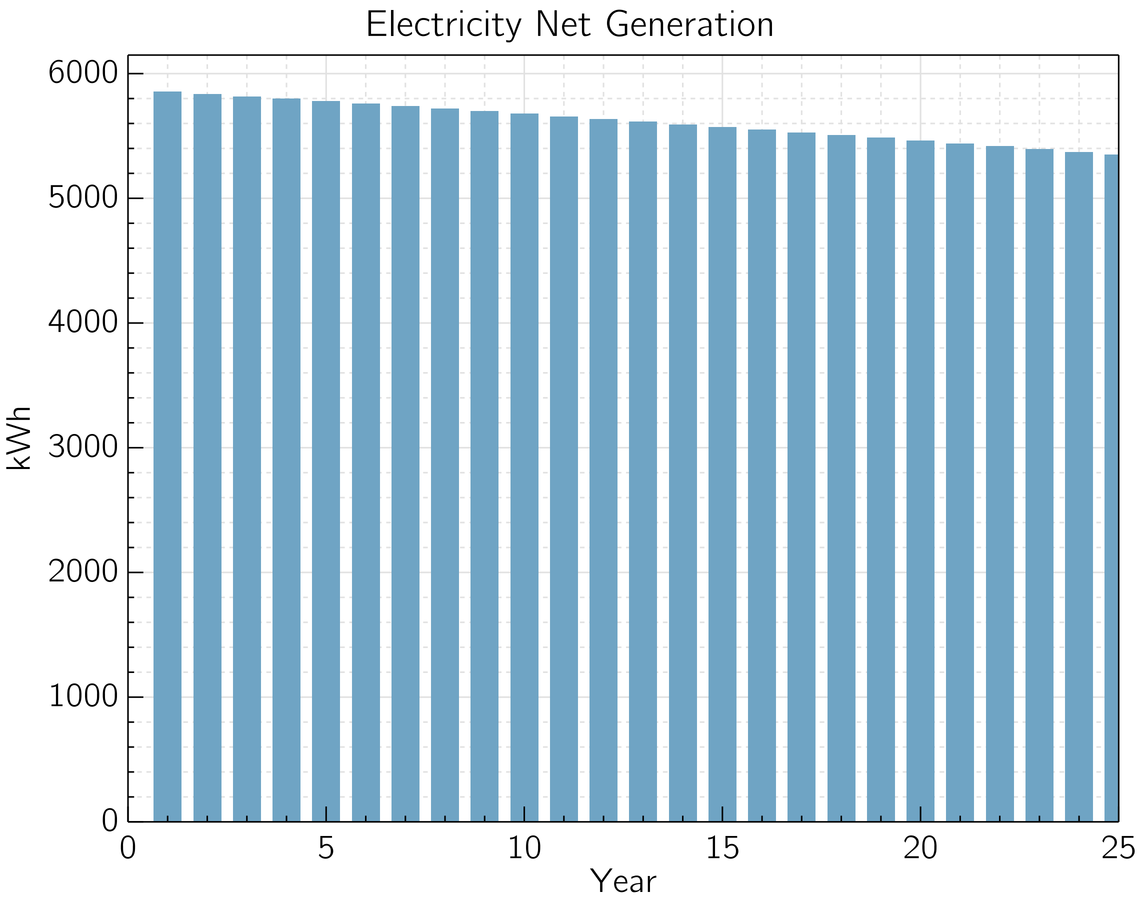


Figure 5: Electricity Net Generation 25 Years, String Inverter (5)

Within Figure 5, a depiction of the 25-year life span is presented, illustrating the net generation of electricity in kilowatt-hours (KWh). This visual representation offers insights into the natural degradation of electrical components over time. Despite this degradation, the graph underscores the system's resilience by showcasing a substantial amount of energy generation throughout its operational life. This sustained production highlights the system's capability to contribute a significant quantity of energy back into the overall system, even as components naturally undergo wear and tear.

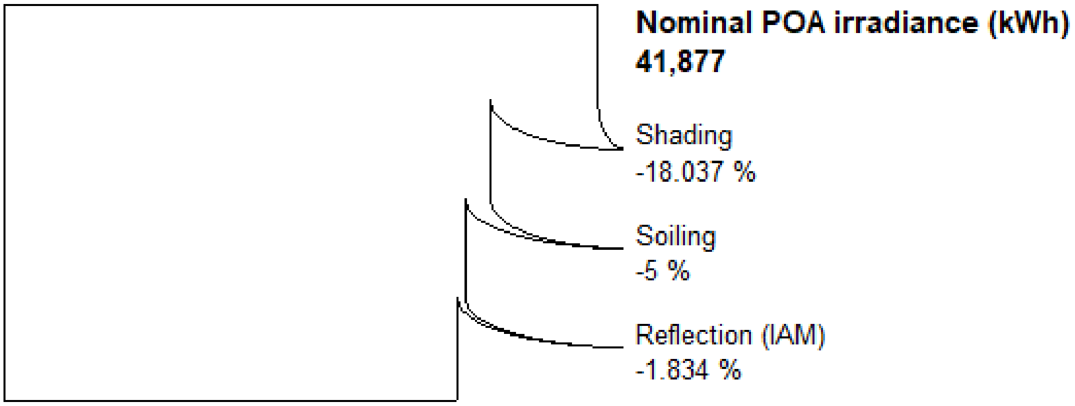


Figure 6: Losses of the System, String inverter (5)

In Figure 6, the graph displays the percentage breakdown of losses within the system, with shading representing the most significant factor, attributed to the shading profile in Houghton, MI. The impact of shading, contingent on local factors such as surrounding trees and buildings, can be mitigated through customized adjustments tailored to the specific housing area of the customer. Another contributing factor is soiling, which involves the accumulation of dust and grime on the panels over time. Regular panel maintenance, involving routine cleaning, serves to minimize these losses. Importantly, the recorded values fall within an acceptable range for the system, indicating that they will not substantially impede the overall electricity output.

