2018 POWERPACK 2

Technology Review

Tesla, Inc.

Document No.: 10127569-HOU-R-01
Issue: D, **Status:** Final
Date: 10 January 2019

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Project name:	2018 Powerpack 2	DNV GL Energy Insights USA, Inc.
Report title:	Technology Review	Energy Advisory
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Date of issue:	10 January 2019	
Project No.:	10127569	
Document No.:	10127569-HOU-R-01	
Issue/Status:	D / Final	

Task and objective:
This report presents the results of the Tesla Powerpack 2 System Technology Review conducted by DNV GL.

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Issue	Date	Reason for Issue	Prepared by	Verified by	Approved by
0	8 September 2017	2017 Powerpack 2 Report	V. Carey	D. Blodgett	M. Kleinberg
A	30 November 2018	Draft Stage 1	A. Rohilla, J. Daggett, P. Sanford, D. Blodgett	V. Carey	M. Kleinberg
B	18 December 2018	Draft Stage 2	A. Rohilla, D. Blodgett	V. Carey	M. Kleinberg
C	31 December 2018	Final	A. Rohilla	V. Carey	M. Kleinberg
D	10 January 2019	Final	A. Rohilla	V. Carey	M. Kleinberg

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1 INTRODUCTION

Tesla, Inc. (“Tesla”) retained DNV GL Energy Insights USA, Inc. (“DNV GL”) to update the technology evaluation of their Powerpack 2 System entitled *Technology Review of Tesla Powerpack 2 Energy Storage System* dated 8 September 2017. This report presents the results of DNV GL’s updated analysis. DNV GL previously conducted a similar technology evaluation for the earlier product configuration that was called the Powerpack. That report was entitled *Technology Review of Tesla Powerpack System* dated 2 May 2016. Some information contained in that report was used in the production of this evaluation.

Like the original Powerpack (referred to in this report as the Powerpack 1 model), Tesla’s Powerpack 2 System is based on the powertrain architecture and energy storage components of Tesla electric vehicles. The Tesla Powerpack 2 System is a stationary energy storage system that can be implemented in a variety of standalone and grid connected applications. The Powerpack 2 System is a modular, fully integrated, AC-coupled energy storage system consisting of rechargeable Tesla Lithium-ion (Li-ion) Powerpacks, a newly manufactured Tesla bi-directional inverter, and a Tesla-designed site level master controller, which manages the system for a variety of energy storage applications.

The smallest modular block consists of a single 65 kW inverter connected to standalone Tesla battery Powerpacks, with quantities of Powerpacks scaled for a given application to meet the hour rating of the system (for example 2, or 4 hours). The resulting AC blocks can be scaled to create multi-MW sites. Like many large, stationary systems, the Tesla Powerpack 2 System is physically integrated on site at the customer’s location. The major components are first factory tested individually, and then interconnected and tested as a system, on location.

The Tesla Powerpack 2 System is designed for implementation in grid connected (60Hz or 50Hz) applications as well as microgrid or backup power applications. When in grid connected mode, the system can be configured to meet the needs of a variety of applications, including but not limited to peak load shaving, energy arbitrage, demand response, energy or load shifting, renewable energy firming and smoothing, and ancillary services.

This Technical Review is limited to the performance and characteristics of the core Powerpack 2 components, integrated into an AC block system, as outlined above; however, the information will translate to multiple blocks combined for specific application requirements, where applicable.

1.1 Report scope of work

The primary objective of this report is to assess factors that would affect the final product’s performance and reliability in the field and the company’s ability to deliver and service the products. Such factors will include the product design, quality of materials, product performance, regulatory compliance, reliability tests, and the manufacturing and quality control processes.

DNV GL has divided the Technical Review into several main topic areas for evaluation.

- Company overview
- Powerpack 2 System overview
- Battery evaluation, including the Pod and Powerpack
- Tesla Inverter evaluation

- Powerpack 2 Controller
- Powerpack 2 System integration and codes and standards
- Powerpack 2 manufacturing, including both the Powerpack battery and inverter components
- System level performance
- Tesla application software, controls and manual override capability evaluation
- Powerpack 2 System installation requirements
- Powerpack 2 Product support evaluation
- Site visit to an operating system in the field

The report concludes with a summary of DNV GL's key findings and opinions.

1.2 Methodology

In general, this report contains information that would be included in a final Independent Engineering review intended for financial institutions, customers, and project developers. DNV GL is uniquely qualified to conduct this study due to its extensive background and experience in solar and energy storage independent engineering and technology due diligence work.

This Report has been updated based on feedback from Tesla on the 2017 Technology Review of Tesla Powerpack 2 Energy Storage System report and the incorporation of additional information. To perform the assessment, DNV GL relied on the 2017 Report, updated documentation provided by Tesla, and conversations with key staff associated with the topic areas covered, as well as leveraging findings from previous site visits conducted by DNV GL to the company headquarters in Palo Alto, California, a Tesla Industrial Powerpack 2 installation at the Southern California Edison (SCE) research and development (R&D) site in Pomona, California, and the Tesla Gigafactory located in Sparks, Nevada.

As noted above, where applicable DNV GL will draw on previous technology review work performed with Tesla for other projects and other clients. Where used, permission was acquired for the use of this information.

Information was aggregated from multiple Tesla sources and provided to DNV GL for generation of the original report and this update by:

- Maud Texier, Products & Analytics – Powerpack
- AJ Booth, Powerpack Engineering Team Manager
- Kevin Kassekert, VP of Infrastructure Development
- Elyse Green, Powerpack Products Sales Engineer
- Hanson Boyd, Product Manager
- Siyi Zhang, Associate Product Manager

1.3 Assumptions

This Report summarizes DNV GL assessment of the technology and relies on the accuracy of the information provided by Tesla. Tesla has been generally open and forthcoming in providing the data that DNV GL has requested. Some data received from Tesla that has been used in the production of this Technology Review, has been omitted from this report based on requirements from Tesla that it remains confidential.

This report is based on some information not within the control of DNV GL. DNV GL believes that the information provided by others is true and correct and reasonable for the purposes of this report. DNV GL has not been requested to make an independent analysis or verification of the validity of such information. DNV GL does not guarantee the accuracy of the data, information, or opinions provided by others.

In preparing this report and the opinions presented herein, DNV GL has made certain assumptions with respect to conditions that may exist, or events that may occur in the future. DNV GL believes that these assumptions are reasonable for purposes of this report but actual events or conditions may cause results to differ materially from forward-looking statements.

2 TESLA MOTORS COMPANY OVERVIEW

Tesla Motors was founded in 2003 by a group of engineers in Silicon Valley who wanted to prove that electric cars could be better than gasoline-powered cars. Tesla's engineers first designed a powertrain for a sports car built around an AC induction motor, patented in 1888 by Nikola Tesla, the inventor who inspired the company's name. The resulting Tesla Roadster was launched in 2008. The Tesla Roadster accelerates from 0 to 60 mph in 3.7 seconds and achieves a range of 245 miles per charge using its own brand of Li-ion battery packs. Tesla has sold more than 2,400 Roadsters, now on the road in more than 30 countries.

Since the launch of the Roadster, Tesla had introduced several more electric vehicles to the market and now boasts more than 170,000 Model S (Tesla's flagship sedan model) vehicles on the road in 30 countries worldwide. Tesla's vehicles are produced at its factory in Fremont, California, previously home to New United Motor Manufacturing Inc., a joint venture between Toyota and General Motors. The Tesla Factory can produce 25,185 vehicles per quarter as of Q3 2016. This capacity is intended to increase in the coming years.

Figure 2-1 Tesla facility in Fremont, CA

Tesla sells their electric vehicles through direct sales and service locations throughout North America, Canada, and in many other countries in Europe, Australia, and Asia.

Figure 2-2 Example Tesla sales and service centers

Below in Figure 2-3 is a high-level company time line showing the introduction of the Tesla Energy products beginning in 2015, illustrating the key Tesla facilities in the U.S. and the Netherlands over time.

