MORNINGSTAR
World's Leading Solar Controllers & Inverters

Heat Dissipation of GenStar MPPT Controllers Inside Enclosures

All power electronics generate waste heat during normal operation. Morningstar's lineup of solar charge controllers are designed to maximize power harvest from photovoltaic (PV) arrays while minimizing energy wasted to heat. It is important to consider the thermal impacts resulting from surrounding enclosures when designing a new system. Even small amounts of heat can cause a significant temperature rise to an enclosure's airspace.

This paper presents a straightforward approach for evaluating the impact of installing a Morningstar GenStar MPPT solar charge controller inside of a common sealed enclosure. The controller's heat sink temperature can be predicted given known system characteristics including; maximum expected solar array power, battery configuration, enclosure size, enclosure construction, the controller's power conversion efficiency, and maximum expected outdoor temperature. After completing the calculation, system designers can verify that the forecasted heat sink temperature falls under the GenStar's self imposed derating temperature limit. In addition, best practices for thermal management are provided to help designers optimize their designs.

Introduction

Choosing a solar charge controller for an off-grid application generally starts with an evaluation of the electrical needs of the load, then sizing a photovoltaic array with a battery bank accordingly. A controller can be selected with compatible electrical ratings and desired features to ensure the system's energy requirements will always be met. However, high temperatures at the site have the potential to limit operation. Since controllers can be hottest during peak conditions when they are working the hardest, thermal shutdowns due to poor system planning can significantly reduce the amount of energy collected. The prudent system designer should consider a controller's thermal ratings and its temperature behavior in the destination environment.

Ensuring that your controller will remain below a temperature threshold during worst-case environmental conditions can be tricky. The maximum temperature at the installation site is hard to predict. There are many environmental factors beyond outside air temperature that impact a controller's operating temperature including; enclosure surrounds, nearby airflow restrictions, solar heat gain on the installation, and wind conditions, just to name a few.

In an ideal world, system designers would create a heat transfer simulation of their proposed layout using software to account for all environmental factors and heat sources. However, this is not realistic for many. Project time constraints and lack of access to expensive thermal modeling packages often prevent this from being a practical approach.

In recognition of this issue, Morningstar presents a simplified method for conducting a thermal forecast of a GenStar MPPT solar charge controller operating inside an enclosure. It assumes the enclosure is shaded, without wind, with uniformly distributed internal air, and adequate spacing around the enclosure. Although not all real world environmental factors can be accounted for when using this procedure, it is a convenient way to identify potential overheating conditions early in the design process. System designers can impose additional safety factors when performing the calculation to ensure adequate margin is provided for unrepresented environmental factors.

Enclosure Mounting

Experience shows that a major temperature influence on controller operation results from the effect of enclosure surround. Morningstar's controllers are typically installed within a protective electrical enclosure, often with other devices that dissipate heat. As a result, the internal enclosure air temperature rises over the outdoor temperature during normal operation. The controller(s) and other devices inside run hotter due to this hotter air temperature surrounding them. Accounting for the enclosure is crucial for ensuring continuous operation of the system during peak temperature days.

Controller Operation

The GenStar MPPT's robust thermal design dissipates heat quickly and reduces the operating temperature of its key electronic components. The amount of heat dissipated is equivalent to how much energy is lost during power transfer inside the controller. The higher the controller efficiency, the higher the usable energy, and the lower the waste heat.

For a proper system design, one must consider a controller operating in worst-case environmental conditions. The goal is to ensure that the maximum temperature experienced by the GenStar's heat sink remains under a safe limit, while ensuring maximum charging current is maintained. Should the temperature threshold be exceeded, the controller is programmed to automatically derate output power level to reduce onboard temperatures. This way, the life of the controller is maximized and your investment is protected.

Below is a graph of the derating curves for GenStar MPPT models. As can be seen, the 60 Amp, 80 Amp, and 100 Amp models all begin to thermally derate battery charging current when the detected heat sink temperature reaches 80°C. There is a linear derate from 80°C to 90°C. At 90°C, charging current will completely pause until temperature conditions improve. If 95°C is reached due to load output and outside influences, the system will completely shut down for protection.

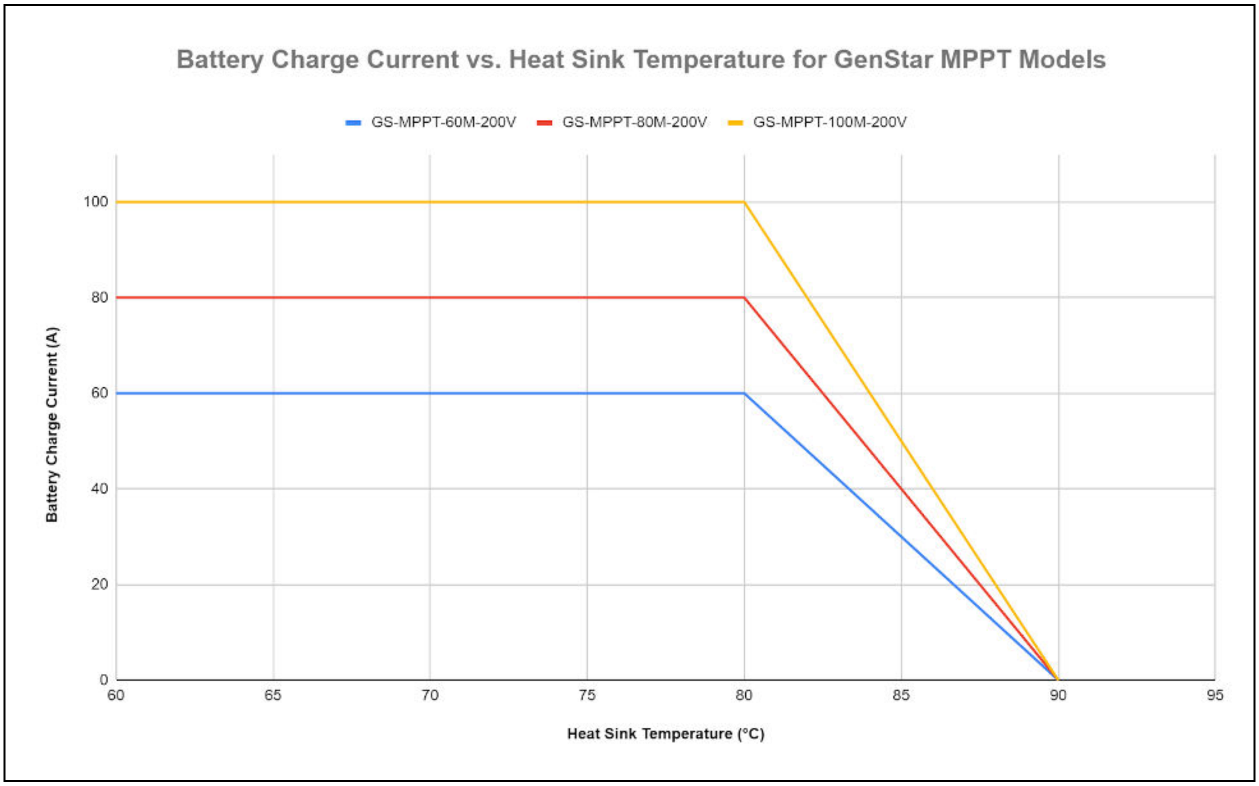


Figure 1. Battery Charge Current vs Heat Sink Temperature for GenStar MPPT Models

Calculation Steps

The procedure for evaluating the thermal performance of your GenStar MPPT in an enclosure breaks down into four primary steps:

1. **Determine the heat dissipation of the controller.**
2. **Determine the temperature rise of the enclosure's internal air ($\Delta T_{AIR\ RISE}$).**
3. **Determine the heat sink temperature rise of the controller ($\Delta T_{HS\ RISE}$).**
4. **Compare the heat sink temperature against controller derating limits.**

1. Determine the heat dissipation of the controller

Since the GenStar MPPT is designed to be compatible with a large range of PV input voltages and nominal battery output voltages, the amount of heat loss during conversion is a function of the system configuration. Calculating an accurate heat dissipation figure involves determining the controller power conversion efficiency based on V_{mp} (voltage at maximum power) and P_{mp} (maximum power) parameters.

Morningstar publishes each controller's efficiency curves in their respective operating manual. The GenStar MPPT manual includes all efficiency graphs in *Section 9.0, Technical Specifications*. The same graphs are included in Appendix A of this document for convenience. For each GenStar model, there are unique performance graphs for nominal battery voltages of 12V, 24V, and 48V. Within each graph, several curves are shown when charging from different PV operating voltages (Vmp). The X-axis is the output power in Watts, and the Y-axis is the controller efficiency percentage. An example of one of these graphs for a 100 Amp GenStar model connected to a 12V battery is shown in Figure 2.