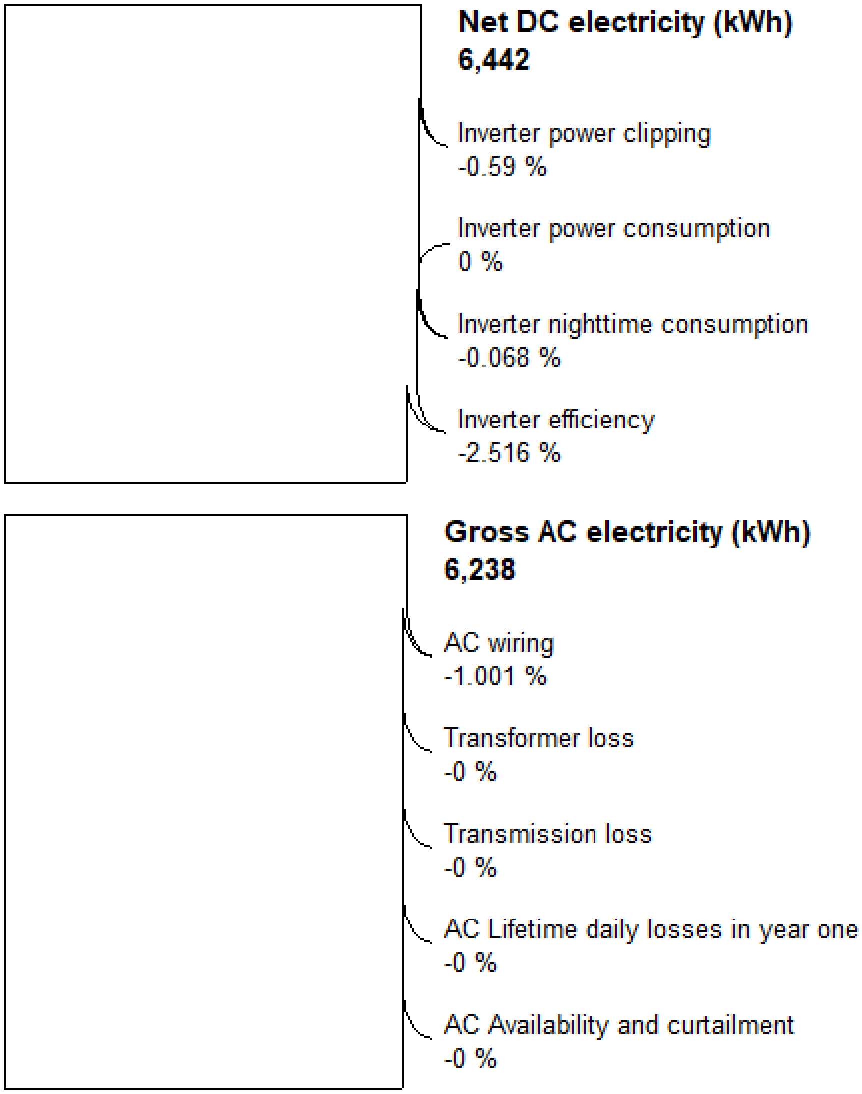


Figure 7: Electric Losses of the System, String inverter (5)

In Figure 6, we observe minimal power clipping, with the primary notable loss attributed to the efficiency of the inverters. However, this loss falls within acceptable tolerance levels. It stems from the normal wear and tear of the electrical components within the system, safeguarded by the protective components detailed in Section 5.1. Moreover, the loss attributed to AC wiring falls within acceptable limits as the chosen wiring size aligns with the design, ensuring optimal output without any energy loss. This choice is deemed satisfactory.

4.2 Performance Metrics for Microinverter System

Similar to the thorough evaluation conducted for the string inverter system, the performance analysis of the microinverter system involves a meticulous examination of critical metrics derived from the specifications outlined in Section 3 and the corresponding panel details highlighted in Section 2.1. This assessment aims, in Table 4, to provide a comprehensive understanding of the microinverter system's efficiency in harnessing solar energy within the specific conditions of Houghton, MI.

Table 4: Performance Metrics, Micronverter

Annual AC energy in Year 1	6,134 kWh
Energy yield in Year 1	1,104 kWh/kW
Electricity bill without system (year 1)	$2,815
Electricity bill with system (year 1)	$1,302
Net savings with system (year 1)	$1,513

The comprehensive summary, depicted in Table 4, provides an intricate overview, allowing for a detailed and technical assessment of the microinverter system's energy production efficiency in Houghton, MI. The system exhibits an impressive Annual AC energy output of 6,134 kWh in Year 1, coupled with a noteworthy Energy yield of 1,104 kWh/kW. This underscores the microinverter system's effectiveness in converting sunlight into usable electrical energy.

Significantly, the microinverter system demonstrates substantial economic benefits, as evident in the reduction of the Electricity bill with the system from $2,071 to $979 in Year 1. This translates to a Net saving with the system amounting to $1,091 in the same period. These financial advantages underscore the microinverter system's economic viability and potential return on investment, paralleling the observed trends in the string inverter system.

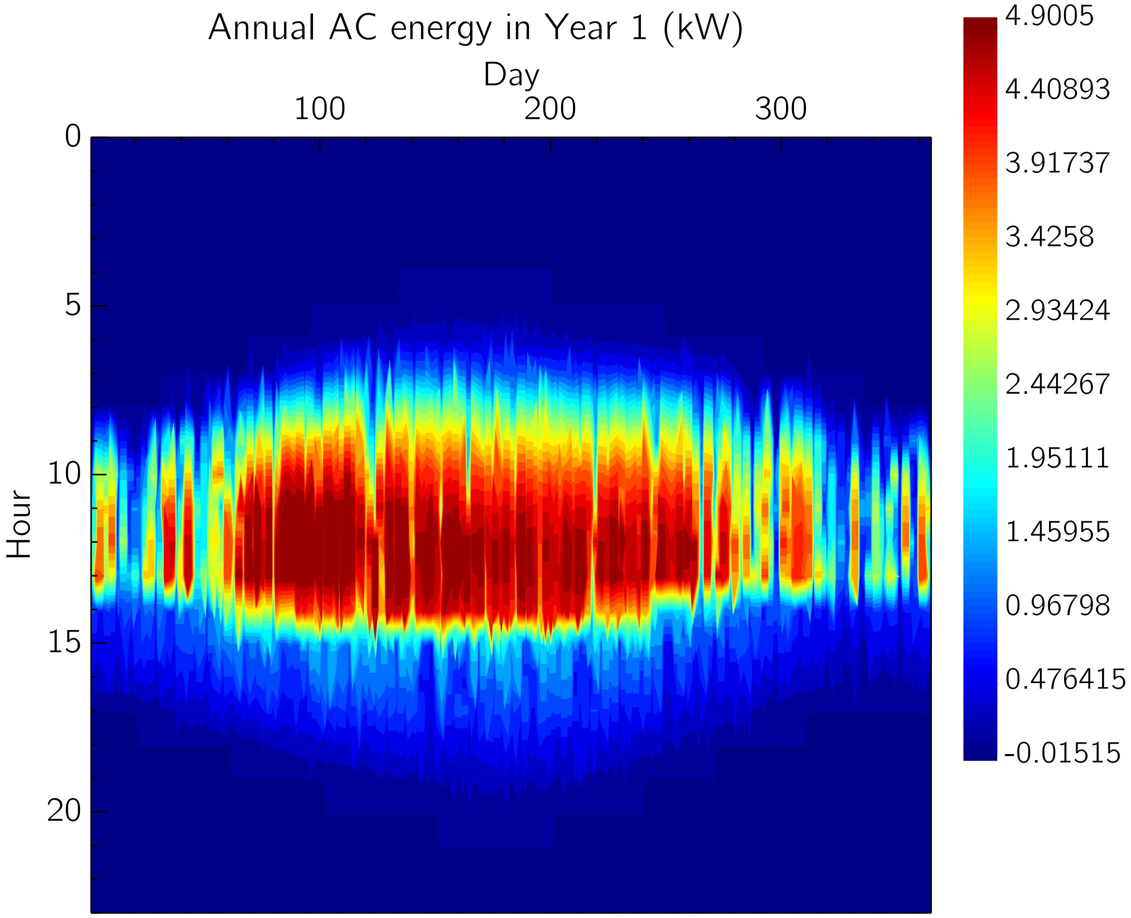


Figure 8: Annual AC energy in Year 1 (kW), Microinverter (5)

In Figure 8, a comparable representation to Figure 5 is presented, yet with a notable distinction of higher AC output, aligning with the data from Table 4. This distinction becomes particularly evident during the summer months when the microinverter system exhibits a more efficient conversion of DC to AC on each panel compared to the string inverter system. The graph underscores the microinverter's capacity to generate a significant AC output, highlighting its enhanced performance during favorable conditions and emphasizing its superiority in certain aspects over the string inverter counterpart.