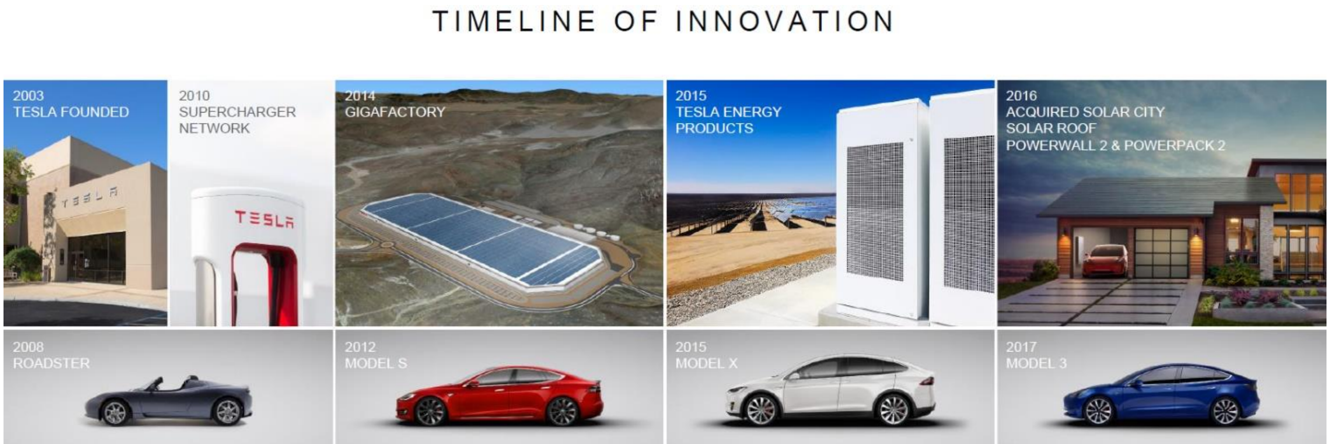


Figure 2-3 Tesla company timeline

Table 2-1 lists additional company information.

Table 2-1 Tesla company information

Name of Corporation	Tesla, Inc.
Date and State of Incorporation	1 July 2003 in Delaware
Ownership Status	Public corporation (NASDAQ: TSLA)
Corporate Headquarters	3500 Deer Creek Road, Palo Alto, CA 94304
Number of Employees	Approximately 44,000 (as of 30 November 2018)

2.1 Tesla stationary energy storage product history

Whereas Tesla has a rich history in developing battery products for their electric vehicles, Tesla started its stationary storage efforts in 2011. The first generation of stationary storage systems (Superpack) was deployed starting December 2012. Tesla has delivered roughly 81 MWh of Superpack systems serving various customers and applications including tariff optimization (peak shaving and energy arbitrage) for Commercial and Industrial (C&I) customers, demand-response, and microgrids.

Tesla Energy was announced in April 2015 and early deployment of DC Powerwall started in December 2015, while customer deployment started in February 2016. Since 2012, Tesla has also delivered tens of thousands of small scale Powerwall stationary residential energy storage systems, accounting for a total of more than 403 MWh of Tesla's installed energy capacity.

In addition to the Powerwall systems, Tesla developed the second generation of larger stationary storage products called the Powerpack 1. Tesla started deploying the Powerpack 1 models in September 2015.

As of 27 October 2018, Tesla reported having 34,000+ stationary storage application installations (Powerwall, Powerpack, and earlier products), with approximately 450 of those being Powerpack (1 and 2) installations. Over 1.1 GWh of Tesla batteries have been deployed in 36 countries. Figure 2-4 demonstrates the relative deployment by region of Tesla energy storage systems.

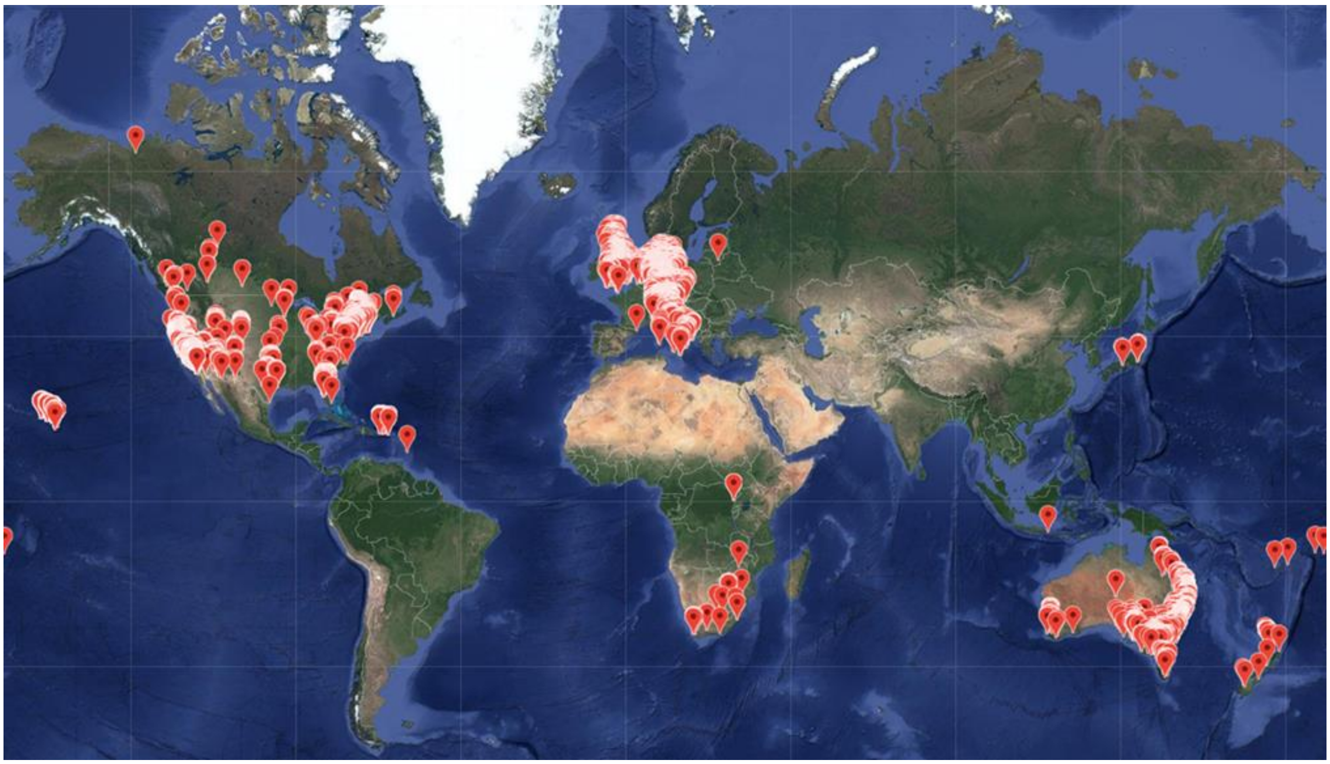


Figure 2-4 More than 1.1 GWh of Tesla energy storage systems deployed as of February 2017

Below in Figure 2-5 are a timeline and graphics depicting the evolution of the original Superpack to today's Powerpack 2 product.

