Powerwall 3 Integrated Inverter Architecture White Paper

2024

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Executive Summary

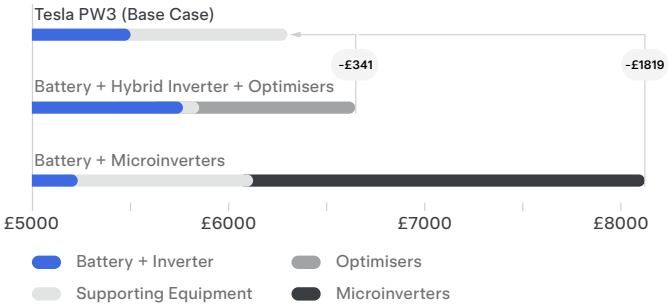
Tesla's mission is to accelerate the world's transition to sustainable energy. To speed up the adoption of solar and storage in the residential energy sector, we've focused on providing products specifically designed for both the system owner and the installer. To develop the Powerwall 3 integrated inverter, we leveraged our deep industry experience to design an inverter that offers the best value for system owners, while being easy for installers to connect, maintain, and service solar PV system.

Value for Owners

£341 - £1819 savings in up-front purchase price

Equipment Cost

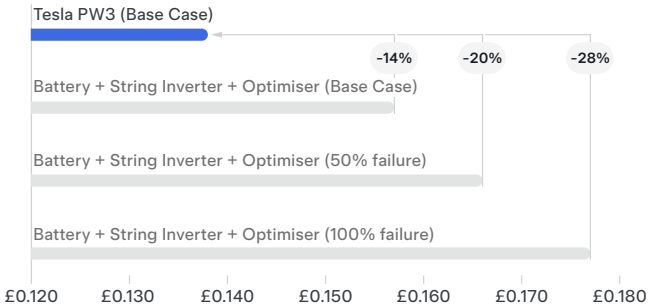
For 13.5 kWh Battery + Hybrid Inverter + 8 kW Solar System



14-28% better LCOE and improved lifetime value

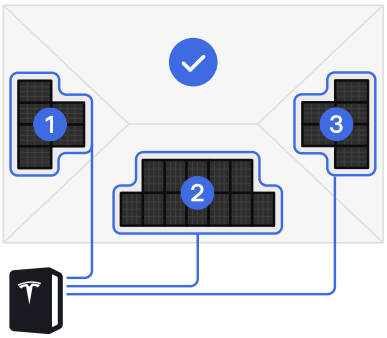
Levelised Cost of Energy (LCOE)

£/kWh, for Solar Exposure Score 8 Sites

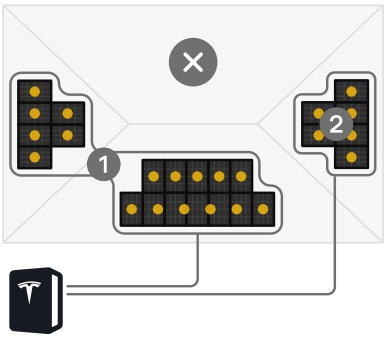


Simplicity for Installers

More MPPTs maximise power, not power electronics



One Powerwall 3 to install, commission, and service



Many devices to install, commission, and service

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 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 an integrated inverter that converts the most energy for the lowest all-in cost over the lifetime of the system.

Levelised Cost of Energy

Throughout the design process, we examined product decisions through the lens of Levelised Cost of Energy (LCOE). LCOE characterises 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 distils the advantages and disadvantages of different solar technologies into a single metric, allowing installers and homeowners to make fair comparisons. To summarise, 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.

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

Factors that Impact LCOE

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

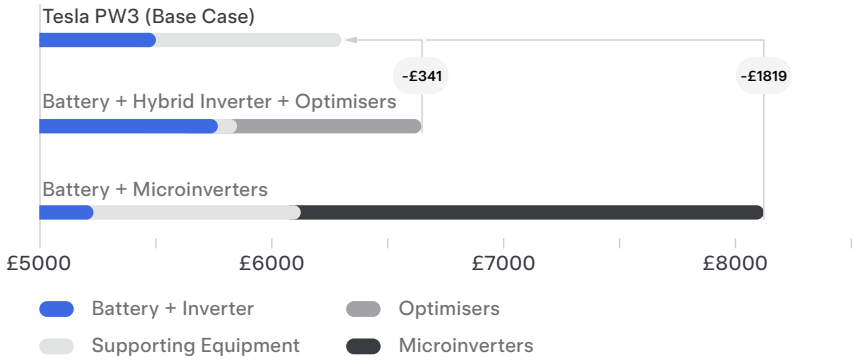
Levelised Cost of Energy, cont.

