# Tesla Solar Inverter Architecture White Paper

2022

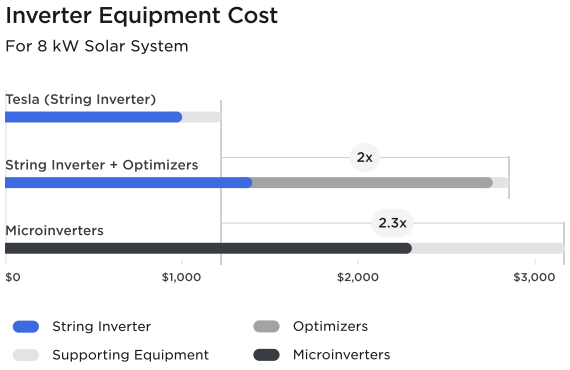
# Contents

# Executive Summary

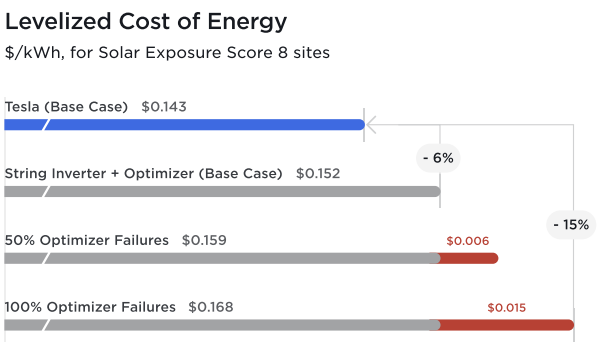
Tesla's mission is to accelerate the world's transition to sustainable energy. To speed up the adoption of solar and storage in the residential energy sector, we've focused on providing products specifically designed for both the system owner and the installer. To develop the Tesla Solar Inverter, we leveraged our deep industry experience to design an inverter that offered the best value for system owners, while being easy to install, maintain, and service.

## Value for Owners

### $1,400-$1,800 savings in up-front purchase price

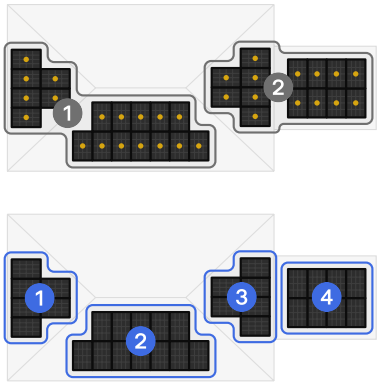



### 6-15% better LCOE and improved lifetime value

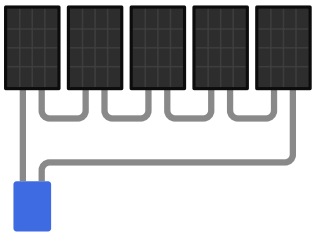



## Simplicity for Installers

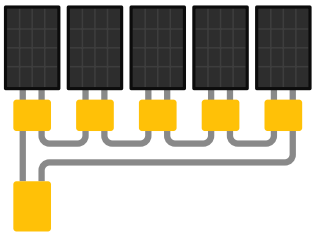
### More MPPTs maximize power, not power electronics




### Easy installation, commissioning, and service



One inverter to install



Many devices to install

## The Power of Tesla

### Inverter Expertise

**33x**

more inverters built and delivered by Tesla vs. SolarEdge and Enphase combined

### Reliability

**38%**

fewer failures compared to leading string inverter

### Scalability

**140M vs. 2.8B**

power electronic devices required to install solar on all American homes

### Ecosystem

**1**

app for the owner to manage all their home energy products

# Value for Owners

As a manufacturer, installer, and service provider, Tesla has a unique perspective on the trade-offs involved in delivering the best value to a residential solar system owner. We leveraged this broad expertise to develop a solar inverter that generates the most energy for the lowest all-in cost over the lifetime of the system.