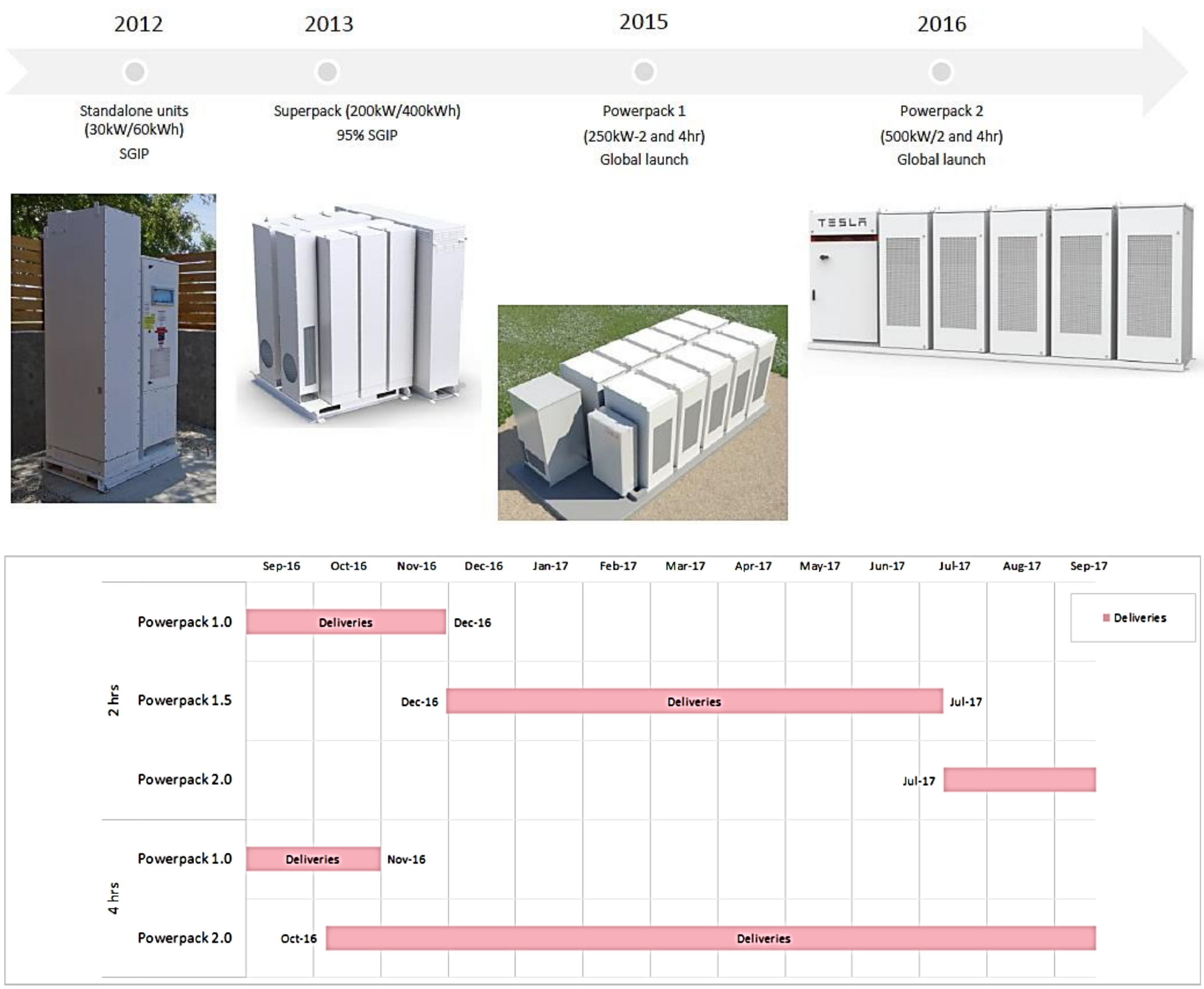


Figure 2-5 The product timeline for Powerpack 2 and earlier generations

Table 2-2 below provides a summary of installed Tesla energy storage systems.

Table 2-2 Summary of installed energy storage systems

Item	Value	As of
Capacity of Installed Energy Storage Systems	1.1 GWh of Tesla batteries deployed in 36 countries	27 October 2018
Number of Powerpack Installations	450	27 October 2018

DNV GL finds the evolution of the products and the scale of stationary energy storage system deployments to be industry leading.

2.2 Intellectual property

Tesla has filed many patents on inventions for its Tesla Energy products. Tesla reports to DNV GL that, as of December 2018, they currently have over 420 issued patents, and more than 290 pending patent applications, in the U.S. and in other countries. Tesla provided DNV GL a full list of Tesla's issued patents which are also publicly available.

Tesla reports that covered features in the products relate to anything from power electronics interfaces to safety mechanisms. Tesla energy storage product features that overlap with technology in Tesla's vehicles may be covered by existing patents from that field.

Tesla has announced a pledge for use of its patents in good faith, in the spirit of the open source movement. However, the pledge specifically prohibits copying of their products. Tesla will not initiate patent lawsuits against anyone who, in good faith, wants to use their technology. As such, Tesla Energy products are protected by Tesla's patent portfolio. DNV GL did not review in detail any of Tesla's patents or applications. Tesla provided DNV GL this link which further describes their philosophy on Intellectual Property, https://www.tesla.com/en_CA/about/legal#patent-pledge.

2.3 Sales revenues

Tesla is a publicly traded company (NASDAQ: TSLA). Corporate financial filings can be accessed on the Tesla web site (http://ir.teslamotors.com/), for further review. DNV GL did not include a comprehensive review of Tesla's financials but includes the following high-level summary taken in part from their Third Quarter 2018 Shareholder letter http://ir.tesla.com/static-files/725970e6-eda5-47ab-96e1-422d4045f799.

The most current financial information is available to the public for review and can be found here, http://ir.tesla.com/sec.cfm.

Tesla Third Quarter 2018 Update

- **GAAP net income of $312M, non-GAAP net income of $516M**
- **Operating income of $417M and operating margin of 6.1%**
- **Free cash flow of $881M supported by operating cash flow of $1.4B**
- **$3.0B of cash and cash equivalents at Q3-end, increased by $731M in Q3**
- **Model 3 GAAP and non-GAAP gross margin > 20% in Q3**
- **Reaffirm expectation of continued GAAP net income and free cash flow in Q4**

Tesla's energy storage business has seen significant growth since the initial version of this report in 2017. Between Q3 2017 and Q3 2018, Tesla's energy storage deployments grew 118%. As of Q3 2018, Tesla has deployed approximately 800 MWh of Powerpack related energy storage projects where over 560 MWh are specific to Powerpack 2 installations. Tesla did not provide DNV GL with specific figures for its Powerpack 2 sales; readers can contact Tesla directly for more details as required. The Q3 2018 update letter referred to above presented the following financial summary.

	Three Months Ended			Change	
	September 30, 2018	June 30, 2018	September 30, 2017	QoQ	YoY
Energy generation and storage revenue ($000)	$ 399,317	$ 374,408	$ 317,505	7%	26%
Energy generation and storage gross margin	17.2%	11.8%	25.3%	543 bp	-804 bp

- Energy generation and storage revenue in Q3 increased by 7% over Q2 and by 26% compared to Q3 2017. This year-over-year increase was mainly driven by a substantial growth in energy storage deployments and higher mix of cash and loan sales for solar deployments.
- GAAP gross margin of the Energy business in Q3 improved significantly to 17.2% compared to 11.8% in Q2 mainly due to cost improvements in our solar and storage businesses.

Figure 2-6 Q3 2018 financial summary for energy generation and storage revenues

In Q4 2018, Tesla also provided DNV GL an updated project reference to recent installations of energy storage projects:

"This project, completed in less than 100 days, is the largest lithium-ion battery storage project in the world and has enough power for more than 30,000 homes in South Australia. This grid scale energy storage project is not only sustainable, but helps solve power shortages, reduces intermittencies, and manages summertime peak load to improve the reliability of South Australia's electrical infrastructure. Additional stored energy could be dispatched into the grid and traded on the electricity market to meet demand and prevent problems with voltage or frequency."

Figure 2-7 Recent project reference

Table 2-3 Recent project reference

Project Name	Hornsdale Power Reserve
Customer Type	Neoen (Private Owner/Operator)
Location	Southern Australia
Distributed Energy Resource	Hornsdale Wind Farm
Storage System Size	100 MW/129 MWh
Application	Grid stabilization/renewable integration
Commissioning	2017

2.4 Tesla manufacturing overview

In addition to their manufacturing facility in Fremont, California, the company is expanding its energy storage manufacturing footprint into other areas, the largest being the Gigafactory in Nevada. To reduce the costs of the Li-ion battery product, Tesla and key strategic partners including Panasonic are constructing the Tesla Gigafactory. The Gigafactory will facilitate further production of a mass-market, affordable vehicles (Model 3), in addition to the full line of Tesla stationary storage systems.

Tesla claims that by 2020, the Gigafactory will produce more Li-ion cells than all the world's combined output in 2013. During the previous evaluation reports battery modules were being manufactured at Tesla's Fremont manufacturing facility. Constructed battery modules were shipped to the Gigafactory facility for integration into the storage products. The battery modules and the inverters being used in the Powerpack 2 energy storage systems are now being manufactured at the Gigafactory. Tesla began manufacturing battery cells at the Gigafactory in January 2017.

An artist's rendering of the planned full Gigafactory depicts the roof housing a large PV array to help offset production energy requirements, as seen below in Figure 2-8.

Figure 2-8 Artist rendering of the planned Nevada Gigafactory with PV array roof

Also, shown below in Figure 2-9 is a photo of the Gigafactory in Nevada during ongoing expansion. Recent photos taken during the first DNV GL visit to the Gigafactory are shown in Section 4, Battery Evaluation.

Information provided in their Q4 reporting suggests future Gigafactories 3, 4, and possibly 5 (Gigafactory 2 is the Tesla solar plant in New York) are being planned.