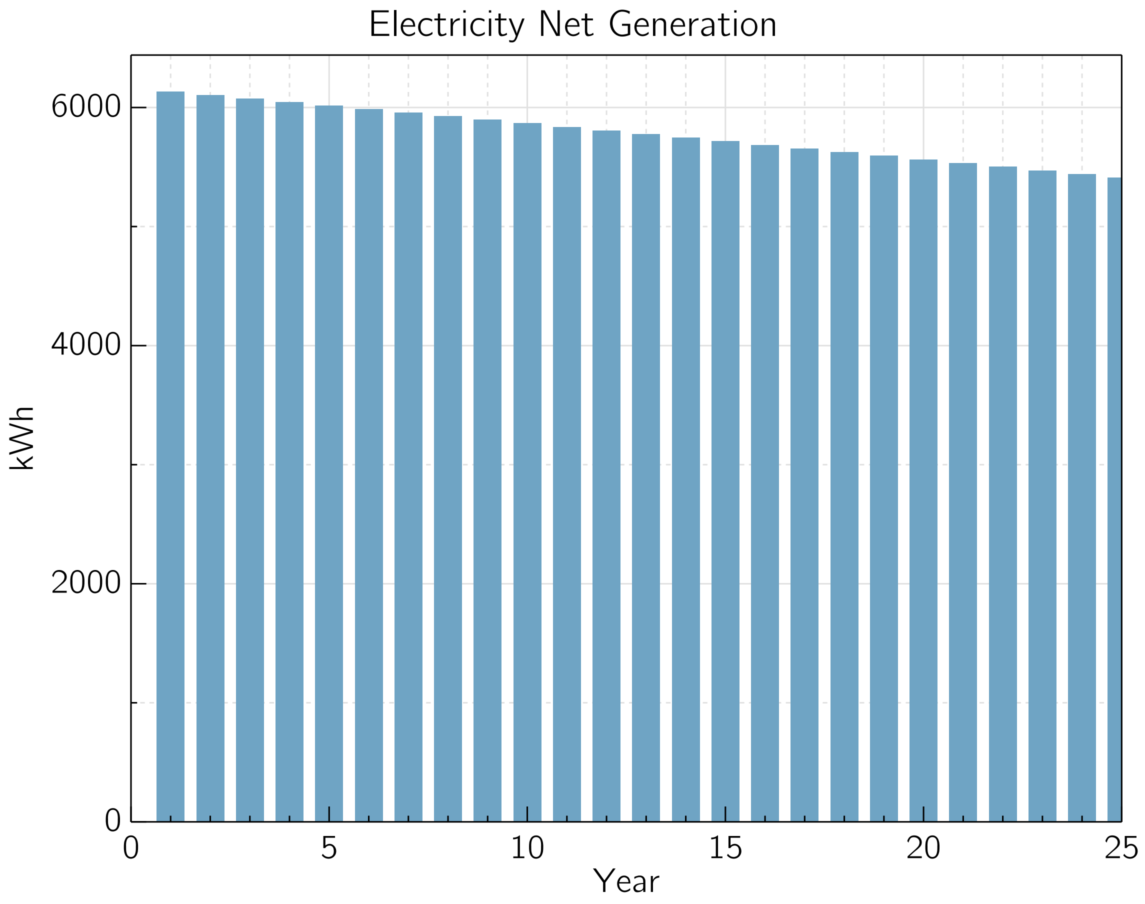


Figure 9: Electricity Net Generation 25 Years, Microinverter (5)

Examining Figure 9, it's evident that both the initial and total net generation of electricity surpass those of the string inverter, as illustrated in Figure 5. This observation is a crucial aspect of the system, highlighting a substantial increase in electricity generation. This difference can have a notable impact on the total net present value, that will be thoroughly discussed in Section 6.

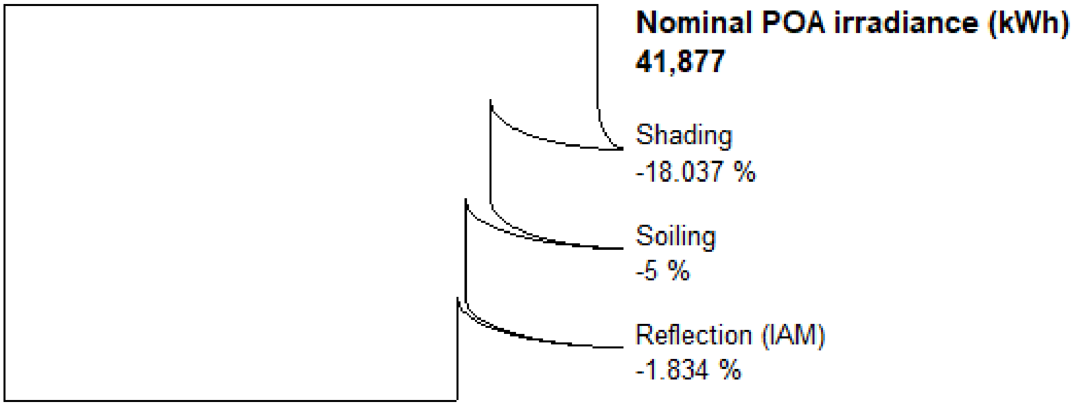


Figure 10: Losses of the System, Microinverter

The losses portrayed in Figure 10 closely resemble those presented in Figure 6, primarily because both systems are installed in the same geographical location. This spatial proximity ensures that the systems encounter similar environmental conditions and shading profiles, thereby contributing to analogous loss percentages. The minimal variation in losses between the two graphs can be attributed to the shared location, which implies a consistent impact on the performance of both the microinverter and string inverter systems.