## Levelized Cost of Energy

Throughout the design process, we examined product decisions through the lens of Levelized Cost of Energy (LCOE). LCOE characterizes the cost of energy generation over the lifetime of a system and can be used to compare the cost effectiveness of different energy generation technologies. LCOE distills the advantages and disadvantages of different solar technologies into a single metric, allowing installers and homeowners to make fair comparisons. To summarize, LCOE is the total cost of installing and owning the system over its life divided by the amount of energy it produces. The lower your LCOE (cost of energy), the better.

$$\text{Levelized Cost of Energy (\$ / kWh)} = \frac{\text{Lifetime cost of system}}{\text{Lifetime energy generation}}$$

### Factors that Impact LCOE

- Up-front cost
- Install complexity
- Energy generation
- Reliability
- Service complexity

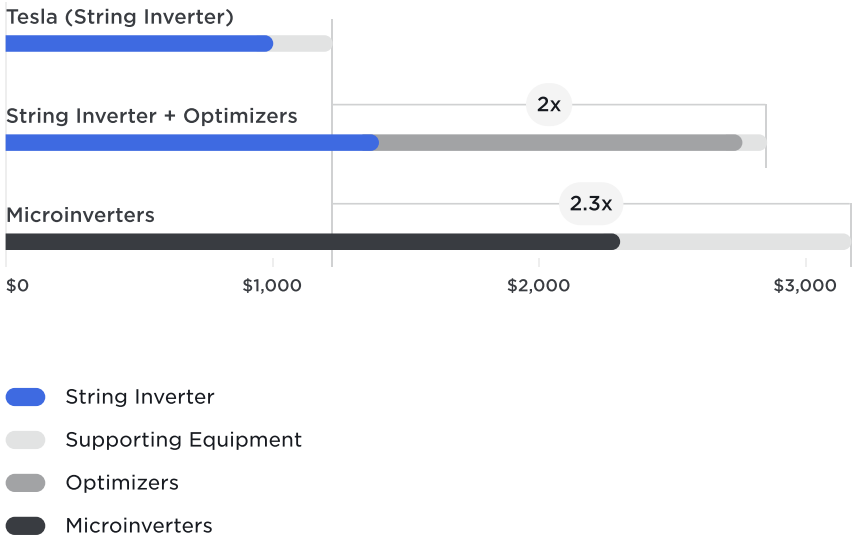
## Levelized Cost of Energy, cont.

When microinverters and power optimizers (often referred to as Module-Level Power Electronics, or MLPEs) were introduced to the solar landscape, they offered reduced LCOE by increasing energy generation.

The trade-off for that improved performance is system cost. In today's market, MLPEs cost approximately 2-2.3 times more than traditional string inverters. This higher cost may have been justifiable when equipment costs were 2-3 times what they are today[1]. However, as PV module and other solar equipment costs have dropped, inverter costs have become a larger portion of the total system cost and a more impactful driver of LCOE. With two important variables to consider, energy output and inverter cost, Tesla took a holistic approach to ensure our solar inverter would provide the best value to our customers.

### Inverter Equipment Cost

For 8 kW Solar System




[1] https://www.nrel.gov/news/program/2021/documenting-a-decade-of-cost-declines-for-pv-systems.html

## Leveraging the Tesla Fleet for Product Development

Tesla owns one of the largest residential solar system fleets in the world, which we used to design a solar inverter that would provide the best value (or lowest $/kWh) for customers. Our fleet of over 500,000 residential solar sites across the US includes inverters from many manufacturers; using data and learnings from the fleet, we chose to build an inverter architecture that leverages the best of string inverter simplicity, reliability, and cost, while still maintaining the design flexibility of MLPEs.

Tesla's inverter has four MPPT inputs, super wide voltage windows, and high efficiency. To prove the value of this approach, we further leveraged our fleet to understand how our inverter compares to other solar inverters with MLPEs.