Figure 2-9 The Tesla Gigafactory under construction in Nevada, as of Q4 2016

Figure 2-10 Gigafactory 2 produces solar panels in Buffalo, NY

Tesla manufacturing employs a comprehensive Quality Assurance Program, based on industry best practices, that complies with ISO 9001 standards.

Tesla provided DNV GL the following description of their manufacturing process:

> Starting with the supply of parts and components, Tesla has a cross-functional supplier selection process managed by the Purchasing, Design Engineering, and Quality departments (also referred to as Product Excellence). Suppliers are then validated by the Supplier Industrialization team (part of Quality) to ensure they are capable of meeting design specifications and capacity requirements.
>
> On the manufacturing line, Tesla performs automated End of Line testing that is interlocked with the manufacturing enterprise system, preventing a product from shipping without a passing test result. Test failures are investigated to determine root cause and appropriate correction, then submitted for cross-functional review administered by Quality and Engineering. Test failures are also tracked in weekly yield meetings, to analyze trends and drive permanent countermeasures for top issues.
>
> Tesla takes field data or expected usage data as appropriate, and translates it into test conditions using known acceleration equations. Accelerated Life Testing (ALT) is only performed where acceleration equations are known to apply (i.e., for temperature cycling, extended time at high temperature, or exposure to temperature and humidity), and only to the degree that such testing does not introduce unrealistic failure modes. ALT is performed at both component and system levels.

Further details concerning DNV GL's assessment of Tesla's specific manufacturing approach are covered in Section 7.

3 POWERPACK 2 SYSTEM OVERVIEW

The Tesla Powerpack 2 System follows the evolution of earlier Powerpack 1 models as a turnkey, stand-alone, or grid-compatible energy storage system comprised of Li-ion based battery "Powerpacks" (the battery stack within the Powerpack 2 system) that can be scaled for both power and energy to achieve desired system power and energy ratings to create multi-megawatt sites. The AC power building block is comprised of one or more Tesla manufactured bi-modal inverters which can be supplied by up to 20 Powerpacks rated approximately 210 kWh each. Each Tesla inverter can be configured with one to ten inverter modules for a power range of 54 kW to 540 kW at 400 V AC line voltage, and 65 kW to 650 kW at 480 V AC. These blocks can then be combined in parallel to increase power and energy system ratings.

The Powerpack 2 system has been designed and configured to offer key advantages in terms of safety, scalability, serviceability, and reliability. The benefits of the various elements of this chosen architecture are described in more detail throughout the report.

Figure 3-1 An example Powerpack 2 showing one inverter module integrated with 10 Powerpacks

As with the earlier models, the Tesla Powerpack 2 System is physically integrated on site at the customer location. The major components are first factory tested individually, packaged and shipped, installed on a concrete pad, and then interconnected, commissioned, and tested as a complete system for the intended application.

The system is interconnected to form a complete energy storage system that includes integrated applications software (Opticaster) which is controlled via the Tesla Site Controller (also referred to in some legacy documentation as the Powerpack Controller or Site Master Controller). The major components are shown in Figure 3-2. The system offers remote real time performance monitoring specific to the intended energy storage application.

Inverter blocks may be aggregated in a low voltage switchboard (voltage based on region of application) and then stepped up via a single transformer for utility interconnection to create an AC block. Tesla design engineers recommend various AC block sizes and configurations based on the specifics of each project. AC blocks are aggregated to create utility-scale systems. All equipment upstream of the inverter is provided and engineered by others; however, Tesla can provide engineering guidance to optimize the system for cost, efficiency, and constructability. Tesla's extensive product support services are described in Section 11.

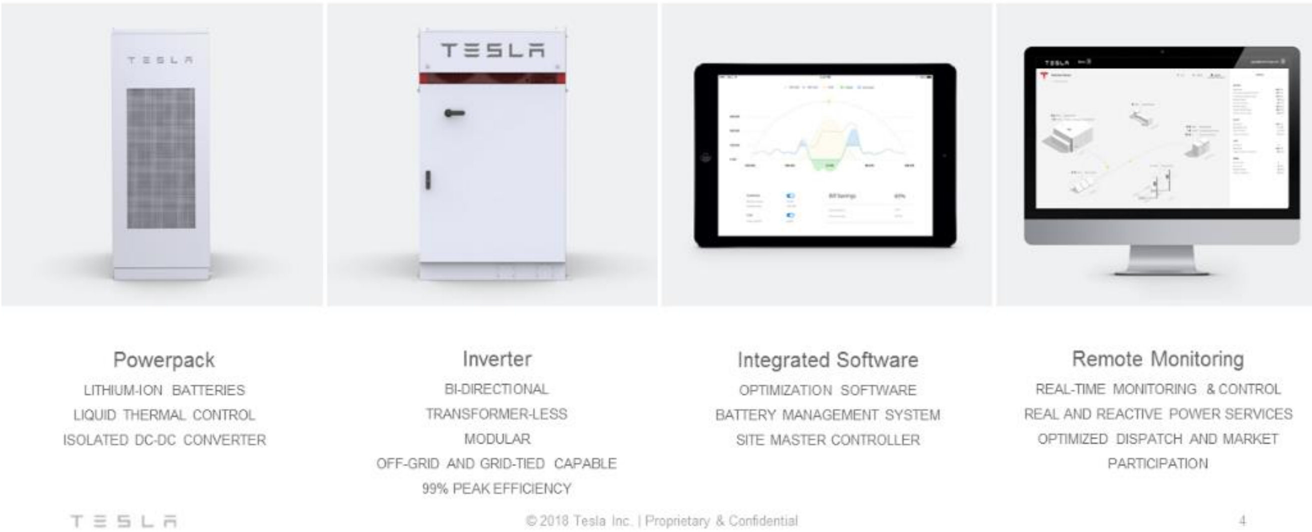


Figure 3-2 Powerpack 2 system components

Tesla provided a company presentation with numerous graphics that depict the key components and architecture of the Powerpack 2. Figure 3-3 shows the components of the Powerpack beginning with the smallest battery cell to the Pod to the full Powerpack cabinet which can hold up to 16 Pods.

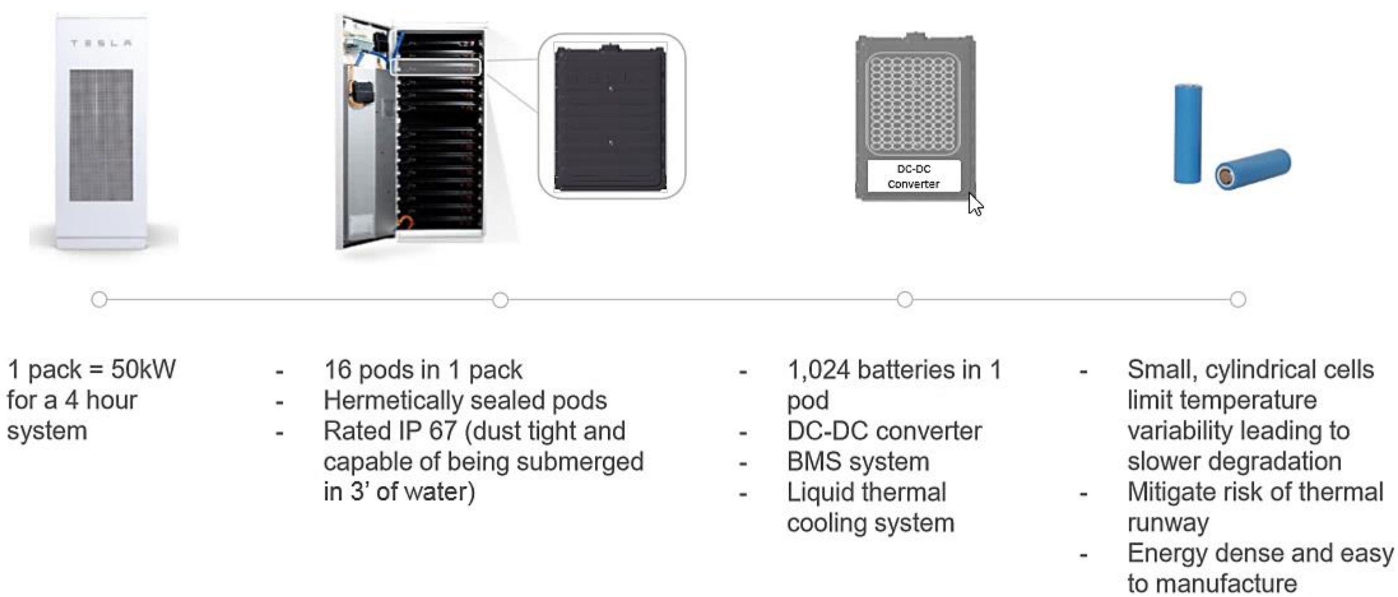


Figure 3-3 The composition of the Powerpack battery components

Each sealed Ingress Protection (IP) 67 Rated Pod includes its own DC-DC converter. Pods are connected in parallel in the Powerpack cabinet which is thermally regulated with an active liquid cooling at the cell level. The configuration of the Pods in the Powerpack cabinet is shown below in Figure 3-4.