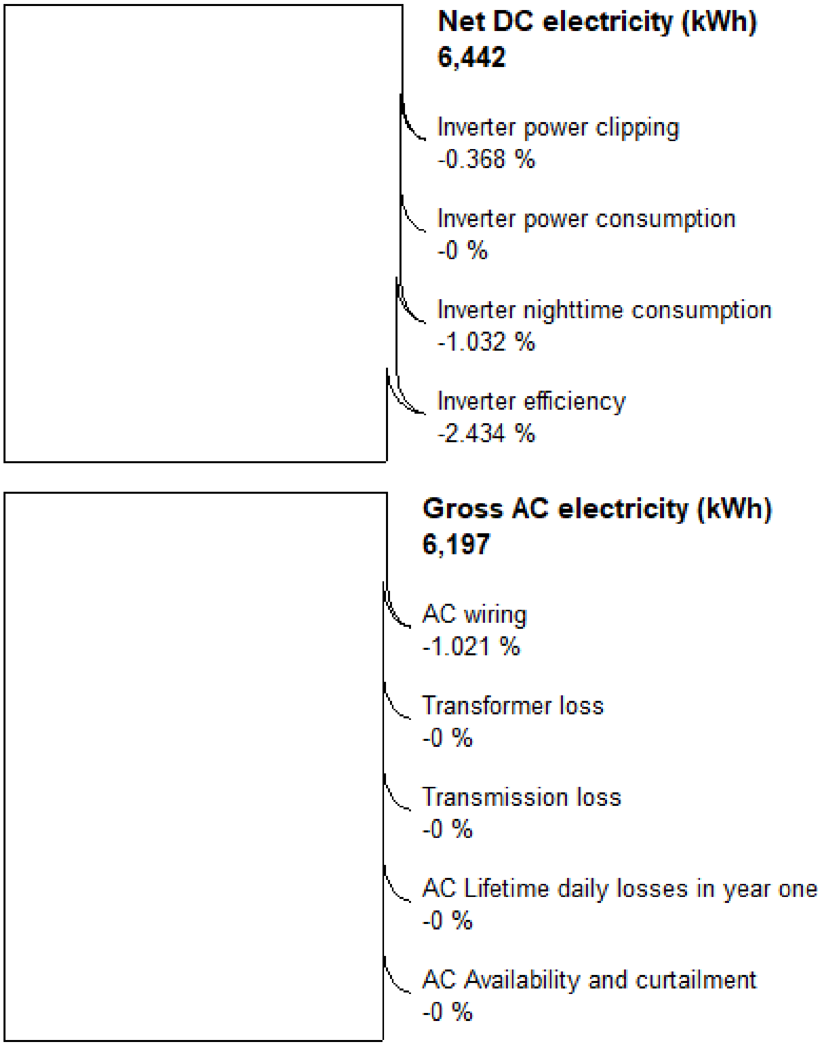


Figure 11: Electric Losses of the System, Microinverter (5)

In the graphical representation presented in Figure 11, the power clipping is observed to be less than 1%, an ideal scenario indicative of efficient performance. Notably, the losses in the microinverter system closely resemble those of the string inverter system, with one notable exception— the Inverter nighttime consumption. Although still minimal, it exhibits a slightly higher percentage compared to that of the string inverter.

5 Installation Costs and Information

This section aims to provide a comprehensive breakdown of each component within the system, offering detailed insights into the selection criteria that guided the choices made for each element. By delving into the specifics of every component, we aim to elucidate the rationale and considerations behind their inclusion in the overall system design. This thorough examination will contribute to a better understanding of the system's composition and help justify the decision-making process behind the selection of each component.

5.1 String Inverter costs and Information

Table 5: String Inverter Costs

Inverter	Model	Cost	Link
Sunny Boy Smart Energy-US 4.8	SBSE4.8	$2,177.93	(6)
AC Disconnect			
SIEMENS Safety switch Non fusible, 30A Indoor/Outdoor	HF321NR	$421.69	(7)
Wire			
10 AWG Solar Wire 600V UL4703 Bare Copper Stranded (19) Insulated XLPE	PVXLU10-FT-BLACK-19 (150′)	$82.50	(8)
	PVXLU10-FT-RED-19 (150′)	$66.00	(8)
6 AWG Princeton URD Direct Burial Aluminum	URDP6600-FT (120′)	$82.50	(8)
MC4 Connectors			
Stauldi MC4 Male & Female Connectors	1577005 (5 Pairs)	$23.00	(9)
Conduit			
1" EMT Conduit	EMT1 (100′)	$179.58	(10)
1" EMT Coupling Rain tight	662RT (25)	$15.72	(10)
1" EMT Connector	252DC2 (10)	$15.35	(10)
	Total Cost of System	**$3,672.14**	

With all components considered, the comprehensive cost of the system's parts amounts to a total of $3,672.14. This estimate incorporates additional parts to account for potential variations based on installer preferences. Notably, the inclusion of an AC disconnect switch aligns with regulatory requirements for PV systems, offering flexibility in mounting options—either within the garage or, ideally, adjacent to the AC distribution panel to facilitate emergency shut-off. The selection of 10 AWG 19-stranded copper wire is driven by its capacity to withstand the current and voltage outputs of the system, ensuring a durable and long-lasting performance. Employing a 6 AWG grounding wire serves as a precautionary measure against unexpected discharges or voltage build-ups, allowing for the safe dissipation of excess energy around the system. The incorporation of MC4 connectors facilitates the seamless installation of wires from the panels to the inverter. Lastly, the choice of conduit aims to prevent roof penetrations, preserving the roof's longevity, while also providing flexibility for installers to route the conduit according to their discretion.

The design of this system prioritizes safety and incorporates a robust, over-engineered approach to ensure compliance with all regulations and laws stipulated by the state of Michigan. It's important to note that the specifics of the design may be subject to revision based on the characteristics of the particular house where the system will be installed. The current design considerations are tailored for a single-story house, accounting for various safety measures and adhering to the regulatory framework in Michigan. However, the adaptability of the design allows for careful reevaluation and adjustments as needed, emphasizing a flexible approach to address the unique features and requirements of the installation site.

5.2 Microinverter Cost and Information

Note Given that the inverters contribute their outputs in parallel, the cumulative amperage entering the system after conversion is 21 amps, (for breaker size).