MLPEs provide more value on sites when sun exposure is diminished, for instance due to shading, multiple mounting planes, or dormers. This has become a well-understood selling benefit of MLPEs. However, we wanted to scrutinize the data to determine what that benefit was in the real world. We analyzed a sample set of approximately 13,000 sites[2], focusing on the sites that theoretically would benefit from MLPEs.

### Summary of Tesla Fleet Analysis

| Analysis Step | Key Finding |
|---|---|
| Classify roofs with Solar Exposure Score (SES) | 80% of roofs in sample have high SES (6-10) and are "good for solar" |
| Evaluate actual performance for similar roof types | MLPEs deliver marginal benefits (1-2% more kWh) to this 80%, and larger benefits to the remaining 20% of customers with low SES |
| Evaluate LCOE for similar roofs | For "good for solar" roofs, any marginal kWh gain from MLPEs is not worth the additional costs |

[2] This sample includes sites in Tesla's fleet that achieved PTO in the first half of 2021. Comparing sites of similar vintages will control for module types, degradation rates, vegetation growth, and other characteristics that change over system life.

## Roof Characterization

The prevailing industry belief is that when site conditions (such as a complex roof) reduce sun exposure, MLPEs will have a greater impact on increasing energy generation. We began our analysis by seeking to understand what percentage of sites have conditions that would justify the cost of MLPEs. For each site in the sample set, a Sun Exposure Score (SES) was calculated by categorizing the site based on production projections normalized to the system size[3]. A site with higher projected production received a higher SES. The data showed that most homes are good for solar and have moderate to great sun exposure.

## Performance Analysis

We then assessed the real-world performance data of these sites to characterize the effects of inverter type on the system's output. We compared actual system performance data of sites with different inverter types but similar SES, ensuring only similar roofs were compared. For the homes that are good for solar (SES 6-10), sites that used optimizers saw energy production gains of 1-2% compared to homes that used Tesla Solar Inverters. When comparing the cost of Tesla Solar Inverter with MLPEs, it begged the question whether the production gains were worth the increased cost of the MLPEs.

## LCOE Comparison

To answer this question, an LCOE analysis was performed to compare two 8 kW solar systems[4]. In the base-case scenario, our analysis found that the Tesla system had a 6% lower LCOE for the most common SES[5]. We also found that, for 93% of sites in the sample, Tesla had a lower LCOE. The difference in LCOE is driven entirely by higher inverter equipment costs. Further, the gap between LCOEs for SES 8 roofs expands to approximately 15% after factoring in the potential failures of optimizers during the service life[6]. These findings prove that over the system's lifetime, the Tesla Solar Inverter will provide energy at a better value for most customers.

[3] Production projections use a standard production estimation method that takes site conditions such as shading, mounting planes, location, etc. into account to estimate the expected annual kWh production of a site.