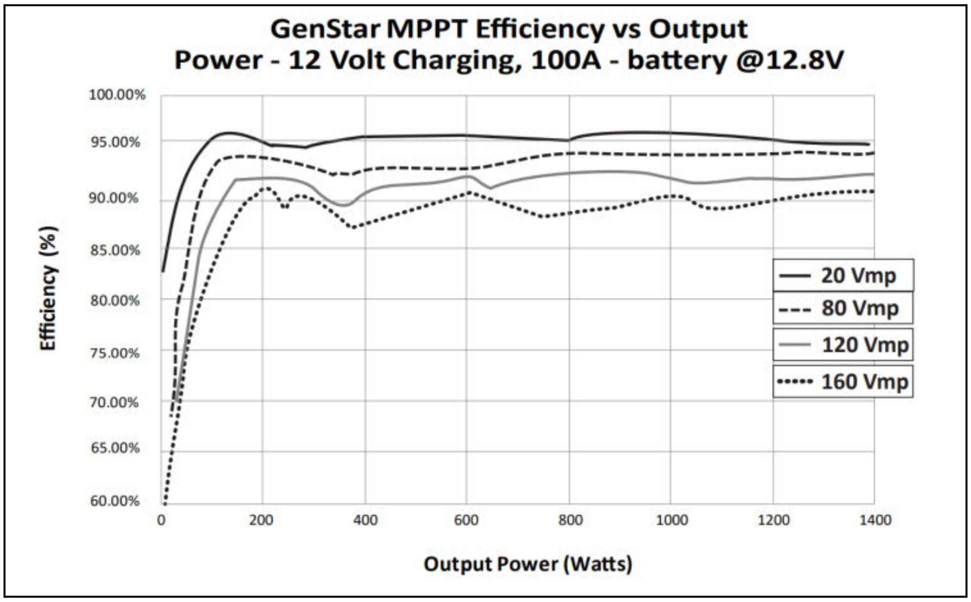


Figure 2. Example Efficiency Curves for the GS-MPPT-100M-200V Operating With a 12V Battery Output at Various PV Array Voltage Inputs

The system designer can determine their array's corresponding V_{mp} and P_{mp} based on knowledge of their chosen PV module's I-V curve and array configuration. Then the appropriate efficiency graph corresponding to the intended GenStar model/nominal battery voltage can be selected. A power conversion efficiency percentage can be determined from the graph corresponding to the operating setpoint of V_{mp} and P_{mp}.

Note, P_{mp} of the array is actually the input power from the controller's perspective. Morningstar's efficiency plots are published with output power on the X-axis to align with industry standards. However, since the efficiency curves are typically flat throughout the usable range, it is still acceptable to use P_{mp} to perform the lookup for determining controller efficiency.

Now, by knowing the controller efficiency and P_{mp} fed to the controller, the thermal loss (Watts) is calculated as follows:

$$Heat\ Dissipation = (100 - Efficiency\,\%)/100\ \times Pmp$$

One may consider the ambient temperature when determining array voltages and power levels because higher temperatures decrease voltage of the PV array. Other factors such as temperature rise influences from mounting can also play a role, but they are not covered in this document. These drops in real world PV power correlate with a reduction of waste heat generated by the controller. Using the STC power level of the array will typically be a conservative estimate to use.

2. Determine the temperature rise of the enclosure's internal air ($\Delta T_{AIR\ RISE}$)

A graph is provided in Figure 3 (originally sourced from a technical briefing published by Hoffman Enclosures Inc.) for determining the internal air temperature rise of a simple sealed enclosure with internal heat generation.

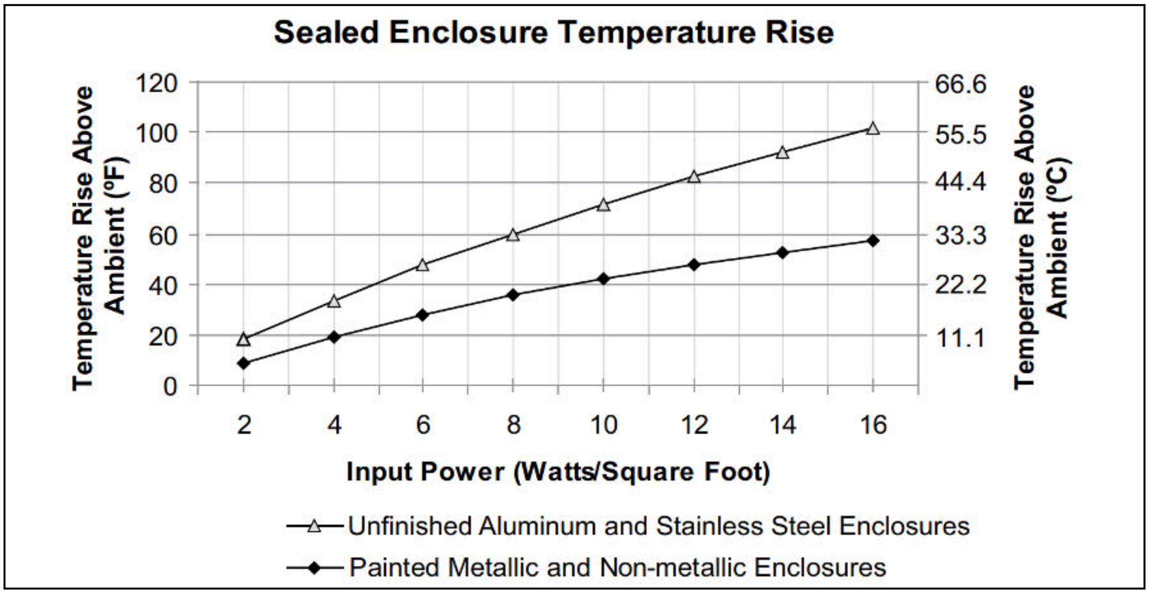


Figure 3. Sealed Enclosure Temperature Rise vs. Power Dissipation

Source: Hoffman Enclosure Inc.'s technical briefing titled "Heat Dissipation in Electrical Enclosures"

The graph correlates internal air temperature rise on the Y-Axis and heat flux (W/ft^2) across all surfaces of the enclosure on the X-Axis. To calculate the enclosure heat flux for your application, perform the following:

- Determine the type of enclosure that best matches the intended choice.
    - Unfinished Aluminum and Stainless Steel Enclosures
    - Painted Metallic and Non-Metallic Enclosures

  Note, higher temperatures can be expected with the unfinished aluminum/stainless steel due to the material's lower radiant heat transfer. Choosing from the 'unfinished' curve can be the conservative choice for this calculation if unsure.

- Calculate the total surface area of all heat dissipating surfaces of the enclosure. Be sure to convert units to feet to correspond with the graph in Figure 3. The basic formula for calculating the area of a six sided enclosure is:

  $$Surface\ Area = 2 \times (Width \times Height) + 2 \times (Depth \times Height) + 2 \times (Width \times Depth)$$

  Morningstar recommends that the enclosure's mounting surface be ignored as a heat transfer surface to remain conservative.

  For Ground Mounted Enclosures:

  $$Surface\ Area = 2 \times (Width \times Height) + 2 \times (Depth \times Height) + 1 \times (Width \times Depth)$$

  For Wall Mounted Enclosures:

  $$Surface\ Area = 1 \times (Width \times Height) + 2 \times (Depth \times Height) + 2 \times (Width \times Depth)$$

- Sum the controller heat dissipation calculated in Step 1 with any other heat dissipation sources to be located in the enclosure.

- Divide the total heat dissipation by the surface area of the enclosure.

- Using the graph in Figure 3, determine the temperature rise of the internal enclosure air over ambient (outdoor) temperature ($\Delta T_{AIR\ RISE}$).

3. Determine the heat sink temperature rise of the controller ($\Delta T_{HS\ RISE}$)

The GenStar MPPT heat sink's temperature rise over ambient ($\Delta T_{HS\ RISE}$) due to heat dissipation during normal operation is provided in Appendix B. It is also shown below in Figure 4 for convenience. Use the appropriate model curve to lookup $\Delta T_{HS\ RISE}$ on the Y-axis by using the heat dissipation of the controller calculated in Step 1 on the X-axis.

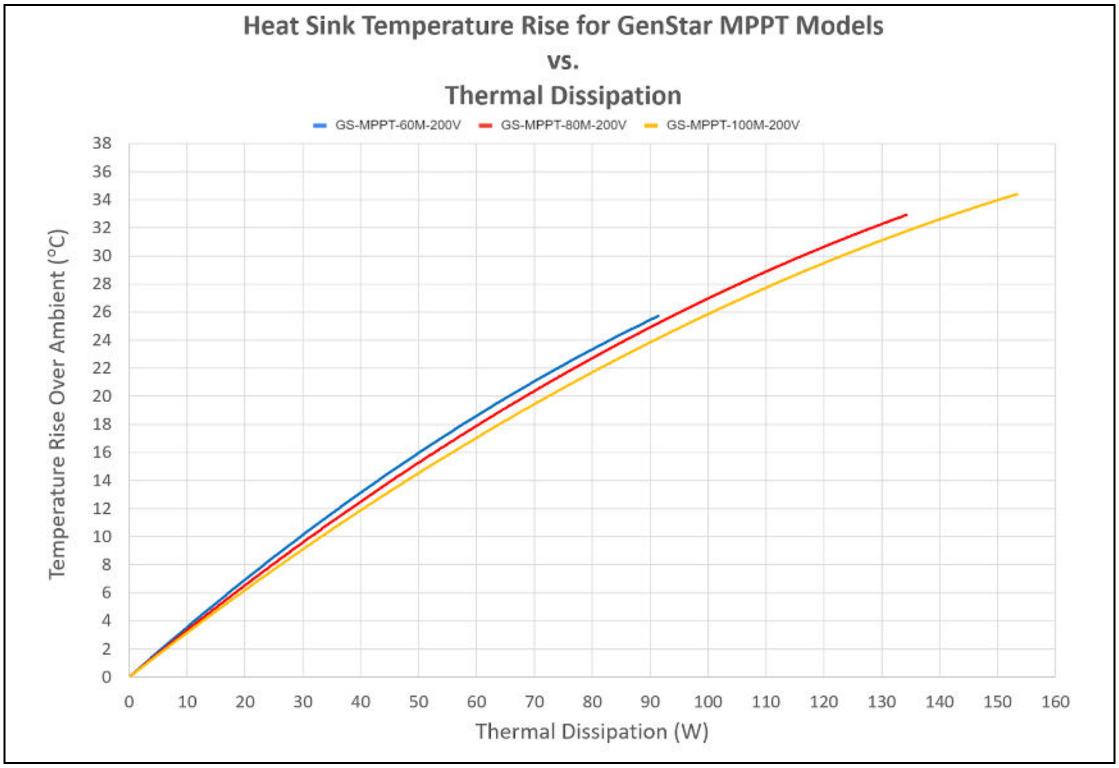


Figure 4. GenStar MPPT Heat Sink Temperature Rise (ΔT_{HS}) Over Ambient

Note, each model's temperature rise curve is projected beyond maximum achievable heat dissipation figures. Worst case maximum heat dissipation for the controller should not be inferred simply by looking at the endpoint of each curve.