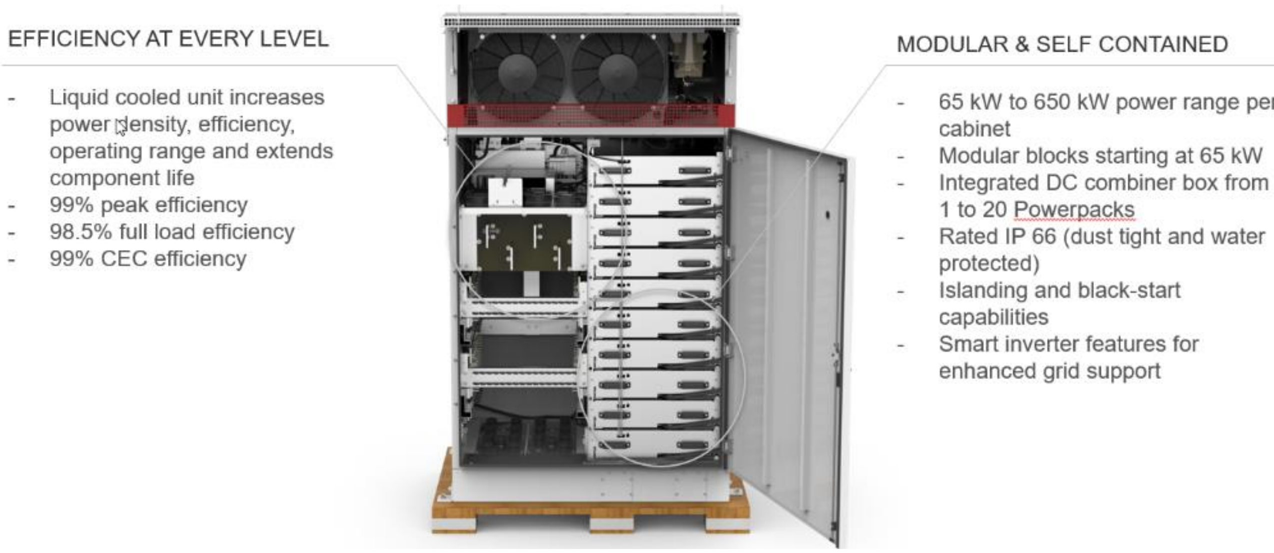


Figure 3-4 Powerpack battery cabinet architecture

The new Tesla designed and manufactured bi-directional inverter is comprised of one to ten 65 kW inverter modules. A bi-directional inverter is a power electronic device that can both deliver AC to the grid from the DC battery bank, as well as convert the AC from the grid to charge the DC battery bank.

The Powerpack 2 includes the Tesla Site Controller which interfaces with the Opticaster application optimization software suite and system monitoring capabilities.

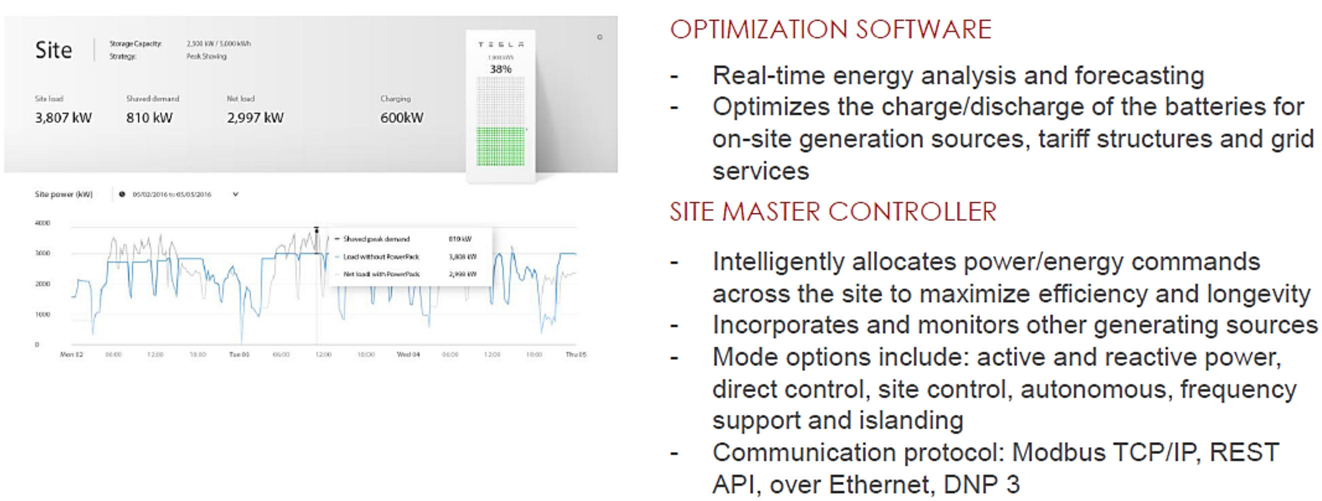


Figure 3-5 Tesla Opticaster specification

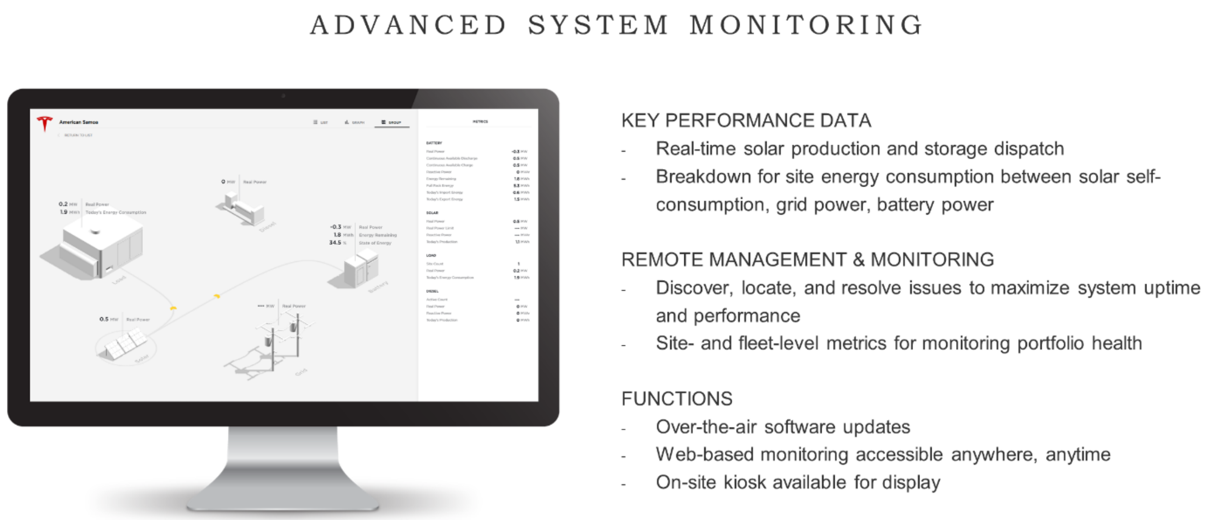


Figure 3-6 The Powerpack 2 system monitoring specifications

Tesla claims that the Opticaster software suite can support a range of energy storage applications as listed below in Figure 3-7. Opticaster capabilities and field history are assessed in further detail in Section 6.