Table 6: Microinverter Costs

Inverter	Model	Cost	Link
IQ8M Microinverter (MC4)	SIQ8M-72-M-US (15)	$ 3142.50	(4)

Continued on the next page

Table 6 – Continued from previous page

	Model	**Cost**	**Link**
Combiner			
IQ Combiner 4	X-IQ-AM1-2404	$733.50	(11)
Wire			
4 AWG XHHW-2 Building Wire	XHW4-FT-BLACK (120′)	$174.00	(8)
	XHW4-FT-RED (120′)	$174.00	(8)
6 AWG Princeton URD Direct Burial Aluminum	URDP6600-FT (120′)	$52.80	(8)
Breakers			
SQUARE D Miniature Circuit Breaker: 30 A, 120/240V AC, Single Phase, 22kA at 120/240V AC, QO, Paddle	QO130VH (3)	$226.80	(12)
Conduit			
1" EMT Conduit	EMT1 (100′)	$179.58	(10)
1" EMT Coupling Rain tight	662RT (25)	$15.72	(10)
1" EMT Connector	252DC2 (10)	$15.35	(10)
	Total Cost of System	**$4714.25**	

The Microinverter system incurs a higher total cost of parts, amounting to $4,714.25 compared to the string inverter system. The decision to choose a specific combiner was motivated by the preference for the same manufacturer as the inverter, ensuring seamless compatibility and support. This combiner is enhanced with an IQ gateway, offering communication and control capabilities for production metering and consumption monitoring. For connectivity, a mobile connect modem, supplied by a local cellular provider, can be integrated. The wiring in this system is of a smaller gauge compared to the string inverter, reflecting the lower current as the inverters are directly connected to the panels. The grounding wire remains consistent with the previous system, constructed from corrosion-resistant aluminum, requiring minimal maintenance for exposed wires. Breakers, as detailed in the note above (Table 6), have been selected, and the conduit remains consistent with the previous system.

5.3 Racking Costs for Both Systems

For both systems, the cost of the racking to mount the panels remains consistent. Assuming the customer's roof provides sufficient space, the panels will be arranged in a landscape orientation. Utilizing Ironridge (13) for this Houghton-based project, the cost analysis includes the XR rail platform, end clamp UFO + stopper sleeve, and adheres to the specified panel details. Environmental conditions are set with a snow load of 80 psf, a wind speed rating of 115 mph, and a wind exposure of B. Assuming the roof is composed of composite shingles, the roof attachment will be FlashVue, employing Square Bolt attachment hardware, QM Conduit Mount, with a default roof plane height of 30 ft, a slope of 30 degrees, and a rafter spacing of 24 inches.

Selecting the XR100 Rail type with a stock length of 168", which can be cut on-site for uniform positioning, the total MSRP comes out to be $7,693.56.

6 System Advisor Modeling (SAM), Financial Information

Utilizing the details gathered in Section 5, we can incorporate this information into the overall installation cost within SAM. By integrating both the component costs and the racking expenses, the total installation costs for both systems are outlined below.

Table 7: String Inverter PV Captial Costs (5)

Direct Capital Costs		
Module	15 units	$5,925.00
Inverter	1 unit	$2,177.93
Balance of system equipment		$11,365.70
Installation labor		$2,000.00
Installer margin and overhead		$2,000.00
	Subtotal	$23,468.63
Contingency	%10	$2,346.86
	Total Direct Cost	$25,815.49
Indirect Capital Costs		
Permitting and environmental studies		$200.00
Grid interconnection		$100.00
	Total indirect Cost	$300.00
	Total install Cost	$26,115.49

Table 8: Micronverter PV Captial Costs (5)

Direct Capital Costs		
Module	15 units	$5,925.00
Inverter	15 unit	$3,142.50
Balance of system equipment		$12,407.80
Installation labor		$2,000.00
Installer margin and overhead		$2,000.00
	Subtotal	$25,475.30
Contingency	%10	$2,547.53
	Total Direct Cost	$28,022.83
Indirect Capital Costs		
Permitting and environmental studies		$200.00
Grid interconnection		$100.00
	Total indirect Cost	$300.00
	Total install Cost	$28,322.83

Considering the insights provided by both inverters, in Table 7 and Table 8, it's understood that the Microinverter option incurs a higher cost. However, this increased expense aligns with the superior performance of the microinverter. Consequently, it would be advisable to recommend the installation of the microinverter system for the customer's home. It's important to note that the final decision rests entirely with the customer, allowing them the flexibility to choose the system that best aligns with their preferences and requirements.

6.1 Incentives

As of writing this report in 2023, The U.S. Internal Revenue Service has a personal tax credit stating "A taxpayer may claim a credit for a system that serves a dwelling unit located in the United States that is owned and used as a residence by the taxpayer. Expenditures with respect to the equipment are treated as made when the installation is completed. If the installation is at a new home, the "placed in service" date is the date of occupancy by the homeowner. Expenditures include labor costs for on-site preparation, assembly or original system installation, and for piping or wiring to interconnect a system to the home. If the federal tax credit exceeds tax liability, the excess amount may be carried forward to the succeeding taxable year. The maximum allowable credit, equipment requirements and other details vary by technology, as outlined below.

Solar-electric property:

- 30% for systems placed in service by 12/31/2019
- 26% for systems placed in service after 12/31/2019 and before 01/01/2022
- 30% for systems placed in service after 12/31/2021 and before 01/01/2033
- 26% for systems placed in service after 12/31/2032 and before 01/01/2034
- 22% for systems placed in service after 12/31/2033 and before 01/01/2035

- There is no maximum credit for systems placed in service after 2008.
- Systems must be placed in service on or after January 1, 2006, and on or before December 31, 2034.
- The home served by the system does not have to be the taxpayer's principal residence."(14)

Another Incentive is Renewable Electricity Production Tax Credit, by the U.S. Internal Revenue Service which states:

"The federal renewable electricity production tax credit (PTC) is an inflation-adjusted per-kilowatt-hour (kWh) tax credit for electricity generated by qualified energy resources and sold by the taxpayer to an unrelated person during the taxable year. The duration of the credit is 10 years after the date the facility is placed in service.

Originally enacted in 1992, the PTC has been renewed and expanded numerous times, most recently by the Inflation Reduction Act of 2022. That bill established new prevailing wage and apprenticeship requirements for larger system to qualify for the full value of the tax credit – 2.6 cents per kilowatt-hour (kWh) for wind, closed-loop biomass, and geothermal energy; 1.3 cents per kWh for open-loop biomass facilities, small irrigation power facilities, landfill gas facilities and trash facilities. In late-2022 or 2023, the Treasury Secretary will issue guidance for these new labor provisions. The credit for different project types and available bonus credits is described below.

Base Credit

Projects under 1 MW (or larger projects that are commenced no more than 60 days after the Treasury Secretary develops labor guidelines) do not need to meet the new labor standards established by the Inflation Reduction to receive the full 1.3 or 2.6 cents/kWh (depending on the facility type) tax credit. This amount may be adjusted annually for inflation. Such projects that begin construction after 2021 and before 2025 can receive the full tax credit. Note, that projects that commence construction on or after January 1, 2025 can receive a tax credit under the new Clean Energy Production Tax Credit (45Y) described below. " (14)

6.2 Electrical Rate

As of the current electricity rates, the compensation rate for net excess generation in Michigan stands at 0.2466 $/kWh, and this rate has a direct impact on the Net Present Values (NPV) of both systems. The NPV for the string inverter is calculated at $1,000, whereas the microinverter system exhibits a significantly higher NPV of $3,133. This financial comparison spans the entire lifespan of both systems and holds substantial weight in influencing the customer's decision-making process. The notable disparity in NPV underscores the potential long-term economic benefits associated with choosing the microinverter system over the string inverter alternative.