4. Compare the heat sink temperature against controller derating limits

The final step is to simply add the highest expected outdoor air temperature, the temperature rise of the air inside the enclosure ($\Delta T_{AIR\ RISE}$) determined in Step 2, and the heat sink temperature rise of the controller ($\Delta T_{HS\ RISE}$) determined in Step 3.

$$T_{HS\ MAX} = T_{MAX\ OUTDOOR} + \Delta T_{AIR\ RISE} + \Delta T_{HS\ RISE}$$

Morningstar recommends that the forecasted heat sink temperature ($T_{HS\ MAX}$) should not exceed 80°C for the GenStar MPPT to ensure full output charging in any condition.

Sample Calculation

Chosen PV Module STC Ratings & Temperature Coefficients

P_{max} = 250W

V_{mp} = 32.5V Temp. Coef. of V_{mp} = -0.42 %/°C

I_{mp} = 9.24A Temp. Coef. of P_{mp} = -0.39 %/°C

V_{oc} = 39.7V Temp. Coef. of V_{oc} = -0.29 %/°C

I_{sc} = 9.83A

System Parameters

10 x 250 W Modules. 2 parallel PV source circuits, 5 series modules per circuit

Array Power (STC) = 2.5 kW

Battery System Voltage: 24 VDC Nominal

GenStar MPPT 80 Amp controller chosen

Hottest Record Temperature for Region = 36°C

Wall Mounted, Sealed Enclosure: 48” H X 36” W X 12” D,
Painted Metallic Type

Roof Mounted Array with 8” Standoffs (Cell Temp.= + 25°C above Ambient Temperature)

Thermal Dissipation from neighboring components in enclosure = 10 Watts Maximum

1. Determine the heat dissipation of the controller

A. *Determine operating temperature of solar panels*

$$\text{Cell Temp.} = \text{Ambient Temp.} + \text{Cell Heating} = 36 + 25 = 61°C$$

B. *Calculate V_{mp} of array during hottest conditions*

For the individual PV module:

$$\begin{aligned} V_{mp\ 61°C} &= V_{mp\ STC}\ X\ [(1 + (\text{Cell Temp.} - \text{STC Temp.})\ X\ (\text{Temp. Coef. of } V_{mp})] \\ &= 32.5\ X\ [(1 + (61 - 25)\ X\ (-.0042)] \\ &= 27.6\ V \end{aligned}$$

For the PV array:

$$V_{mp\ array\ 61°C} = V_{mp\ 61°C}\ x\ 5\ (\text{series string arrangement}) = 27.6\ x\ 5 = \mathbf{138\ V}$$

C. *Calculate Maximum Power (Pmp) during hottest conditions*

$$\begin{aligned} P_{mp\ 61°C} &= P_{mp\ STC}\ X\ [(1 + (\text{Cell Temp.} - \text{STC Temp.})\ X\ (\text{Temp. Coef. of } P_{mp})] \\ &= 2500\ X\ [(1 + (61 - 25)\ X\ (-.0039)] \\ &= \mathbf{2149\ W} \end{aligned}$$

D. *Use the applicable efficiency graph to determine the controller efficiency*

Refer to Section 9.0, Technical Specifications of the GenStar MPPT manual or Appendix A of this document. The 24 VDC efficiency graph for the 80 Amp model is shown in Figure 5.

Use the calculated V_{mp} and P_{mp} during hot conditions to find the approximate efficiency of the unit at those conditions. Figure 5 shows that 138 V_{mp} lands between the listed plots of 120 V_{mp} and 160 V_{mp}. At 2149 W of array power, the efficiency of the GenStar will be approximately 95%.

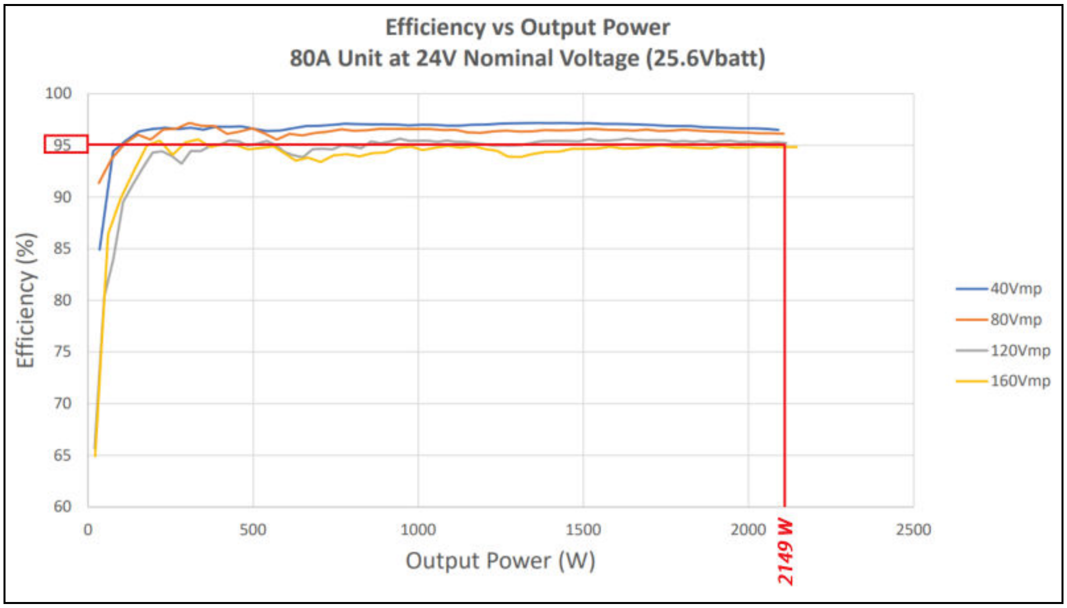


Figure 5. Power Conversion Efficiency Lookup

E. Calculate Thermal Loss of GenStar MPPT Controller

$$Heat\ Dissipation = (100 - Efficiency\,\%)/100\ \times Pmp$$

$$= (100 - 95)/100 \times 2149$$

$$= \mathbf{107.5\ W}$$

2. Determine the temperature rise of the enclosure’s internal air (ΔT_{air})

A. Type of Enclosure

Wall Mount, Painted Metallic Type

B. Surface Area Contributing to Heat Transfer

$$Surface\ Area = 1 \times (Width \times Height) + 2 \times (Depth \times Height) + 2 \times (Width \times Depth)$$

$$= (36'' \times 48'') + 2 \times (12'' \times 48'') + 2 \times (36'' \times 12'')$$

$$= 3744\ in^2$$

$$= 3744\ in^2 \times (1\ ft^2/144\ in^2)$$

$$= \mathbf{26.0\ ft^2}$$

C. Sum All Internal Heating

$$107.5\ W + 10\ W = \mathbf{117.5\ W}$$

D. Calculate Heat Flux of Enclosure

$$117.5\ W / 26.0\ ft^2 = \mathbf{4.5\ W/ft^2}$$

E. Lookup Temperature Rise ($\Delta T_{AIR\ RISE}$)

Using the Hoffman Sealed Enclosure Temperature Rise graph, it can be seen that the air temperature rise inside the cabinet is expected to be **12°C** given the internal power dissipation levels and construction of the cabinet.

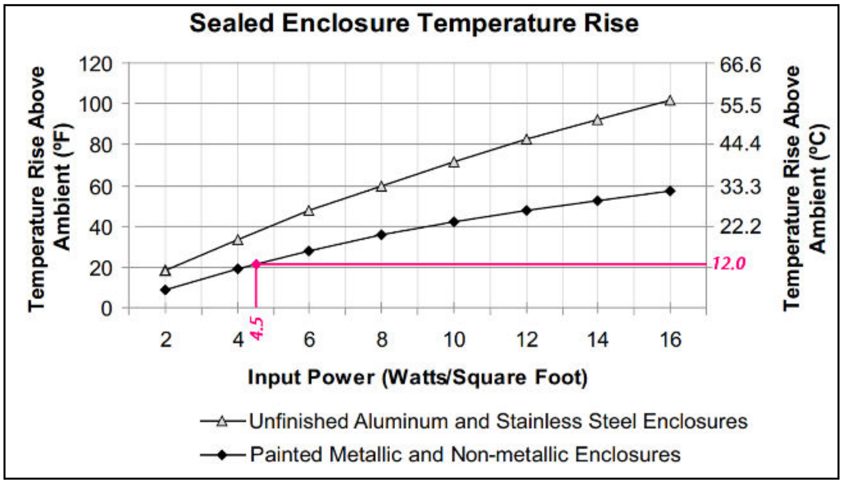


Figure 6. $\Delta T_{AIR\ RISE}$ In the Enclosure Lookup

3. Determine the heat sink temperature of the controller ($\Delta T_{HS\ RISE}$)

Using the Heat Sink Temperature Rise vs. Thermal Dissipation graph provided in Appendix B, it can be seen that the heat sink of the 80 Amp GenStar MPPT will rise by approximately **28.5°C** due to the power conversion losses of 107.5 W.