When microinverters and power optimisers (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 5-29% 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 integrated inverter with MPPTs would provide the best value to our customers.

Equipment Cost

For 13.5 kWh Battery + Hybrid Inverter + 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 an integrated 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.

The Powerwall 3 integrated inverter has three MPPT inputs, super wide voltage range, 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 scrutinise the data to determine what that benefit was in the real world. We analysed 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 permission to operate (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 Characterisation

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 categorising the site based on production projections normalised 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 characterise 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 optimisers 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 Powerwall 3 system had a 14% 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 28% after factoring in the potential failures of optimisers during the service life[6]. These findings prove that over the system's lifetime, the Powerwall 3 integrated 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.

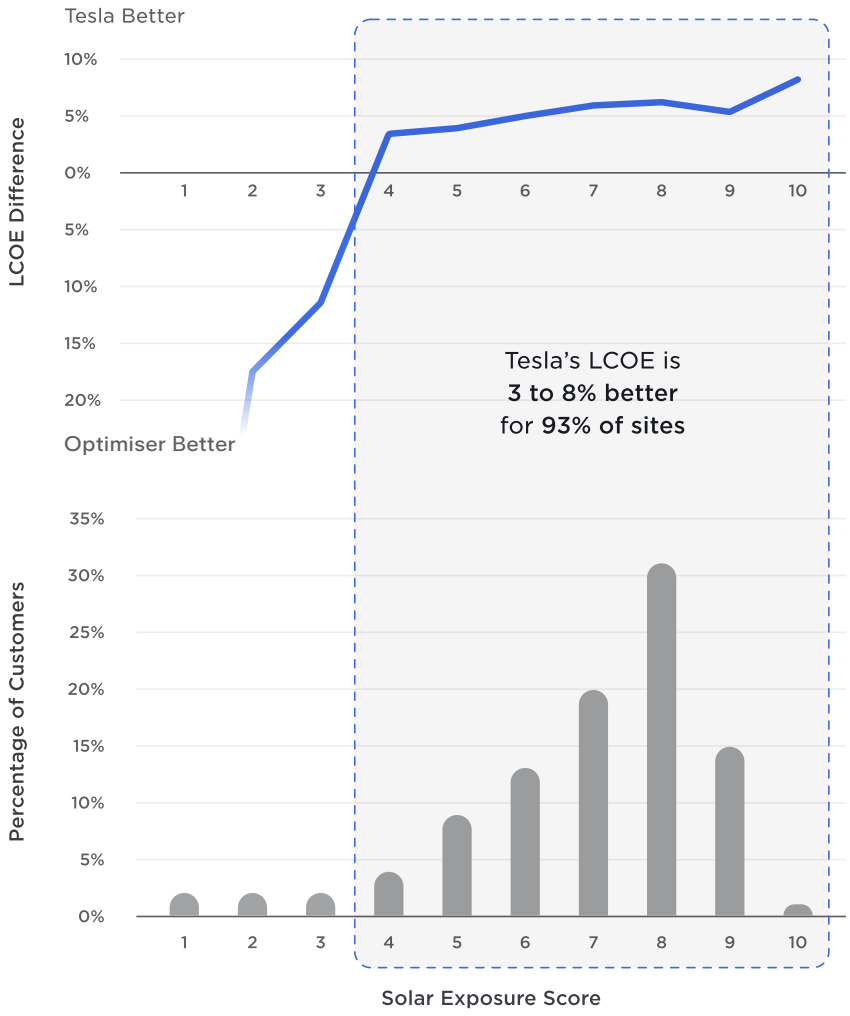
[4] Both systems have identical SES values of 8 (the most common SES), but one system uses string inverters + optimisers, and the other uses Tesla's inverter. Discount rate of 7.7% assumed, based off of discount rate used in Lazard's LCOE Analysis.

[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.