7 Maintenance of the Systems

The maintenance protocol for both systems entails regular cleaning of the solar panels to ensure optimal electricity production. Additionally, an annual inspection of the wiring and any exposed electrical components is recommended, with a preference for professional oversight due to the inherent voltage and current associated with each system. Any upgrades or modifications to system components should be carried out by professionals, potentially requiring permits and incurring additional costs. However, the systems outlined in this report are designed with the expected lifespan of each component in mind, contributing to long-term reliability and efficiency.

8 Conclusion

In conclusion, this report has undertaken a comprehensive analysis and provided recommendations for the design of a solar PV system, considering both a 15-panel array configuration with a string inverter and a microinverter-based configuration. The evaluation was conducted with a focus on the specific conditions and regulations in Houghton, MI, laying the foundation for safe and compliant installations.

The selection of Panasonic EVERVOLT 370 Panels, with their high module efficiency, low degradation rate, and shading resilience, establishes a robust foundation for both configurations. The array layout, adopting a landscape orientation and three-string configuration, optimizes performance while managing costs associated with inverters. The choice between string inverters and microinverters is nuanced, considering factors such as shading, installation size, and cost efficiency. The detailed metrics presented in Table 3 and Table 4 offer a thorough understanding of the energy production, cost implications, and financial benefits associated with each system.

The integration of SAM into the analysis enhances the economic modeling and decision-making process, providing a comprehensive view of the viability and potential returns of the proposed solar PV systems. Notably, the string inverter system demonstrates significant energy savings, as evidenced by the reduced electricity bill and positive net savings in Year 1. The microinverter system, while presenting a higher initial cost, showcases optimal performance with a 0% clipping rate, ensuring maximum AC power output.

The detailed breakdown of component costs, including the use of an AC disconnect switch, appropriate wiring, and safety measures, contributes to the overall reliability and longevity of the systems. The over-engineered approach, prioritizing safety and compliance with Michigan regulations, ensures adaptability to various installation scenarios, with potential revisions based on specific house characteristics.

Maintenance protocols emphasizing regular panel cleaning and professional inspections, coupled with a focus on the expected lifespan of components, underscore the long-term reliability and efficiency of both systems.

In summary, this report serves as a comprehensive guide for the design and implementation of solar PV systems, providing valuable insights for homeowners and installers involved in renewable energy projects. The recommendations aim to facilitate informed decision-making and contribute to the sustainable adoption of solar energy in Houghton, MI.

References

[1] Panasonic. Evervolt™ pk black series solar module (370-360w). https://na.panasonic.com/us/energy-solutions/solar/evervoltr-solar-modules/evervoltr-pk-black-series-solar-module-370360w.

[2] SMA America, LLC. Sma sunny boy smart energy. https://www.sma-america.com/products/solarinverters/sunny-boy-smart-energy.

[3] National Renewable Energy Laboratory (NREL). PVWatts. https://pvwatts.nrel.gov/.

[4] Enphase Energy. Enphase iq8 microinverter. https://enphase.com/store/microinverters/iq8-series/iq8m-microinverter.

[5] National Renewable Energy Laboratory (NREL). System advisor model (sam). https://sam.nrel.gov/.

[6] SolarFlexion. Sma sunny boy smart energy series sbse4.8-us-50 single phase hybrid inverter. https://www.solarflexion.com/product-p/sbse4.8-us-50.htm.

[7] GRAINGER. Siemens solar safety disconnect switch: Non-fusible, 30 a, 600v ac, indoor/outdoor, 11 in x 6 1/2 in. https://www.grainger.com/product/SIEMENS-Solar-Safety-Disconnect-Switch-30J360?opr=PDPRRDSP&analytics=dsrrItems_30J356.

[8] Wire Cable Your Way. Wire selection. https://www.wireandcableyourway.com/.

[9] Signature Solar. Stäubli mc4 male and female connector. https://signaturesolar.com/staubli-mc4-male-and-female-connector/.

[10] Elliot Electric. Conduits and accesories. https://www.elliottelectric.com/P/.

[11] ENPHASE. Iq combiner 4. https://enphase.com/store/communication/gen2/iq-gateway-and-combiner/iq-combiner-4.

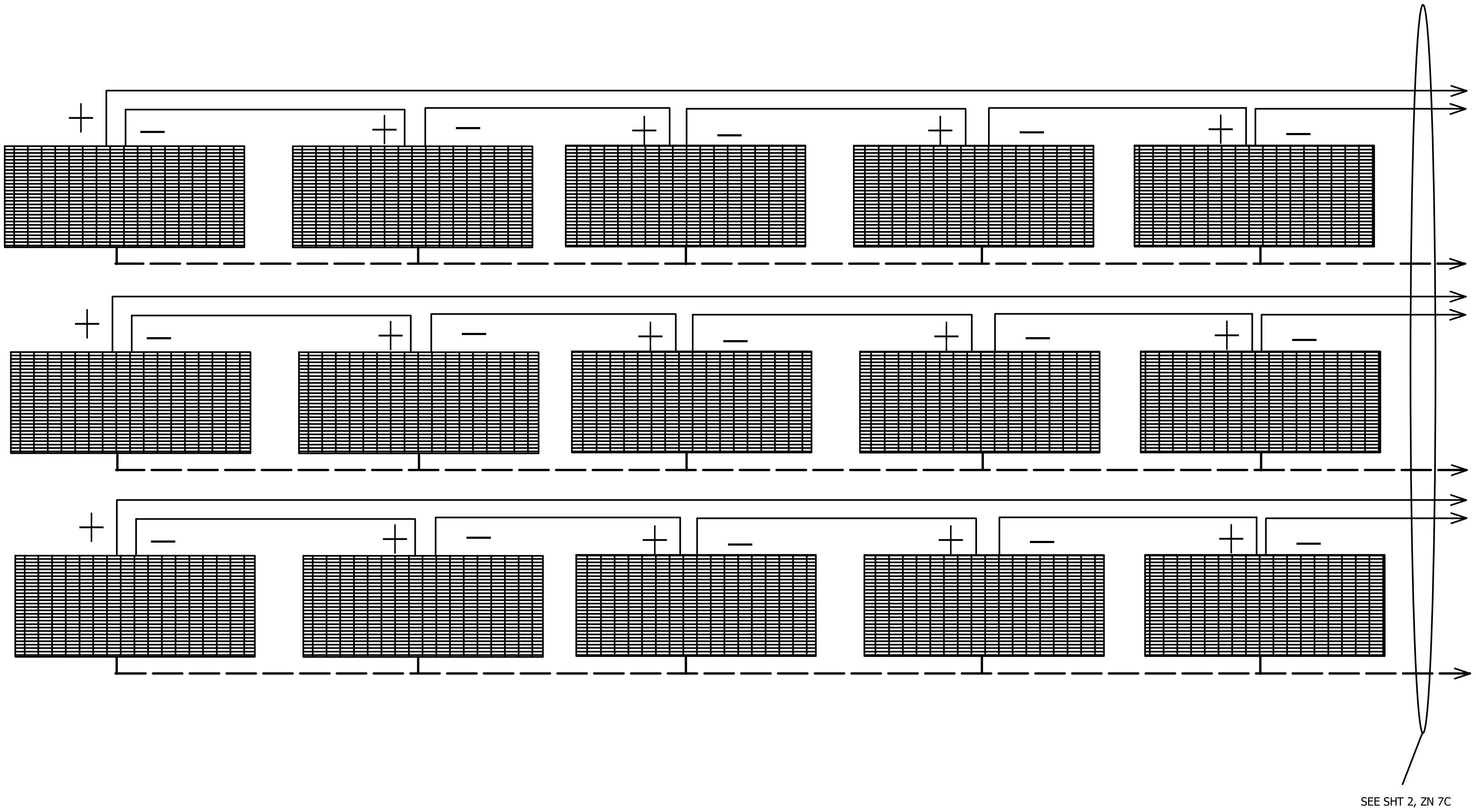
[12] GRAINGER. Square d miniature circuit breaker: 30 a, 120/240v ac, single phase, 22ka at 120/240v ac, qo, paddle. https://www.grainger.com/product/SQUARE-D-Miniature-Circuit-Breaker-1D242.