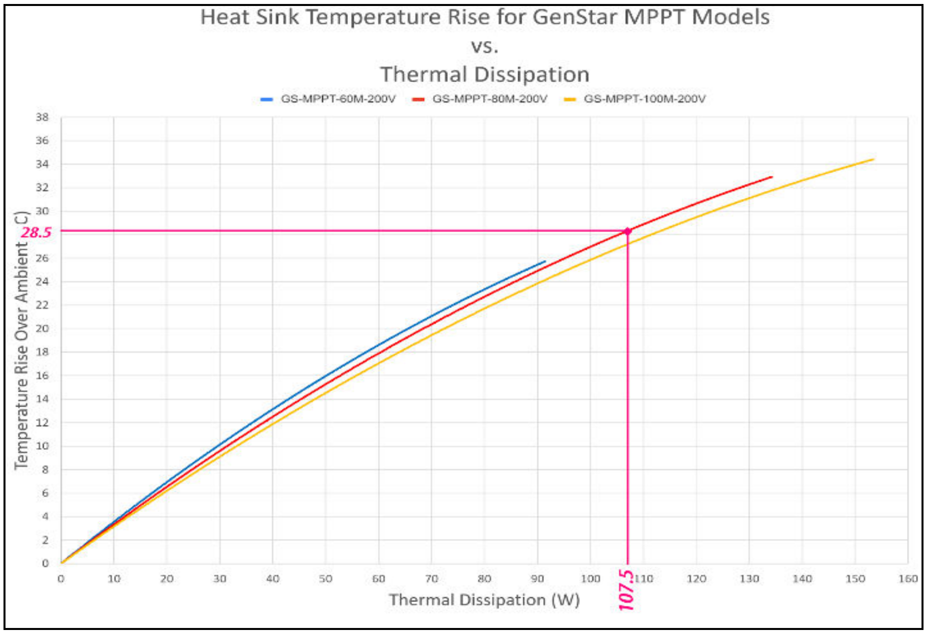


Figure 7. $\Delta T_{HS\ RISE}$ Lookup

4. Compare the heat sink temperature against controller derating limits

$$\begin{aligned} T_{HS\,MAX} &= T_{MAX\,OUTDOOR} + \Delta T_{AIR\,RISE} + \Delta T_{HS\,RISE} \\ &= 36.0 + 12.0 + 28.5 \\ &= \mathbf{76.5\,^{\circ}C} \;\; < 80\,^{\circ}C \; \boxed{\checkmark} \end{aligned}$$

Since the maximum heat sink temperature is less than 80 °C, this is considered an acceptable design. The enclosed GenStar MPPT in this example is not expected to enter into thermal derating, even for the scenario of the hottest day at full PV power. However, that leaves only about 3.5 degrees of margin which is not substantial. As described earlier in the document, there are other environmental factors that can contribute to additional temperature rise (e.g. radiation from the sun) not reflected in this calculation. The following section provides “best practices” to optimize the thermal performance of your controller and techniques to gain additional operating margin.

Thermal Management Best Practices

Morningstar Corporation is committed to supplying the solar off-grid market with charge controllers and inverters with industry leading reliability. A cornerstone of our reliability strategy involves oversizing thermal management components such as heat sinks in our designs. This enables us to offer longer warranty periods than our competition and save installers money over the total life cycle of a system installation.

A rule of thumb prevalent in the electronics cooling industry states that for every 10 degree increase in temperature, a product’s life expectancy is cut in half. In reality, the physics of failures involved with electronics is much more complicated than that ratio predicts. However, there is truth in the message and solar system designers should be aware of the relationship of temperature and lifespan of all electronics when developing new designs.

The derating scheme of the GenStar MPPT is engineered to ensure that the internal power electronics are never overstressed or damaged. This paper presented a method to ensure that the derate temperature threshold would not be reached in an enclosure on the hottest day; guaranteeing full system output year round. Even when calculations show significant margin, it is always a good idea to take as many steps as is practical to reduce installation temperatures. The following best practices represent tips and suggestions for installers to minimize temperatures and maximize the life of their GenStar MPPT.

- When mounting the GenStar MPPT inside an enclosure, ensure proper clearances are maintained as shown in Figure 19. Failure to maintain these clearances will likely result in higher operating temperatures for the GenStar than what is projected using the method in this paper.

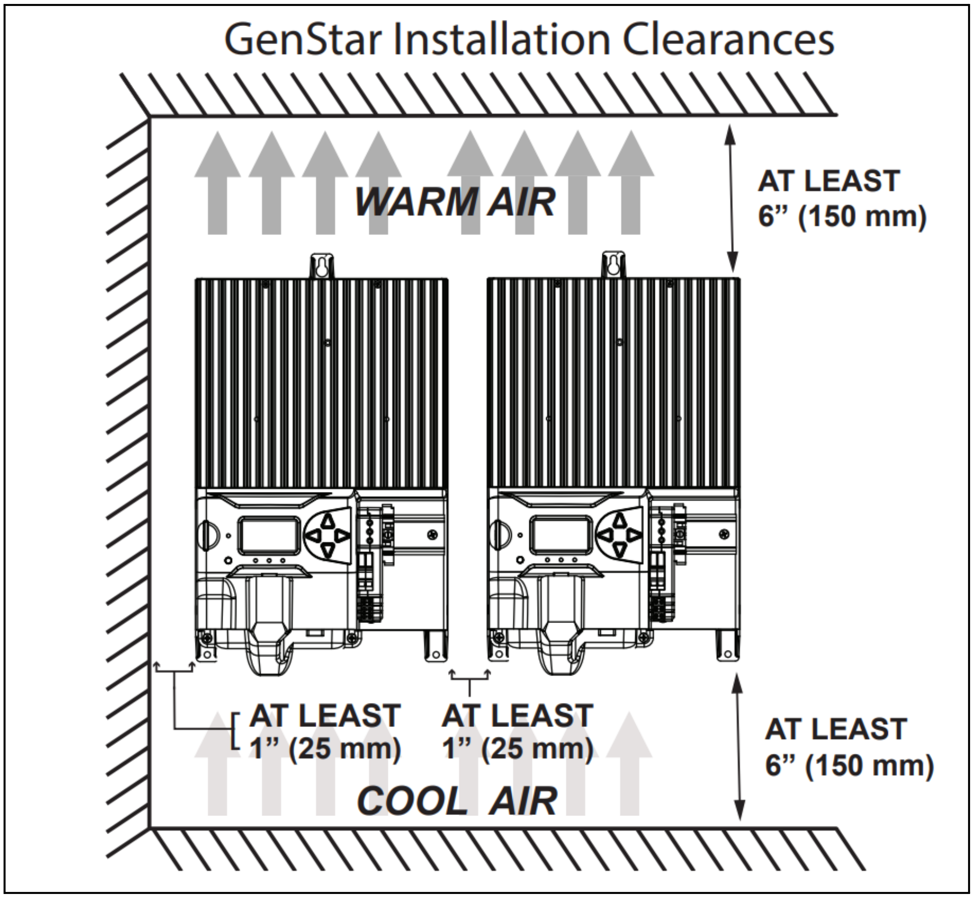


Figure 19. Required Mounting Clearances for Proper Airflow

- Due to natural convection, the air at the bottom of a sealed enclosure can be several degrees cooler than at the top, so it is better to mount towards the bottom of the enclosure.

- The GenStar MPPT is recommended to be mounted vertically on a wall as depicted above in Figure 19. The GenStar not only features a large extruded aluminum heat sink on the face of the controller, but the backside structure is manufactured as a finned aluminum casting. This casting body also plays a sizable role in dissipating heat. The buoyancy driven airflow from natural convection works best when air is allowed to rise unimpeded through the fin channels on the front and back simultaneously.

  For spatially constrained installations, mounting the unit horizontally can still work since the large heat sink on the face does the majority of the heat transfer to surrounding air. A reduction in thermal performance is expected from being horizontal. Contact

Morningstar technical support for further information regarding horizontal mounting for your application. See Figure 20 for depictions of the recommended vertical mounting orientation, the degraded horizontal mounting orientation, and improper mounting orientations.