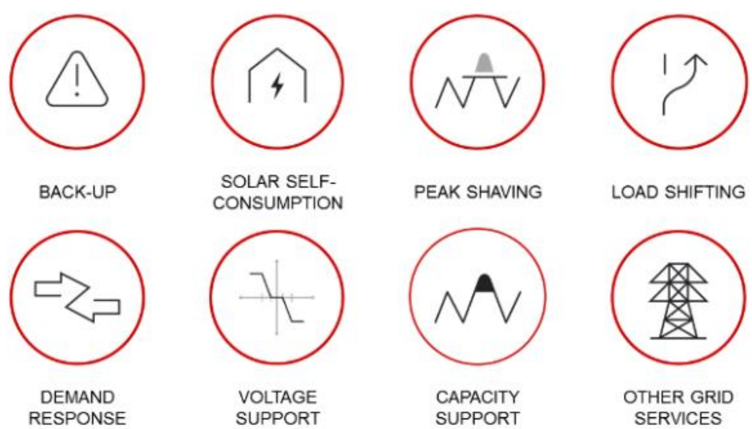


Figure 3-7 Powerpack 2 system's claimed energy storage application capabilities

4 BATTERY EVALUATION

This section of the report will focus on the DC battery Pod and Powerpack components of the Tesla Powerpack 2 System. The review highlights several design improvements over the previous generation Tesla battery systems.

4.1 Stationary battery product history

The first generation of Tesla energy storage system, also called the Superpack, was deployed in December 2012. Tesla delivered roughly 77 MWh of Superpack systems serving various customers and applications including tariff optimization (peak shaving and energy arbitrage) for C&I customers, demand-response, and microgrids.

Superpacks directly leveraged the mechanical and electrical design of the vehicle battery engineering expertise. Each battery enclosure contained a rack of modules with a battery management system (BMS) and an array of enclosures / packs supported by a thermal management unit. The battery module is the base building block of the battery system architecture and defines the mechanical and electrical arrangement of the cells, temperature and voltage sensing, and module level BMS. The battery module architecture employed in the Superpack system is the same module used in the electric vehicle. This does not imply the same cells are common between the vehicle and stationary modules, but rather used the same cell form factor and chemistry family (Li-ion). A group of such enclosures are mounted on a mechanical skid to enable easy outdoor installation.

Applying learnings from prior installations and years of operation of the Superpack systems, Tesla developed the second generation of stationary storage products, called the Powerpack 1. The Powerpack 1 largely leveraged the advantages of the modular design used in the Superpack product while incorporating some key design improvements focused on system safety and performance. In 2016, Tesla announced the development of the Powerpack 2. This second iteration of the Powerpack 1 product includes updates to battery cells and cell interconnections, which were also rolled out to the residential Powerwall 2 product, as well as the inclusion of a Tesla-manufactured inverter (discussed in detail in Section 5 of this report). These design changes are highlighted in the following review of the Pod and Powerpack units.

Tesla produces the Powerpack 2 in both a 2-hour and 4-hour configuration. The 2-hour and 4-hour Powerpack 2 systems utilize different battery cell chemistries. As such, where necessary in this section, the two systems will be discussed under separate headings to delineate their differing technical specifications.

4.2 Battery Pod evaluation

The battery Pod is the core modular unit of Tesla's Powerpack 2 energy storage systems. It is a field-replaceable unit consisting of an isolated DC/DC converter, BMS, and Li-ion batteries. These batteries are cylindrical Li-ion 2170 cells assembled in series and parallel arrays, similar to the modules used in Tesla's electric vehicles. The 2170 cells replace the cylindrical 18650 cells utilized in the original Powerpack Pods, being slightly longer and wider, with higher energy density. The 2-hour and 4-hour systems both utilize cells of this same form factor; however, the chemistries between the two cells vary to optimize for different discharge durations. The cells in both the 2-hour and 4-hour systems' Pods are also interconnected in an updated more efficient packing method. Together, these changes result in Pods with approximately double the rated energy density from the Powerpack 1.

The Pod modules are complete with packaging, liquid thermal management cooling loops, DC connections, and traditional BMS functions including associated cell sensing. Each individual Pod's DC outputs and communications are consolidated at a Powerpack level. An illustration of the battery Pod and its placement within a Powerpack is shown in Figure 4-1.

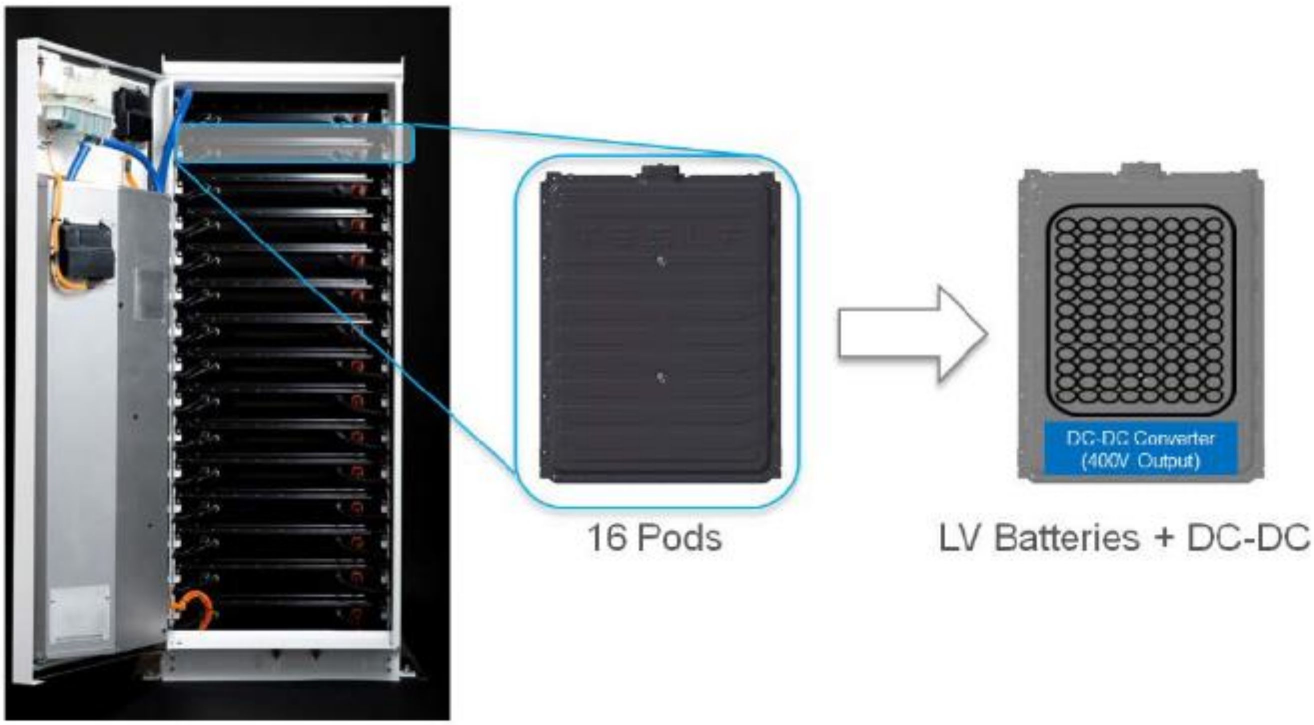


Figure 4-1 Battery Pods are consolidated at the Powerpack level

The Pods are connected in parallel on the high voltage side of their DC/DC converters. Key benefits of the Pod architecture are highlighted below:

- Eliminates high voltage batteries – Pods keep the batteries at a low voltage behind a power electronics interface. The earlier generation system, Superpack, connected the batteries in series and parallel to build up a battery pack, resulting in high voltage and current, which has been a typical configuration of most competing products on the market, at Tesla's stationary storage product inception. DNV GL has observed the industry shifting to include DC/DC converters in other battery products, a method that Tesla has helped pioneer.
- Isolated DC/DC increases safety – Faults inside the Pod will not affect the rest of the system. Faults on the high voltage DC bus will experience significantly less fault energy due to the power limited power electronics interface.
- Systems can scale in a modular fashion because Pods are all coupled to a regulated DC bus. Pod charge and discharge is regulated with droop control, so the addition of Pods does not increase

engineering integration or site-specific validation. This can provide customers with design flexibility and, potentially, cost savings.

- Each Pod has its own BMS, further distributing and localizing this functionality.