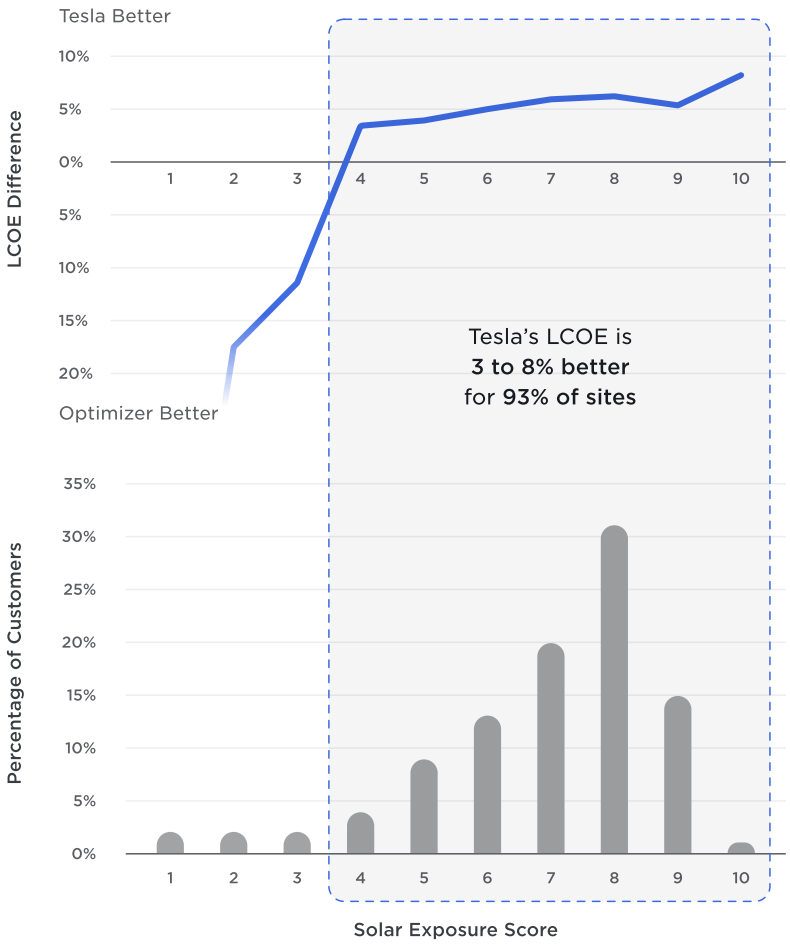
[4] Both systems have identical SES values of 8 (the most common SES), but one system uses string inverters + optimizers, and the other uses Tesla's inverter. Discount rate of 7.7% assumed, based off of discount rate used in Lazard's LCOE Analysis.

[5] Base-case scenario is defined as no inverter failures under warranty, one string inverter replacement at year 12.5 (out of warranty) for both systems.

[6] While system owners are not responsible for the cost of replacing equipment in warranty, the installer is responsible for a portion of the service costs and will include this cost in their pricing.

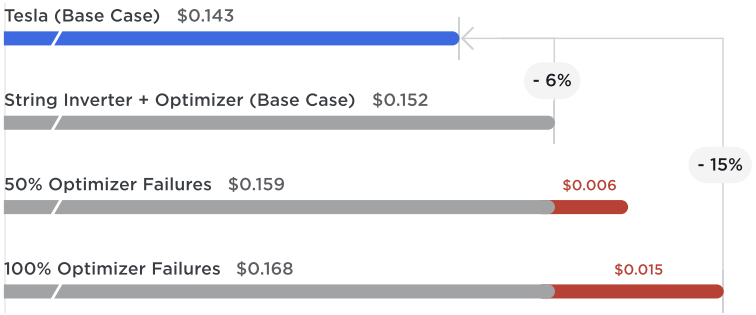
## LCOE Comparison, cont.

### Tesla vs. String + Optimizer LCOE




### Levelized Cost of Energy

$/kWh, for Solar Exposure Score 8 sites



# Flexibility for Installers

One of the more important features that MLPEs introduced to the industry was design flexibility. As installers ourselves, we deliberately designed an inverter architecture with the installer and service provider in mind. The Tesla Solar Inverter architecture offers features that improve site design flexibility and simplify the installation, commissioning, and service processes. This enables more modules on a roof, different planes of array, shading tolerance, and string length variability all without putting power electronics on the roof.

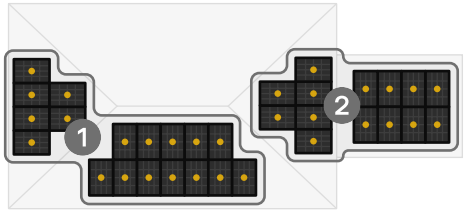
## Site Design Flexibility

The Tesla Solar Inverter architecture offers two key features that improve site design flexibility. These features provide power optimization and flexibility benefits that are better than traditional string inverters and drastically reduce the need for MLPEs.