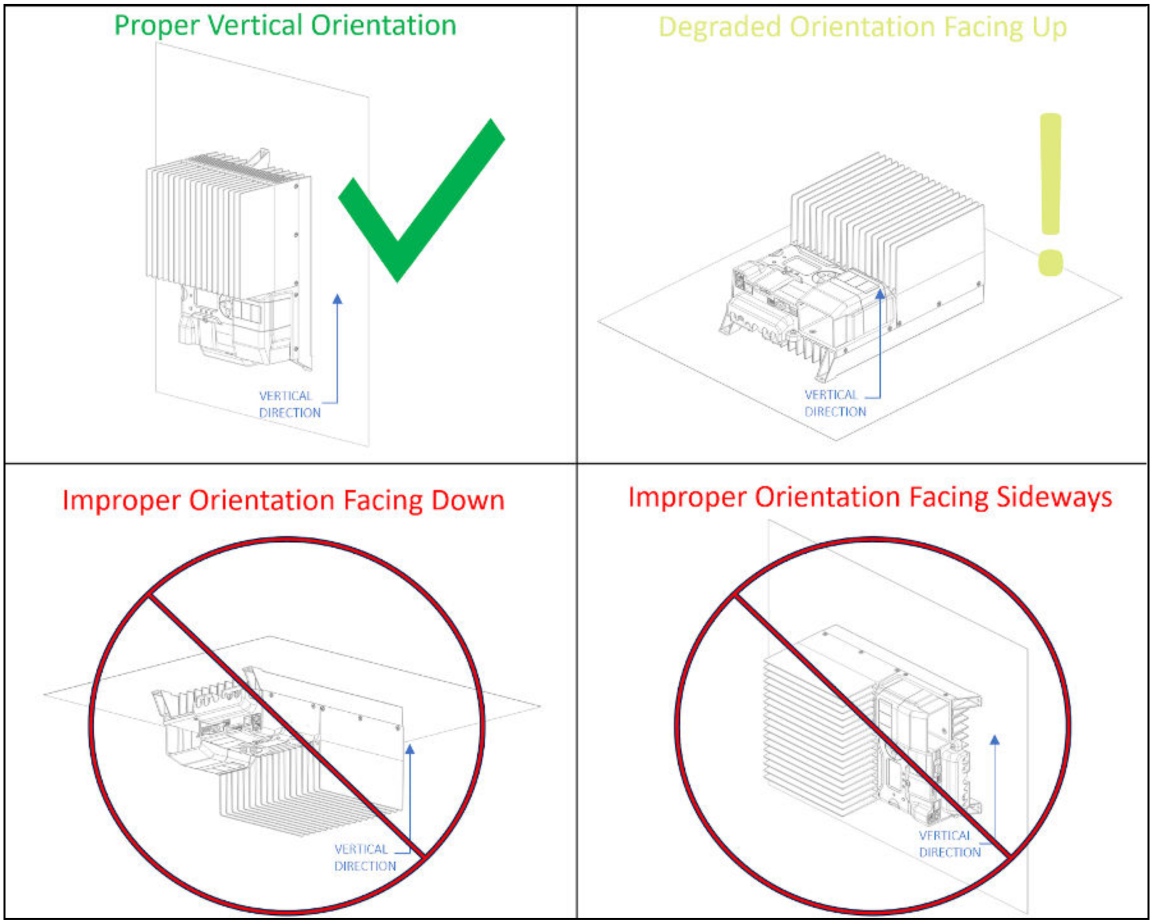


Figure 20. Proper, Degraded, and Improper Mounting Orientations

- Moving to a larger enclosure is a cost effective means for reducing internal air temperature rise if space is not at a premium. The larger the enclosure, the lower the thermal impedance to outdoor air from the controller.

- Solar heat shields are a relatively low cost method for shading an enclosure. Many electrical enclosures offer compatible shields that help reflect solar radiation, and minimize solar heat gain experienced by them.

- Using an enclosure with upper and lower ventilation is an effective passive cooling technique. Internal air temperature rise can be greatly reduced without adding additional complexity from a fan. However, ingress protection (IP) methods are necessary to avoid water or debris from entering the enclosure.

- For highly challenged temperature environments, the addition of a fan may be warranted. Even a sealed enclosure can still benefit from a fan circulating internal air without exchanging with the surroundings. A typical 120 mm axial fan only adds a modest (several Watts) of heat to the enclosure internal air space. However, there will likely be a lower enclosure air temperature overall. This is due to the enhanced convective heat transfer from the controller heat sink and to the enclosure walls, as a result of the extra velocity of the air. The forced convection from the fan also adds turbulence to the air helping to break up boundary layers along surfaces, increasing convection. In addition, a fan will mix the enclosure air and reduce temperature gradients, especially helpful if the controller must be mounted at the top of a cabinet.

  A ReadyRelay is a perfect option for directly controlling a fan. Like all Morningstar ReadyBlocks, the ReadyRelay is designed to directly mount onboard the GenStar MPPT in a seamless fashion. The ReadyRelay can be set to trigger a fan based on heat sink temperature. In this way, the life of the fan can be extended and energy harvest can be maximized for all conditions.

Appendix A - GenStar MPPT Efficiency Graphs

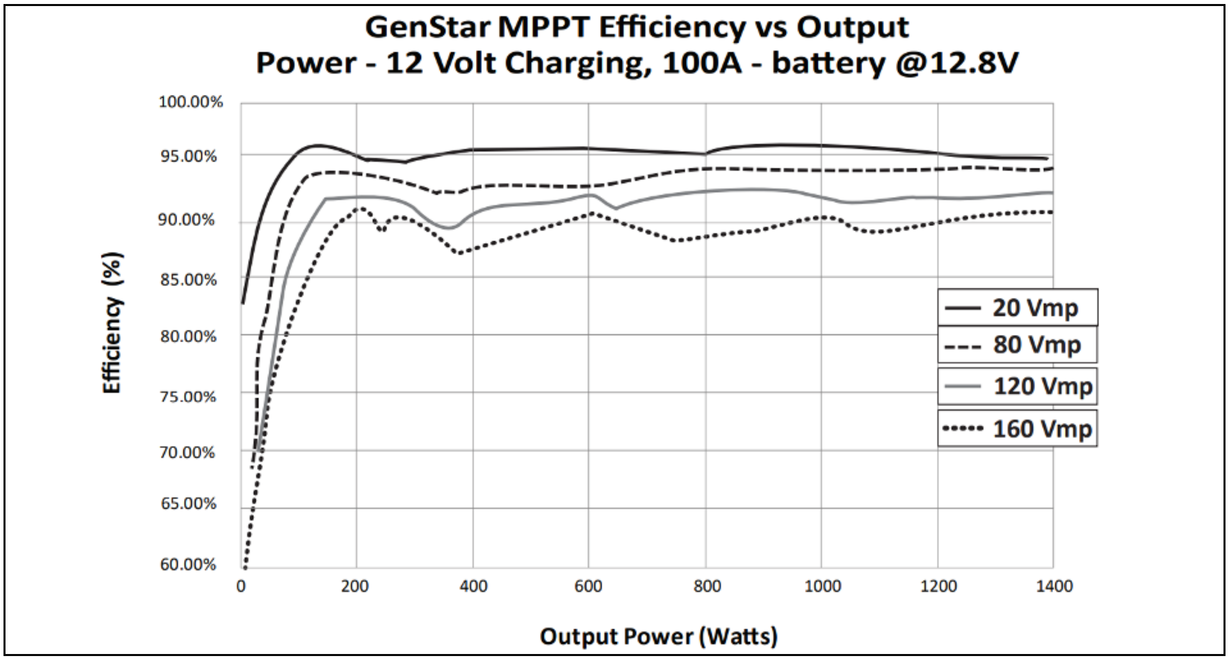
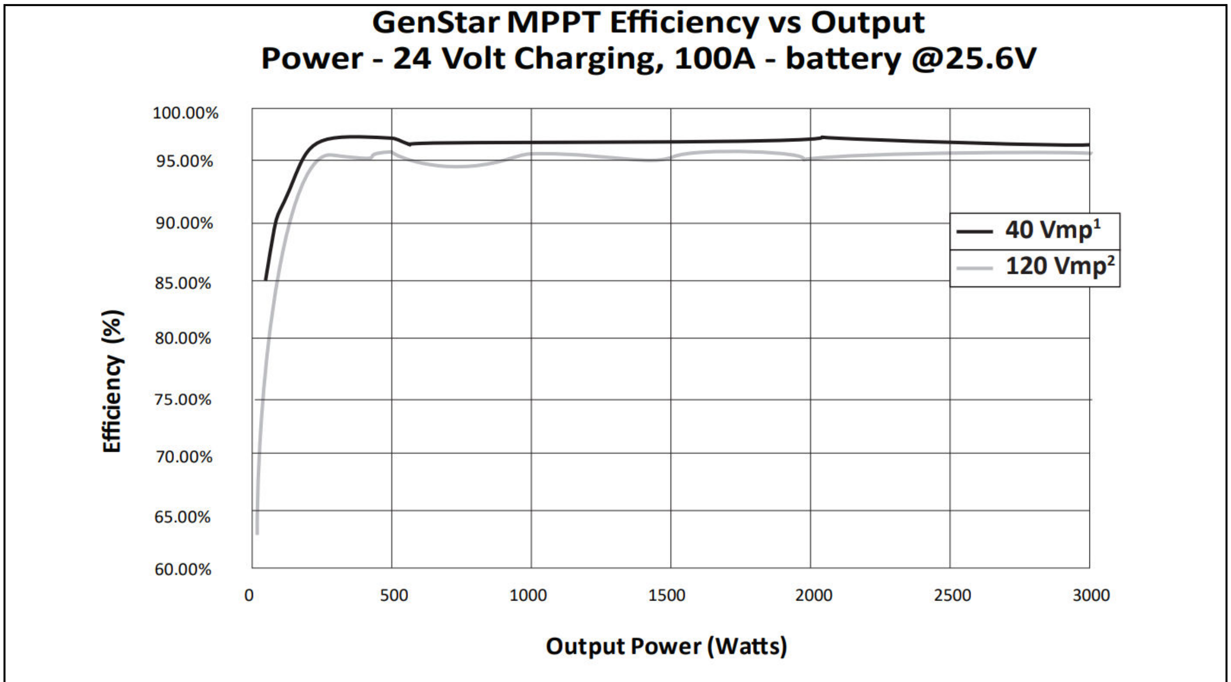


Figure 8. Efficiency vs. Output Power Curves for the GS-MPPT-100M-200V Operating With a 12 V Battery Output at 20 Vmp, 80 Vmp, 120 Vmp, and 160 Vmp Inputs



NOTES:

[1] 80 Vmp curve is very close to 40 Vmp, but most power points are slightly less efficient.

[2] 160 Vmp curve is very close to 120 Vmp, but most power points are slightly less efficient.