In addition to the safety features previously mentioned, the Pod level DC/DC converter facilitates mixing and matching of cell chemistry and age behind the same DC/AC inverter. Battery performance and optimization occurs at the Pod level, allowing for old Pods to be swapped out for new Pods as well as allowing fully charged Pods to operate alongside Pods at a low state of energy. The DC/DC architecture is also designed to ensure backwards compatibility with future cell technology changes, offering the flexibility to upgrade the cell technology without changing the basic Pod architecture. As Tesla transitions from the 18650 cell type to the new 2170 cells, this is especially beneficial for upgrades to previously deployed units. DNV GL has not reviewed field data specifically demonstrating this functionality, and recommends this report be updated when such replacements have occurred, to assess any potential impact on performance. Four-hour system Pods are designed with a single DC/DC converter, while two-hour systems utilize two DC/DC converters running in parallel per Pod. In both cases, the DC/DC converter(s) steps the battery voltage up to 870-960V DC.

Each Pod is contained in an IP 67 enclosure, which is dust tight and capable of submersion in water up to 1 m. DNV GL finds the inclusion of a second layer of weather protection, beyond the full Powerpack enclosure's NEMA 3R rating, to be beneficial for the sheltering of the Pod electronics and batteries.

Each Pod is cooled via a liquid thermal management system controlled at the Powerpack level, and discussed in further detail in Section 4.3. The Pods have an inlet and outlet for the liquid coolant, and a coolant loop which interacts with each individual cell and the DC/DC converter. This liquid thermal management is a unique feature of the Tesla stationary energy storage system design, as opposed to more widely used containerized solutions with a central heating, ventilation, and air conditioning (HVAC) system and forced air cooling. The Tesla liquid cooling loop design allows for balanced cooling of all cells, regardless of placement within their respective module, enabling improved operational efficiency and increased lifetimes.

4.3 Powerpack evaluation

4.3.1 System design and ratings

The Powerpack, within the context of the Powerpack 2 system's overarching architecture, is shown in Figure 4-2. Self-contained Powerpacks are individually mounted on a concrete pad, connected via a Tesla provided wire harnesses to the inverter. Each Powerpack includes a thermal management system, a common DC rail for connection in parallel, and a common communication and control infrastructure for external connections.

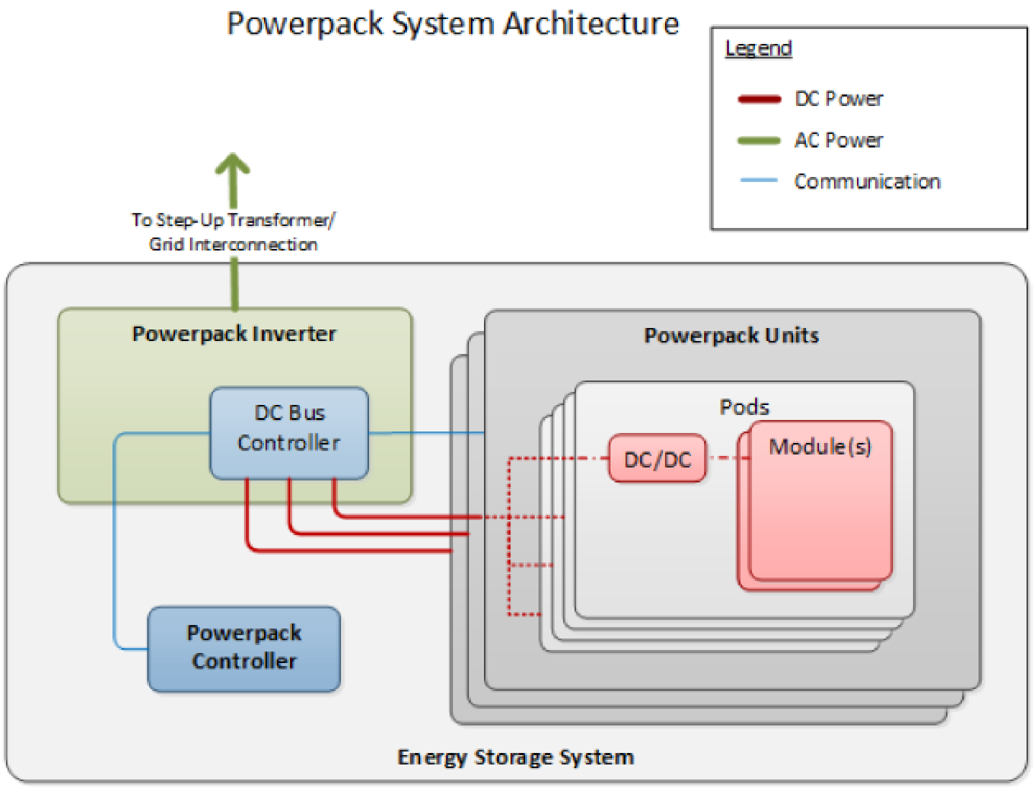


Figure 4-2 Powerpack 2 architecture

4.3.1.1 Two-hour system

There are four standard configurations for the two-hour Powerpack, including a 2-hour and 1.6-hour option that can both be arranged in "Large" and "Small" configurations, described in Table 4-1. A Small 2-hour Powerpack system consists of one Powerpack (16 Pods) and one inverter, and is rated at 87 kW/174 kWh as measured at the AC terminals of the inverter. A Small 1.6-hour option, also made up of one Powerpack and one inverter, but is instead rated at a higher power but lower energy of 105 kW/169 kWh. The Large 2-hour and 1.6-hour configurations use six and five Powerpacks, respectively, with a single inverter, and are rated at 522 kW/1,044 kWh and 528 kW/845 kWh.

If acting under its peak power mode, rather than discharging for the full 2 hours, the system can discharge for 1.2 hours at 130 kW. This mode is available for specific applications, enabling a 30% increase in real discharge power for limited periods of time. The conditions for the use of this mode are defined in customer contracts. DNV GL was not provided with further details on what applications specifically utilize this mode, nor how contract terms are directly affected.

Table 4-1 Standard two-hour Powerpack system configurations

STANDARD CONFIGURATIONS

Large	2 hr	1.6 hr
Configuration:	6 Powerpack, 1 Inverter	5 Powerpack, 1 Inverter
400V/480V	522 kW / 1,044 kWh	528 kW / 845 kWh

Small	2 hr	1.6 hr
Configuration:	1 Powerpack, 1 Inverter	1 Powerpack, 1 Inverter
400V/480V	87 kW / 174 kWh	105 kW / 169 kWh

4.3.1.2 Four-hour system

A single Powerpack 2 four-hour unit has rated power capacity of 53 kW and energy capacity of 210 kWh. As with the two-hour system, it consists of 16 field-replaceable Pods. A sample layout diagram included in Tesla's product documentation indicates that a system can be scaled by combining up to 20 units with a common inverter block. The power capacity of the inverter block will reach a maximum after 10 units are combined. Adding units beyond this limit will increase duration and energy capacity as power capacity is limited by the inverter. Standard configurations for the four-hour system are shown below, in Table 4-2. Although the 4-hour system is optimized for a 4-hour discharge, it can discharge in shorter durations; it does not, however, have the peak power mode, which is available for the 2-hour system.

Table 4-2 Standard four-hour Powerpack system configurations

STANDARD CONFIGURATIONS

Large	
Configuration:	6 Powerpack, 1 Inverter
400V/480V	315 kW / 1,044 kWh

Small	
Configuration:	1 Powerpack, 1 Inverter
400V/480V	53 kW / 210 kWh

4.3.2 Thermal management system

Each Powerpack comes with a self-contained thermal management system. The thermal management architecture for Tesla stationary energy storage systems, originally deployed in the Powerpack 1 and maintained through the Powerpack 2, leverage Tesla's electric vehicle architecture with several components being the same as the vehicle, such as the pump. Each Powerpack thermal door assembly houses its thermal management system and is highlighted in Figure 4-3 below. The thermal management system is composed of a circulation pump, radiator, and fan. The fluid used is a 50/50 mixture of ethylene glycol and water. The only service to these items is required at 5 years, for pump replacement and refrigerant refill. Tesla also inspects these components on each unit annually as part of its preventive maintenance program. A coolant loop into each Pod allows the fluid to interact with each individual cell. This liquid thermal management is a unique feature of the Tesla stationary energy storage system design. As previously noted, the liquid cooling loop design allows for balanced cooling of all cells, regardless of placement within their respective Pod, enabling improved operational efficiency and increased lifetimes. The DC/DC converter and other power electronics are also included in the coolant loop.