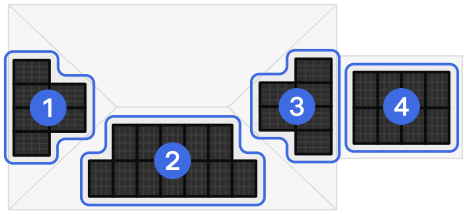
## More MPPTs

The Tesla Solar Inverter offers more MPPTs than competitive string inverters. This gives designers more flexibility to put MPPTs on different mounting planes, reducing the need for MLPEs on more complicated roofs.

Using a string inverter with only two MPPTs results in the layout in grey. This system needs to use optimizers, or the system will under perform significantly.



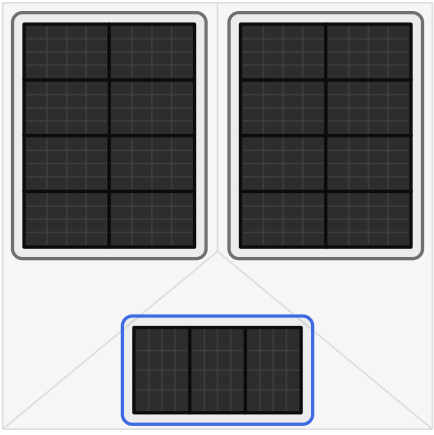

The four MPPTs in a Tesla Solar Inverter allow for the layout in blue, eliminating the need for MLPEs.




## Low Input Voltage Allows Shorter Strings

A lower minimum input voltage per MPPT allows for shorter string lengths, giving site designers more layout flexibility. Tesla Solar Inverter can have strings as short as two modules and still maintain >97% efficiency.

Designers can now place panels on roof sections that previously required MLPEs or additional inverters to optimize output; Tesla Solar Inverter can maintain efficiency for all three strings on the right, including the three modules outlined in blue.

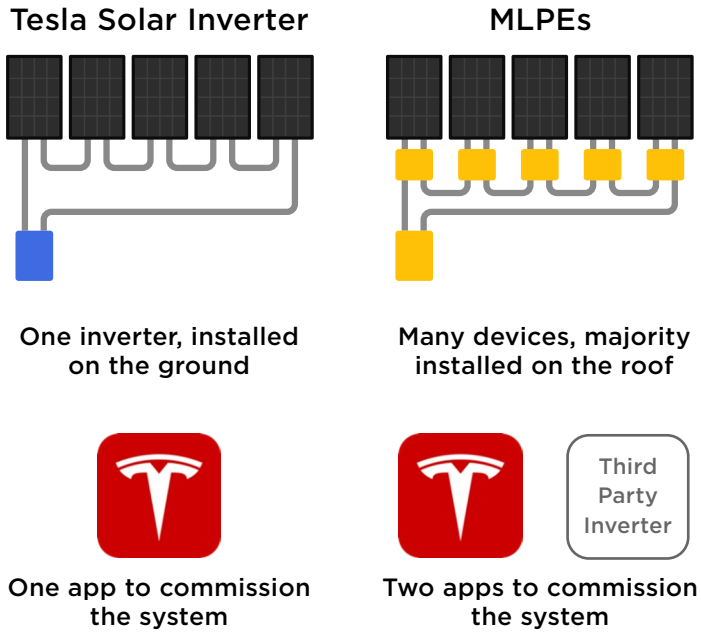


## Ease of Installation, Commissioning, and Service

The Tesla Solar Inverter allows for faster installation by simplifying the installation process. Having one string inverter instead of multiple MLPEs reduces the number of components to install, results in fewer things on the roof, and reduces the amount of wiring and connectors required, decreasing the scope of work for installation crews. Tesla Solar Inverter further reduces required wiring with an MPPT paralleling feature that allows installers to combine parallel strings on the roof and run up to 2 combined strings to the inverter.

The Tesla Solar Inverter also streamlines the commissioning process. There is only one inverter to set up instead of 10-20 MLPEs and supporting equipment. If there is an installation error, Tesla Solar Inverter has built-in cellular, Wi-Fi, and Ethernet connectivity and is easy to inspect and repair with a single unit that is accessible from the ground. In comparison, if there is a wiring or communication issue on a single microinverter or optimizer, professionals must climb on the roof and remove modules to troubleshoot and perform remediation, a physically challenging and dangerous process. If the system includes energy storage, installing Powerwall+ instead of a Powerwall 2 with a third party inverter reduces the number of unique components on site and moves all commissioning activities into a single app.