Figure 9. Efficiency vs. Output Power Curves for the GS-MPPT-100M-200V Operating With a 24 V Battery Output at 40 Vmp and 120 Vmp Inputs

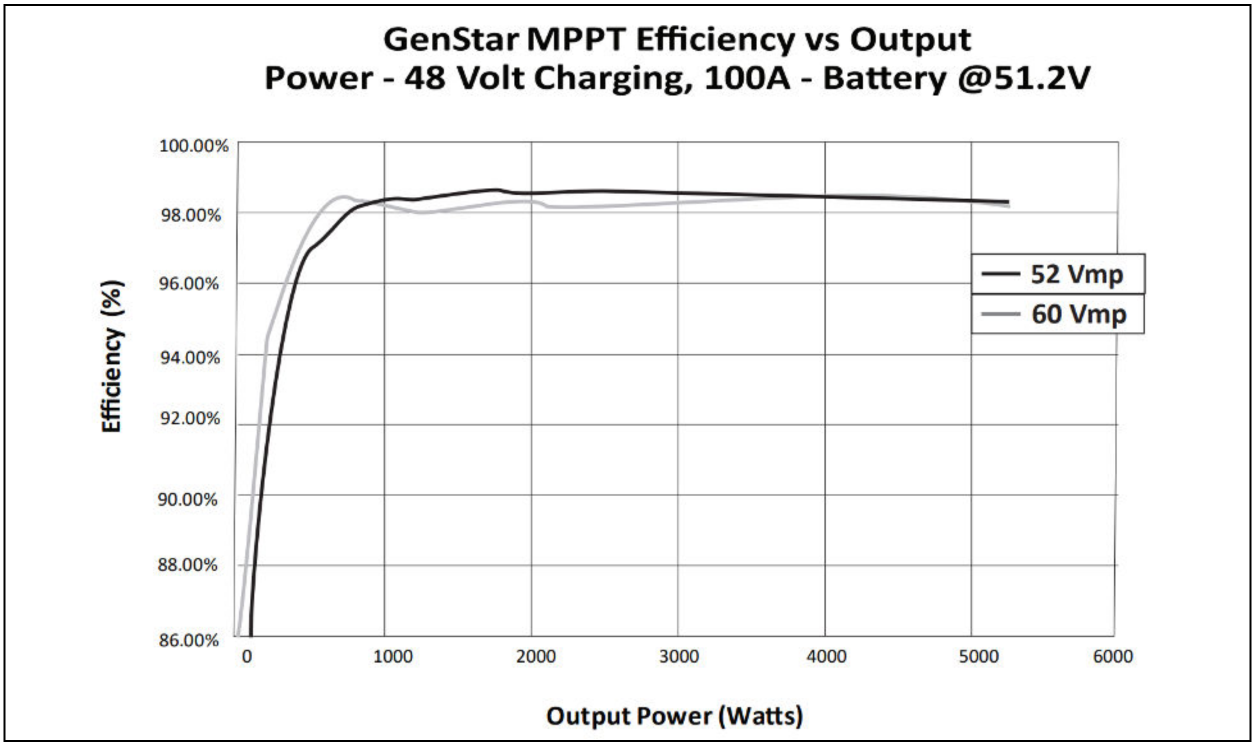
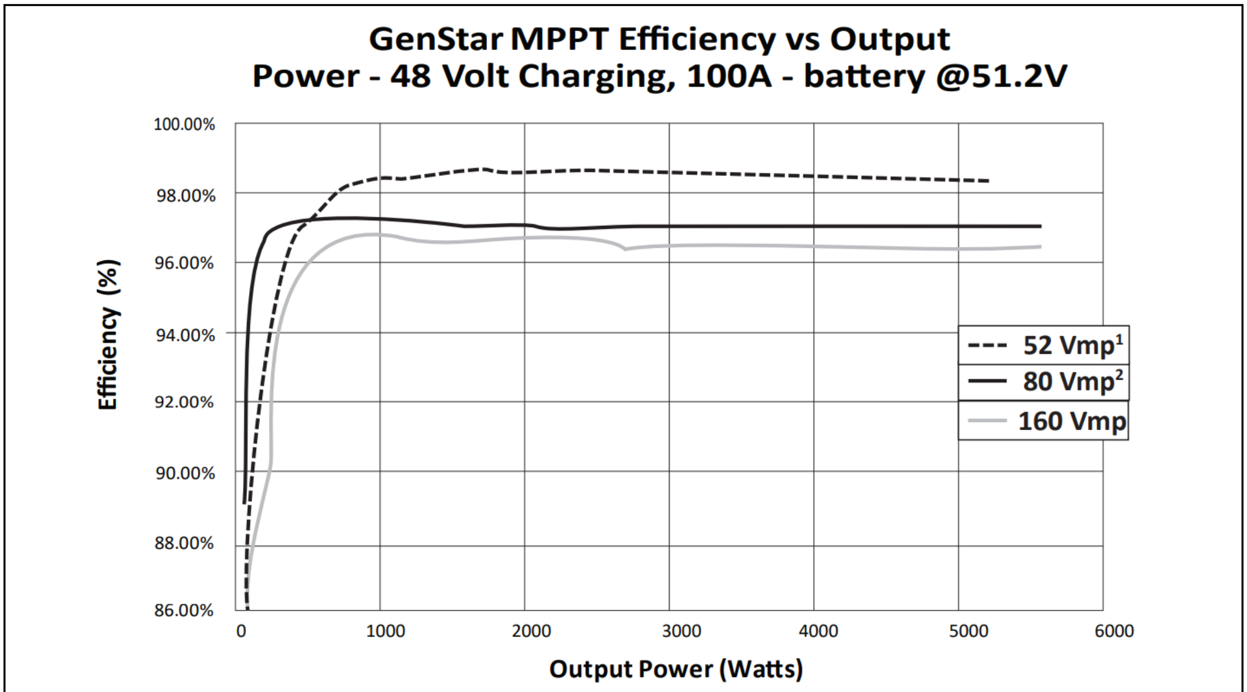


Figure 10. Efficiency vs. Output Power Curves for the GS-MPPT-100M-200V Operating With a 48 V Battery Output at 52 Vmp and 60 Vmp Inputs



NOTES:

[1] 60 Vmp curve is very close to 52 Vmp, but most power points are slightly less efficient.

[2] 120 Vmp curve is very close to 80 Vmp, but most power points are slightly less efficient.

Figure 11. Efficiency vs. Output Power Curves for the GS-MPPT-100M-200V Operating With a 48 V Battery Output at 52 Vmp, 80 Vmp, and 160 Vmp Inputs

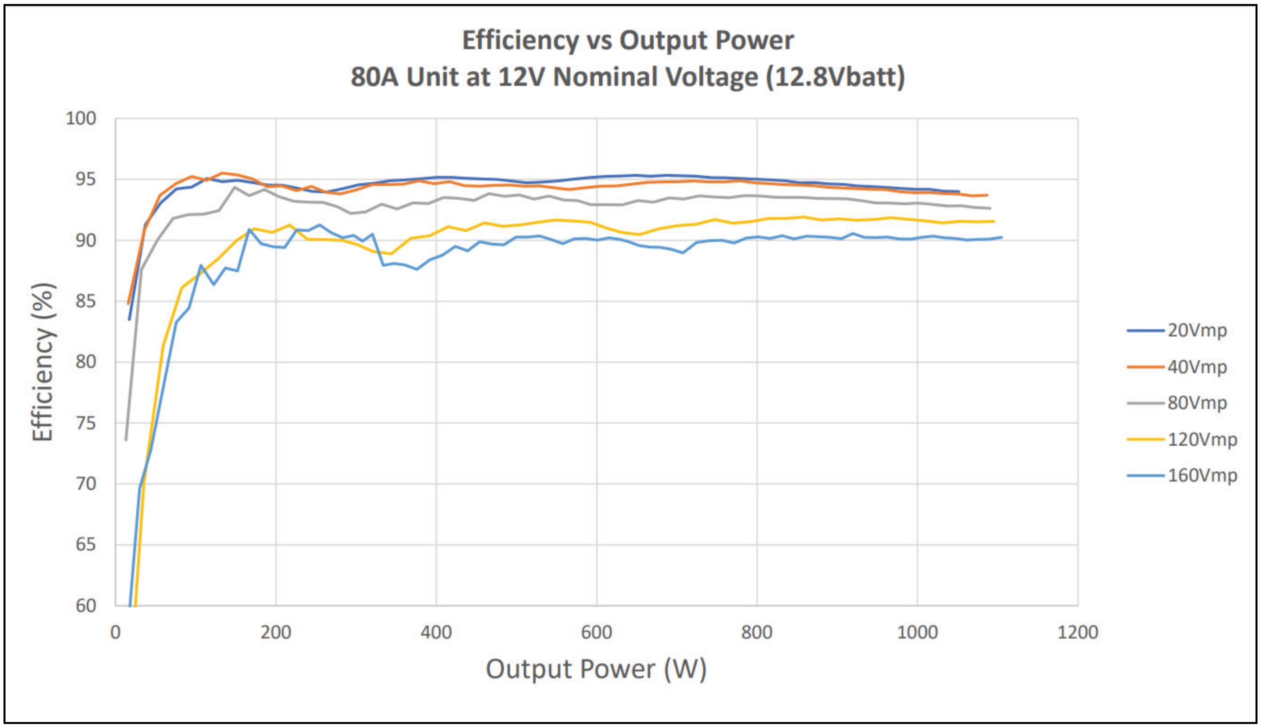


Figure 12. Efficiency vs. Output Power Curves for the GS-MPPT-80M-200V Operating With a 12 V Battery Output at 20 Vmp, 40 Vmp, 80 Vmp, 120 Vmp, and 160 Vmp Inputs