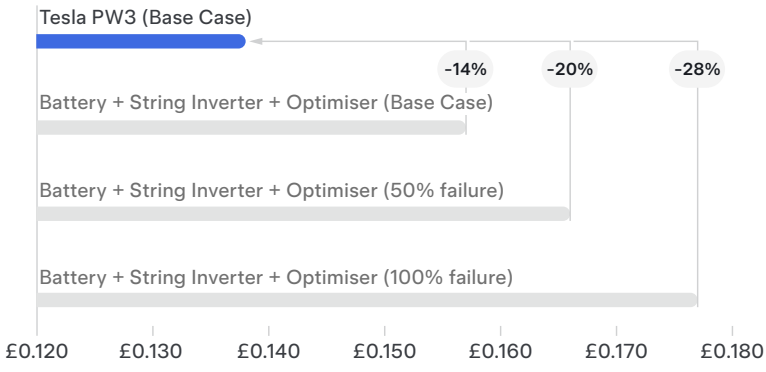
LCOE Comparison, cont.

Tesla vs. String + Optimiser LCOE



Levelised Cost of Energy (LCOE)

£/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 Powerwall 3 integrated 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.

Side Design Flexibility

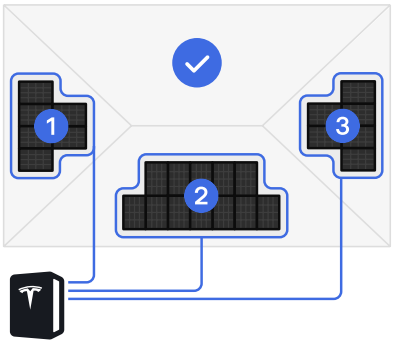
The Powerwall 3 integrated inverter architecture offers two key features that improve site design flexibility. These features provide power optimisation and flexibility benefits that are better than traditional string inverters and drastically reduce the need for MLPEs.

Three MPPTs

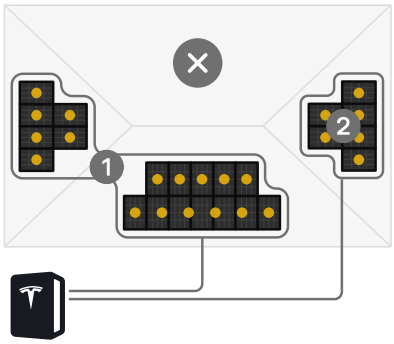
The Powerwall 3 integrated inverter offers three MPPTs. This gives designers more flexibility to put MPPTs on different mounting planes, reducing the need for MLPEs on more complicated roofs.

The three MPPTs in the Powerwall 3 integrated inverter allows for the layout in blue, eliminating the need for MLPEs.

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



One Powerwall 3, installed on the ground



Many devices, majority installed on the roof

Ease of Installation, Commissioning, and Service

The Powerwall 3 integrated inverter allows for faster installation by simplifying the installation process. Having one system instead of multiple MLPEs reduces the number of components to install, results in fewer components on the roof, and reduces the amount of wiring and connectors required, decreasing the scope of work for installers. The Powerwall 3 integrated inverter further reduces required wiring with the MPPT paralleling feature that allows installers to combine parallel strings on the roof up to the voltage and current ratings of the MPPT.

Ease of Installation, Commissioning, and Service, cont.

The Powerwall 3 system also streamlines the commissioning process. There is only one device to setup instead of an additional third-party inverter and 10-20 MLPEs. If there is an installation error, the Powerwall 3 system's built-in cellular, Wi-Fi, and Ethernet connectivity allows for easy inspection and repair with a single unit that is accessible from the ground. In comparison, if an inverter or MLPE fails or if there is a wiring or communication issue on a single microinverter or optimiser, installers must climb on the roof and remove modules to find the issue, troubleshoot, and perform remediation, a physically challenging and dangerous process.

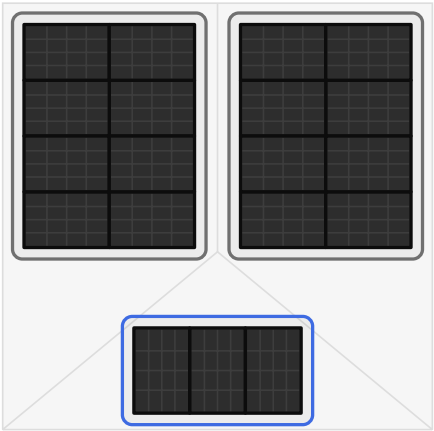
One app
to commission the system

Two apps
to commission the system

Three Low Input Voltage Allows Shorter Strings

A lower minimum input voltage per MPPT allows for shorter string lengths, giving site designers more layout flexibility. The Powerwall 3 integrated 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 optimise output; The Powerwall 3 integrated inverter can maintain efficiency for all three strings on the right, including the three modules outlined in blue.