Finally, the Tesla Solar Inverter is simple to service if something does happen to the inverter during its lifetime; there is only one component, accessible from the ground, which makes it easy to locate, access, and fix. If an MLPE fails, an installer must go on the roof and remove solar panels to find and replace the faulty device.

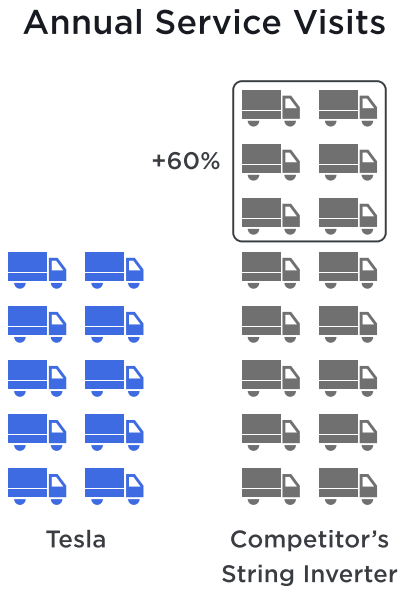


## Leveraging Inverter Expertise to Design Reliable Products

Across all vehicles and energy products, Tesla has built and delivered more than 1.4 TW of inverters. By comparison, the two leading residential solar inverter suppliers in the US have only produced 42.6 GW[7]. We specialize in power electronics, and we harnessed our expertise to produce a reliable solar inverter.

Failure data from our fleet of solar systems shows that a leading competitor's string inverter fails 60% more often than the Tesla Solar Inverter[8,9]. A Tesla system will be up and running for longer, generating more electricity and savings for its owner. Additionally, installers can expect fewer service calls and fewer trips to the field to repair or replace devices. Improved reliability reduces both hard and soft costs over the lifetime of a system. These costs can often be the most important as they're not usually well understood until a project is 7 or more years old and component failures and service visits start to add up and drive customer LCOEs higher.

The Tesla Solar Inverter architecture also reduces the number of ways the system can fail. Using one string inverter instead of an MLPE per module decreases the number of potential failure points, resulting in an overall more reliable system. Additionally, the Tesla Solar Inverter is installed near the electrical panels in what should be a relatively cool environment and has a liquid thermal management system. In contrast, MLPEs are mounted directly under solar panels on the roof and are subjected to constant extreme temperatures, reducing system life.




[7] SolarEdge: 27.6 GW, Enphase: 15 GW.

[8] Tesla sample includes inverters installed between 1/21 and 7/22. Competitor inverter sample includes inverters installed between 7/21 and 7/22. Samples have equal average age.

[9] Failure rate = # of failures in sample / # of total devices in sample. Failure rate for competitor's string inverters was 60% higher during this period.

## The Tesla Ecosystem

For the customer, Tesla Solar Inverter completes their Tesla ecosystem. System owners use a single app to monitor and manage their entire home energy system. Instead of sorting through multiple apps to make sure all devices are working properly, the Tesla app displays all Tesla products, including solar, Tesla vehicles, and charging. The intuitive app experience allows the customer to view and manage home energy usage across these devices, with the system optimizing for savings and efficiency. As new features are developed, they are automatically made available in the Tesla app, ensuring customers can unlock the full potential of their home energy system.

# Conclusion

Using Tesla's inverter architecture realizes the following benefits:

1. The best lifetime value and lowest up-front cost for system owners
2. Simplified site design, installation, commissioning, and service for installers
3. Superior reliability, supply scalability, and a full product ecosystem by leveraging the power of Tesla

We look forward to extending these advantages to installers and system owners across the world to accelerate the transition to a sustainable future.