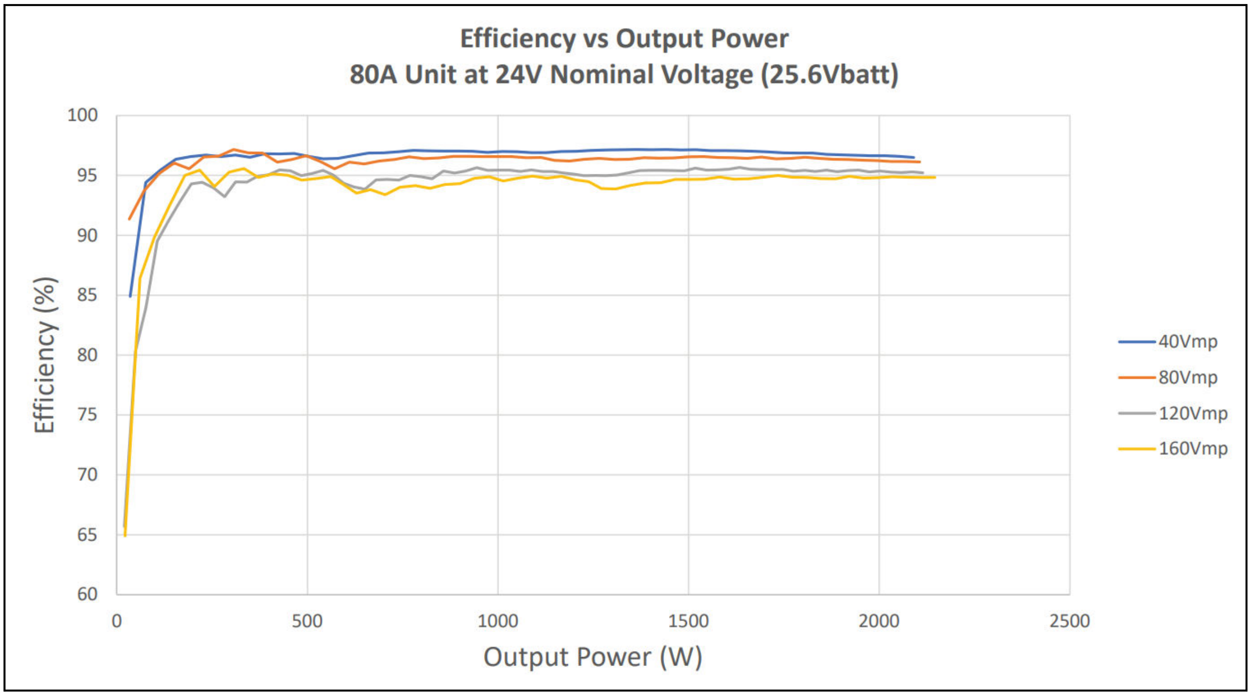


Figure 13. Efficiency vs. Output Power Curves for the GS-MPPT-80M-200V Operating With a 24 V Battery Output at 40 Vmp, 80 Vmp, 120 Vmp, and 160 Vmp Inputs

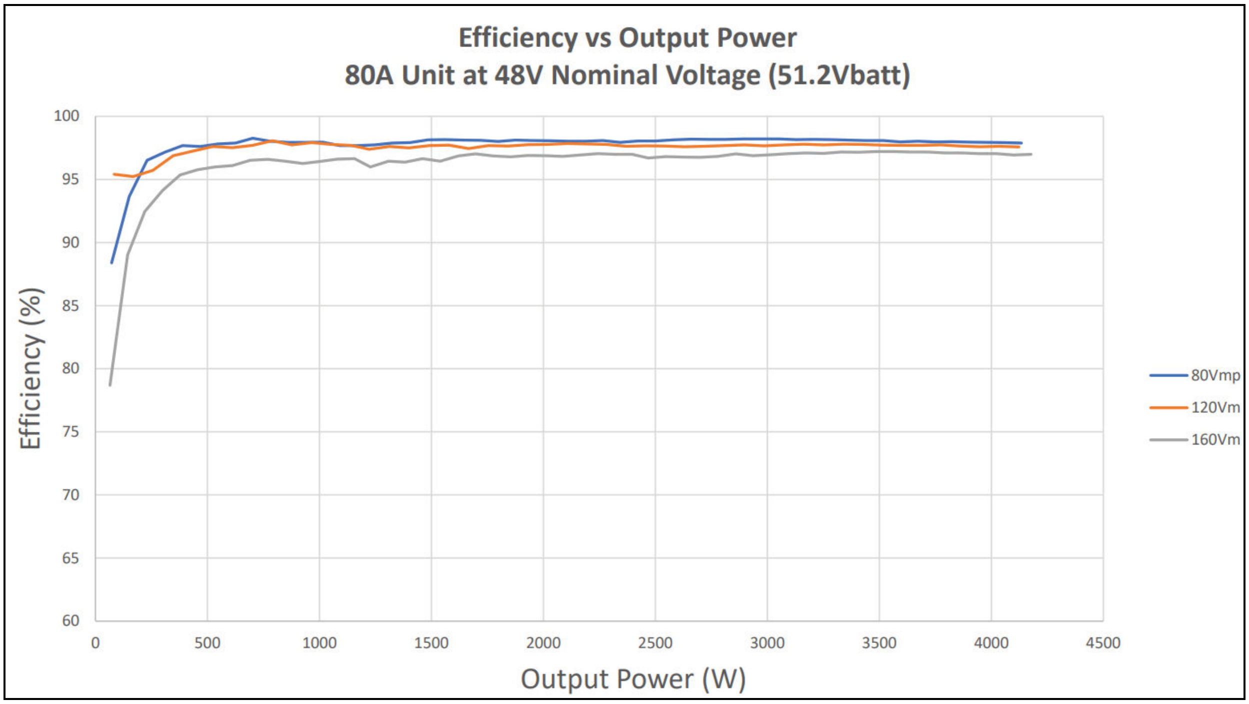


Figure 14. Efficiency vs. Output Power Curves for the GS-MPPT-80M-200V Operating With a 48 V Battery Output at 80 Vmp, 120 Vmp, and 160 Vmp Inputs

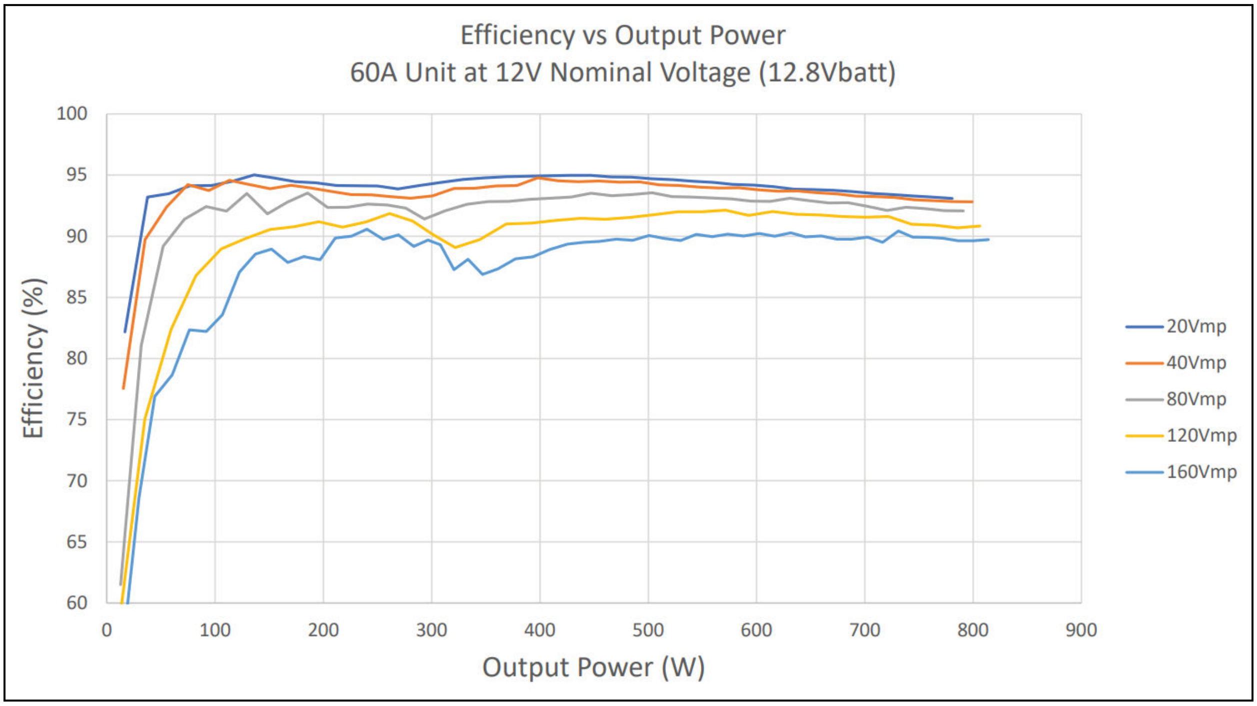


Figure 15. Efficiency vs. Output Power Curves for the GS-MPPT-60M-200V Operating With a 12 V Battery Output at 20 Vmp, 40 Vmp, 80 Vmp, 120 Vmp, and 160 Vmp Inputs