Our inverter operates through a Perturb & Observe (P&O) function at an optimised 2 Hz frequency, ensuring precise and rapid adjustments to maximise energy harvest. By calculating the change in power (dP), it intelligently steers the system toward the Maximum Power Point, where solar panels deliver peak performance. The system seamlessly transitions through power control, voltage control, and current control phases, incorporating a power limiter for safety and stability. This advanced control strategy ensures maximum efficiency, reliable energy delivery, and optimal use of sunlight, all while operating effortlessly in the background for a smarter, greener energy solution.

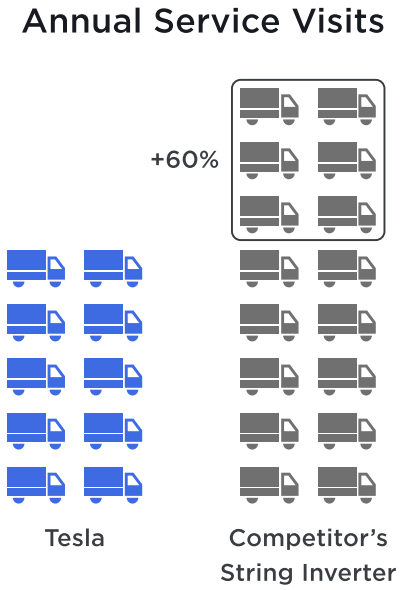
The Power of Tesla

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 integrated inverter.

Failure data from our fleet of solar systems shows that a leading competitor's string inverter fails 60% more often than the inverter developed by Tesla[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 Powerwall 3 integrated 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 Powerwall 3 system has built-in fans and thermal management system to keep the integrated inverter relatively cool. In contrast, MLPEs are mounted directly under solar panels on the roof and are subjected to constant extreme temperatures, reducing system life.



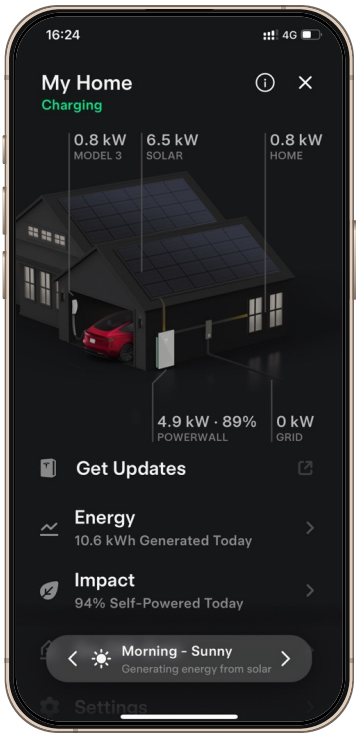
[7] SolarEdge: 27.6 GW, Enphase: 15 GW.

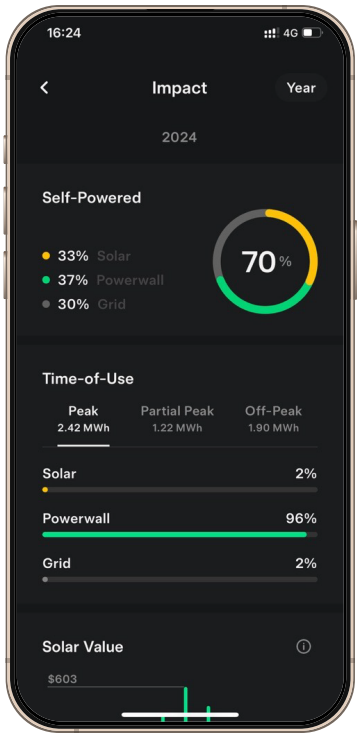
[8] Tesla sample includes inverters installed between 1/21 and 7/22. Competitor inverter sample includes inverters installed between 7/21 and 7/22. Samples have equal average age.

[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

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 Tesla vehicles and charging. The intuitive app experience allows the customer to view and manage home energy usage across these devices, with the system optimising 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 the Powerwall 3 integrated inverter architecture realises the following benefits:

1. The best lifetime value and lowest up-front cost for system
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.