[13] Ironridge. Racking installation costs. https://www.ironridge.com/.

[14] DSIRE NC Clean Energy Technology Center. Solar technology incentives 2023. https://programs.dsireusa.org/system/program/mi.

9 Appendix

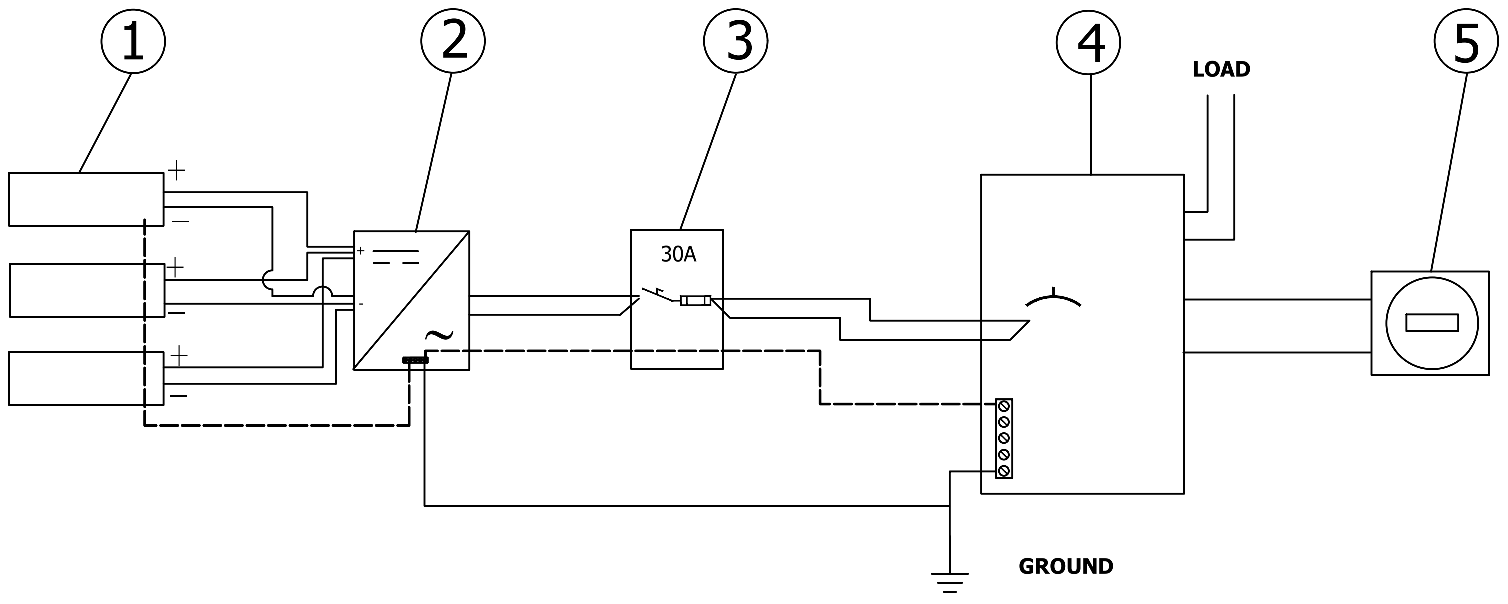
The next pages are detailed schematics showing the two different systems for permitting purposes.



Electrical Data for String with Panasonic EVERVOLT 370 Panels EVPV370	
Min Voltage	121.08 V
Max Voltage	218.2 V
Max Current	11.25 A