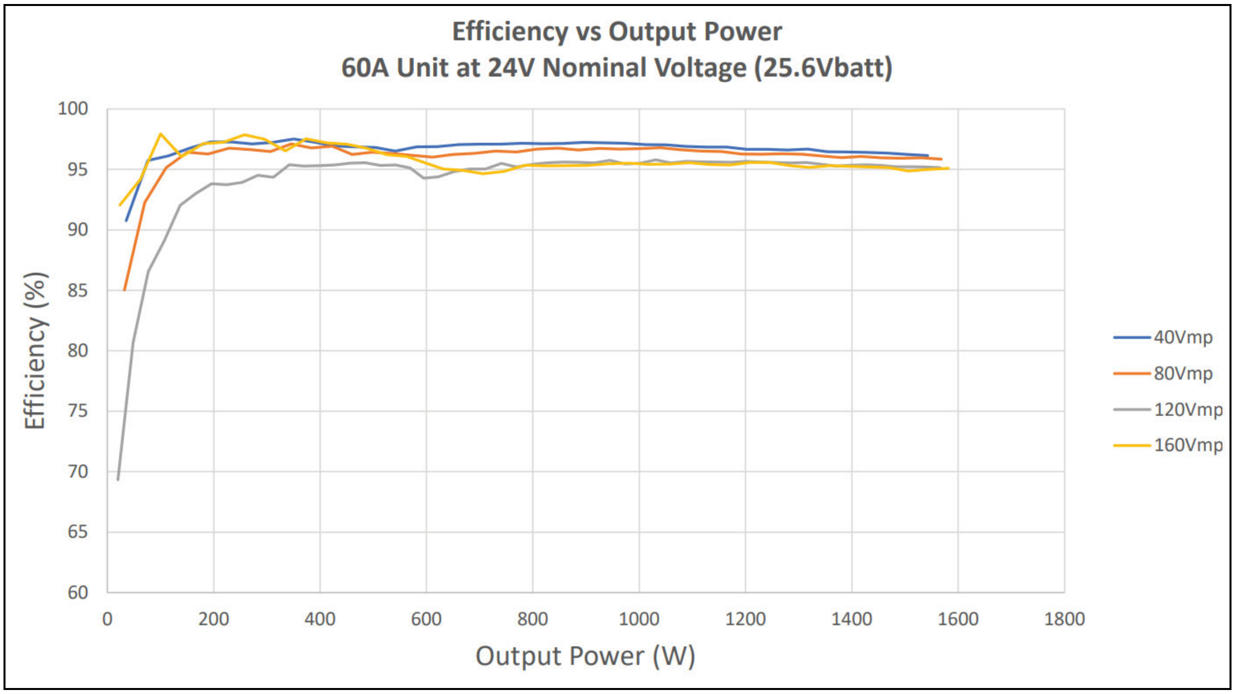


Figure 16. Efficiency vs. Output Power Curves for the GS-MPPT-60M-200V Operating With a 12 V Battery Output at 40 Vmp, 80 Vmp, 120 Vmp, and 160 Vmp Inputs

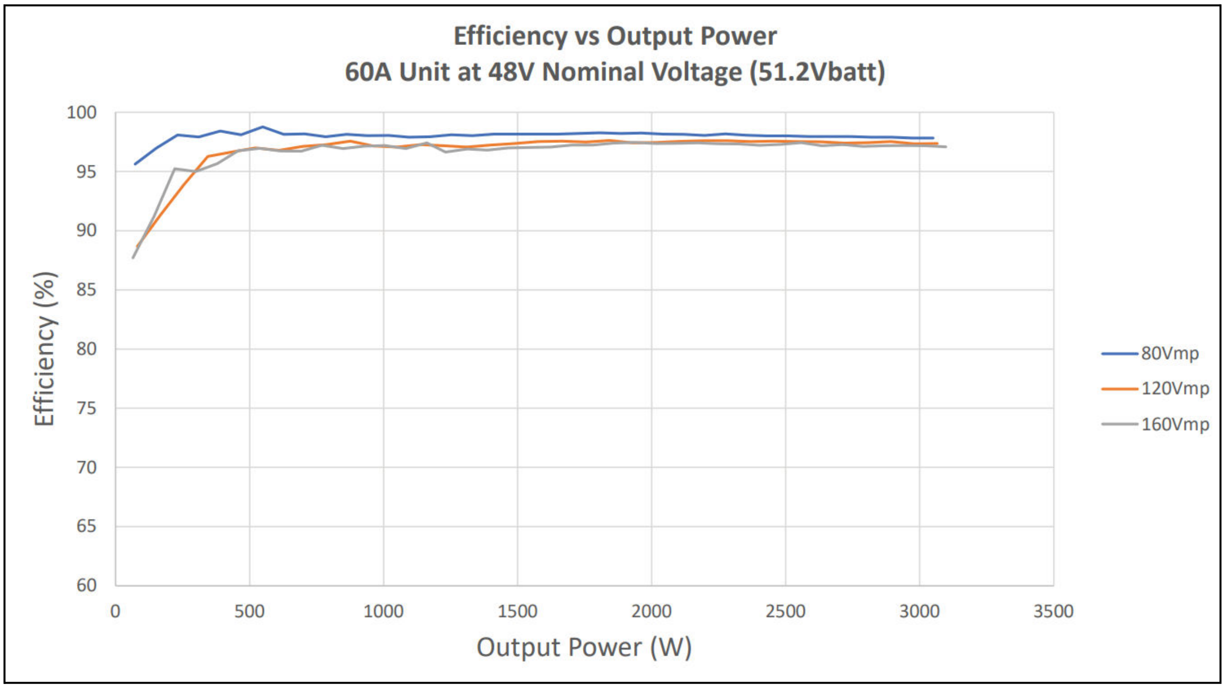


Figure 17. Efficiency vs. Output Power Curves for the GS-MPPT-60M-200V Operating With a 12 V Battery Output at 80 Vmp, 120 Vmp, and 160 Vmp Inputs

Appendix B - GenStar MPPT Heat Sink Rise vs. Thermal Dissipation

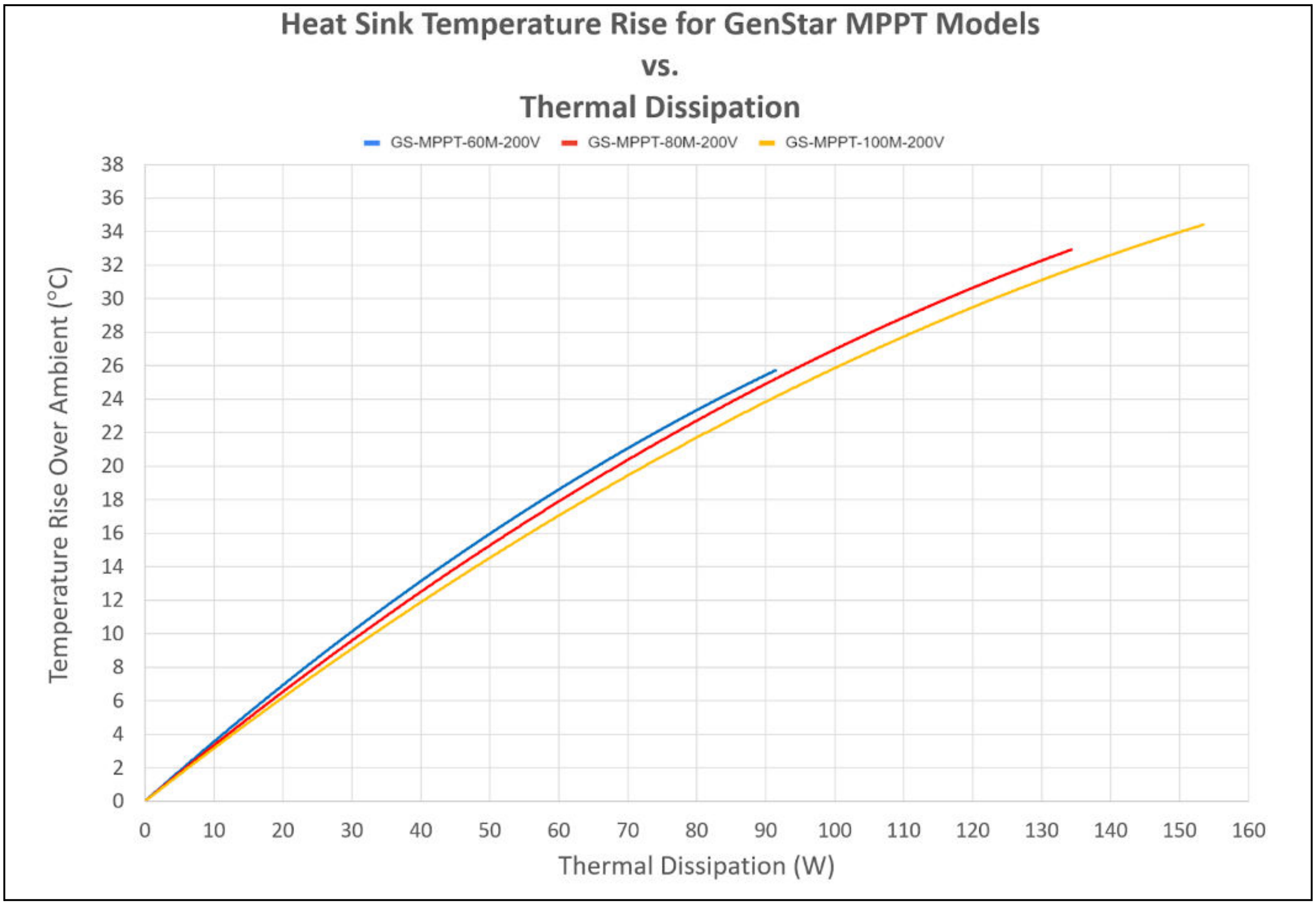


Figure 18. GenStar MPPT Heat Sink Temperature Rise (ΔT_{HS}) Over Ambient