SOLAR PANEL ARRAY-IN SERIES FOR STRING INVERTER

SIZE	**DATE**	**Drawing No.**	**REV**
ANSI A	11/20/2023	S1	
SCALE: NONE	**DRAWN BY: STEVEN ARAKI**	**SHEET 1 OF 4**	

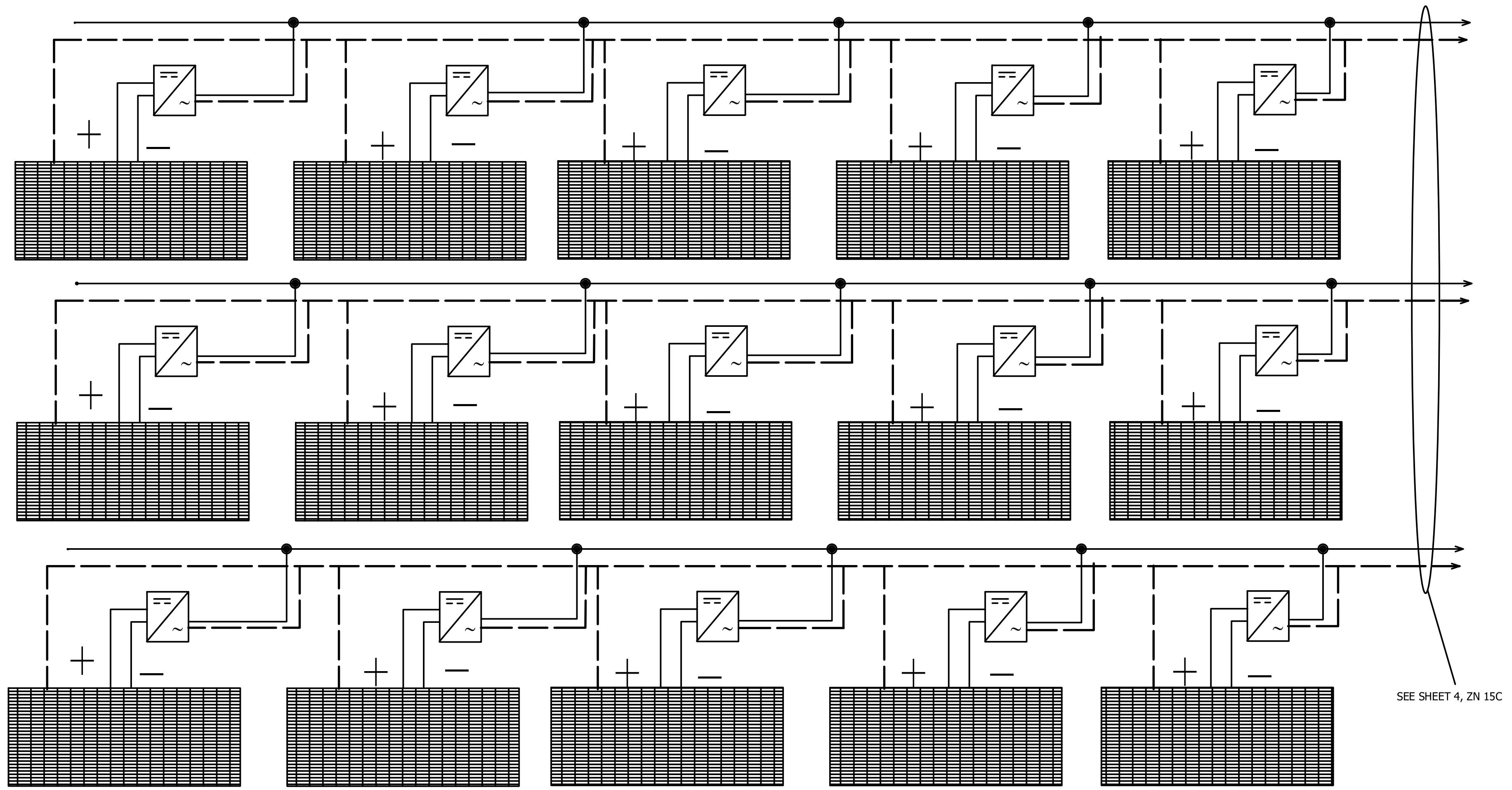


EQUIPMENT SCHEDULE

TAG	DESCRIPTION	PARTNUMBER
1	SOLAR PV ARRAYS 15 MODULES PER STRING	EVPV370
2	DC/AC INVERTER	SBSE3.8
3	AC DISCONNECT	HNF361RPV
4	AC DISTRIBUTION PANEL	PROVIDED WITH HOUSE
5	METER	PROVIDED WITH HOUSE

ONE-LINE STANDARD ELECTRICAL DIAGRAM FOR SMALL-SCALE, STRING INVERTER PV SYSTEMS

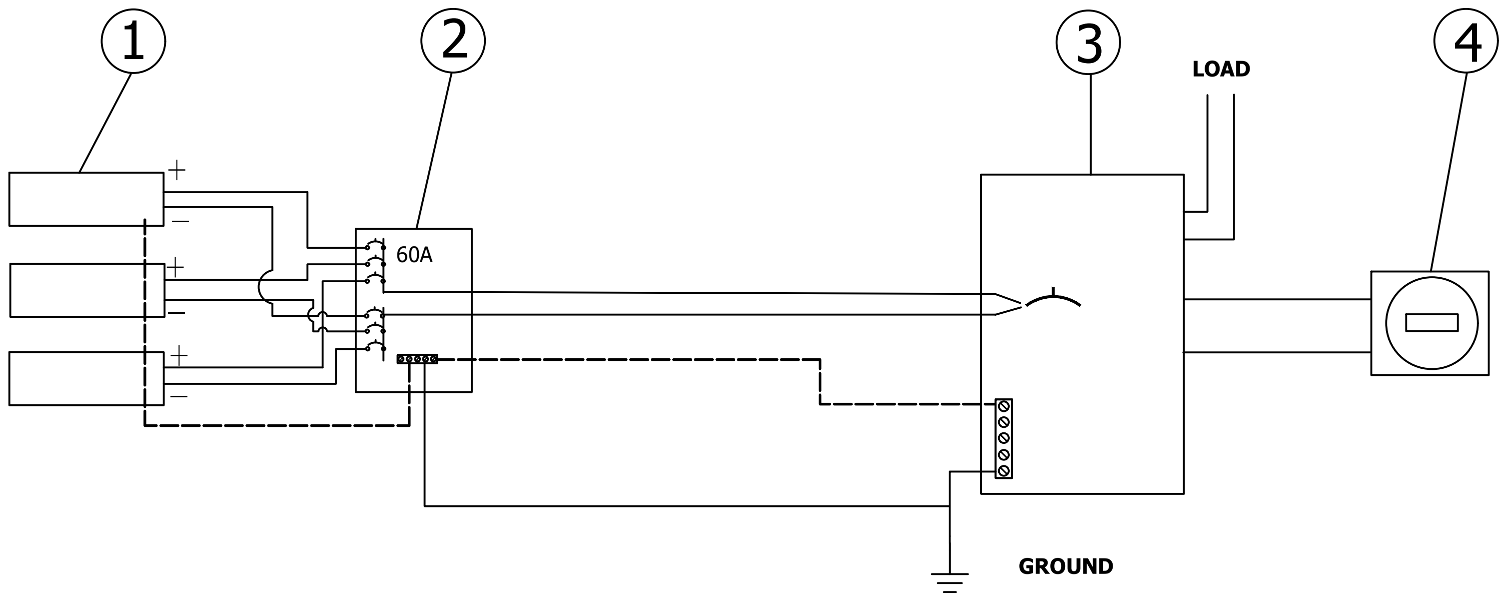
SIZE	**DATE**	**Drawing No.**	**REV**
ANSI A	11/27/2023	S1	
SCALE: NONE	**DRAWN BY: STEVEN ARAKI**	**SHEET 2 OF 4**	



Electrical Data for String with Panasonic EVERVOLT 370 Panels EVPV370	
Min Voltage	30.27 V
Max Voltage	43.64 V
Max Current	56.25 A

SOLAR PANEL ARRAY - FOR MICRO INVERTER ENPHASE IQ8M-72-2-US

SIZE	DATE	Drawing No.	REV
ANSI A	11/20/2023	S1	
SCALE: NONE	DRAWN BY: STEVEN ARAKI	SHEET 3 OF 4	



EQUIPMENT SCHEDULE

TAG	DESCRIPTION	PARTNUMBER
1	SOLAR PV ARRAYS 15 MODULES PER STRING	EVPV370
2	IQ COMBINER 4C	X-IQ-AMI-2404
3	AC DISTRIBUTION PANEL	PROVIDED WITH HOUSE
4	METER	PROVIDED WITH HOUSE

ONE-LINE STANDARD ELECTRICAL DIAGRAM FOR SMALL-SCALE, MICROINVERTER PV SYSTEMS

SIZE	DATE	Drawing No.	REV
ANSI A	11/30/2023	S1	
SCALE: NONE	**DRAWN BY: STEVEN ARAKI**	**SHEET 4 OF 4**	