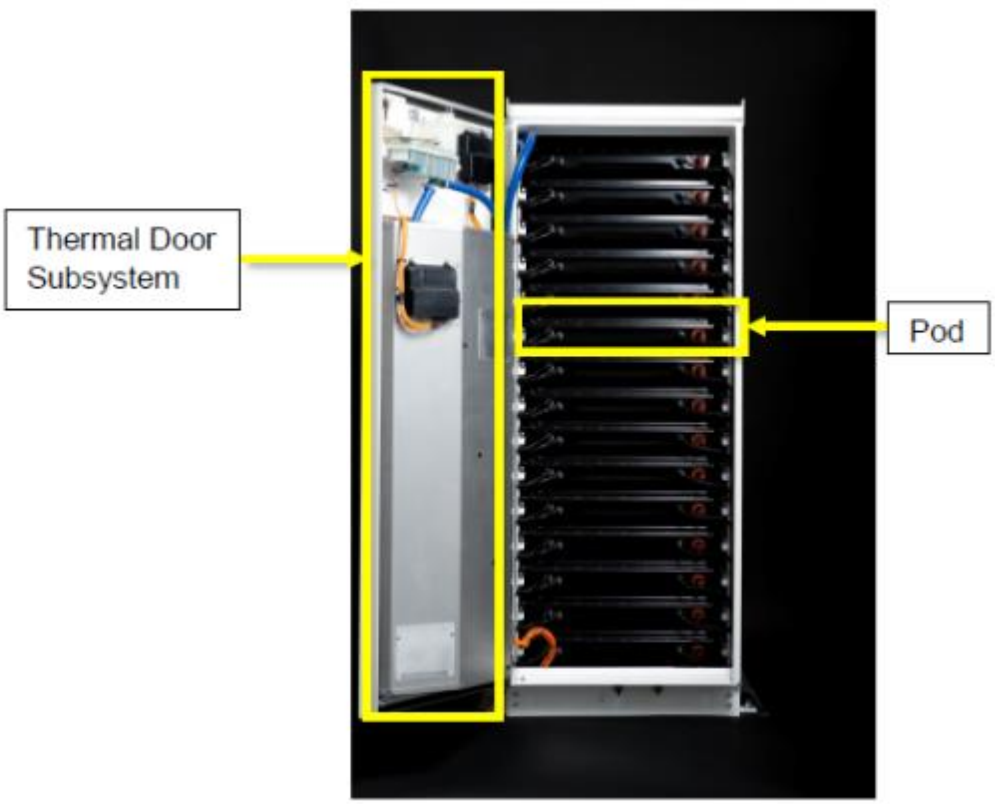


Figure 4-3 Powerpack enclosure denoting thermal door assembly and internal configuration of Pods

The liquid thermal management system is designed to cool the system during operation in warm environments as well as provide a mechanism to increase temperature to the acceptable threshold in cold environments utilizing its Heat Mode. Tesla provided DNV GL documentation demonstrating the modeled impact of ambient temperature on cell temperature. Due to the combined impact of the thermal management system and cell thermal mass, cell temperatures take more than 10 hours to approach the ambient extreme temperatures outside approved ranges. In DNV GL's opinion, this thermal management system thus provides the Powerpack the ability to operate in the appropriate temperature range, regardless of ambient temperatures, in line with Tesla's claimed ratings.

4.3.3 Environmental ratings

With the previously described thermal management system, the Tesla Powerpacks are rated for full operation in ambient temperatures from -30°C to 50°C, and can withstand temperatures of -40°C to 60°C for up to 24 hours. Tesla provided DNV GL with internal testing on the Powerpack 2 to demonstrate this rating and the thermal management system's capabilities to support it. The testing procedure involved cycling of a Powerpack through two or more full cycles in a 50°C chamber, varying the thermal management system's operation. In all provided results, the modules were maintained below 41°C and power output met expectations. DNV GL finds this level of at-scale testing to go beyond standard industry practices, and the results to be in line with Tesla's temperature range claims.

Regarding forces beyond temperature, the Powerpack enclosure is rated for NEMA 3R and IP 35, which is generally weather resistant. This provides protection against falling dirt and precipitation, and prevents damage by ice formation. Further, the enclosures can withstand wind gusts of up to 150 mph per ASCE 7-10, are qualified for "High" seismic level by IEEE-693-2005, and have an IK rating of IK09 for impact protection. These ratings demonstrate the applicability of the Powerpack over a wide range of environmental conditions, in-line with current standards for commercial Li-ion battery systems.

When storage of the system is necessary, a Powerpack shall be able to withstand temperatures of -40°C to 60°C for up to 24 hours. Tesla's specification states that Powerpacks stored up to one month shall be stored at temperatures between -30°C and 45°C and humidity <95% non-condensing. Powerpacks stored for longer than one month and up to 12 months shall be stored at temperatures between -20°C and 30°C, humidity <95% non-condensing, and with 25% initial State of Energy (SOE). The maximum acceptable storage duration, without measures to maintain function, is 12 months. DNV GL believes these ranges are well-defined and are in-line with industry standards.

4.3.4 Safety and regulatory

Tesla has claimed that the Powerpack is designed to be compliant with several standards that are generally accepted to demonstrate minimum safety considerations in the system design. These standards include certifications of the batteries by Underwriters' Laboratories (UL) 1642, UL 1973, UL 9540, and United Nations (UN) 38.3, and of the DC/DC converter by TÜV Rheinland to IEC 62109-1, and will be discussed in more detail in Section 8.2 and 8.3. DNV GL agrees that design to these standards is in line with best practices, and has received documentation demonstrating that testing and certification to these standards by a nationally recognized testing laboratory (NRTL) or equivalent have been completed for both the 2-hour and the 4-hour systems.

The Powerpack houses a common plenum connecting vents at the back of each Pod to an exhaust port at the top of the unit. This plenum is designed to allow for a controlled release of any gases generated in the case of thermal runaway. DNV GL believes that this system of thermal management and off-gas mitigation addresses several safety concerns specifically related to propagation of failures within battery energy storage systems. DNV GL believes that such designs will be beneficial to support compliance with emerging standards in the industry for cascading protections.

DNV GL believes Tesla has appropriately mitigated the risk of a single point of failure in its battery pack design. The interconnection of the cells in series and parallel allows Pods to continue operation even in the case that a single cell fails. Further, the loss of a single or even multiple Pods within a Powerpack will not cause a fault of the total unit and should have minimal impact on system performance. In addition, highly modular design allows for efficient servicing, as such operations primarily consist only of swapping out Pods. Thermal management is also handled at the Powerpack level and thus not subject to a single point of failure for the entire Powerpack 2 system, as could be the case for containerized systems with a single HVAC unit.

4.4 Battery evaluation summary

The modularity of the Powerpack design allows for flexibility with respect to meeting project specific needs with a standardized set of modular components. These attributes provide an advantage for safety, the ease of maintenance, system resiliency, capacity management, and system expansion.

DNV GL views the battery Pod design as a key differentiating element in Tesla's energy storage system design, allowing for ease of maintenance and doubled enclosure protection. The liquid thermal management system, used to regulate battery temperature within each of the two battery modules in the Pod, is unique among stationary energy storage for grid applications. DNV GL believes managing temperature in this way provides distinct lifetime performance and safety advantages.

DNV GL believes that the DC/DC converter interconnection between each Pod and the system DC bus offers Tesla's system measurable benefits from a safety, scalability, and manufacturing perspective. The safety benefits of the DC/DC converter design are achieved through hardware isolation of energized battery modules in the event of a fault, while also eliminating much of the protection complexity found in prevalent contactor based protection and isolation systems.

Additionally, the container rating and environmental ranges for operation and storage are in line with industry standards for outdoor installations, especially with the liquid thermal management system. The system's design, if demonstrated to meet the standards claimed, meets current industry standards for safety and has a high level of mitigation against cascading failures.

5 INVERTER EVALUATION

This section evaluates the DC/AC inverter component of the Powerpack 2 System. The Powerpack 2 inverter, developed and manufactured by Tesla is a bi-directional, transformerless inverter with multiple inverter module blocks. The inverter can be configured with one to ten inverter modules for a power range of 54 kW to 540 kW at 400 V AC line voltage, and 65 kW to 650 kW at 480 V AC. Shown in Figure 5-1, the inverter achieves a peak efficiency of 98.9%.

Figure 5-1 Tesla Powerpack 2 Bi-directional Inverter

5.1 Inverter topology

An energy storage inverter is bi-directional, converting the DC electricity generated by the battery into AC power compatible with the utility grid, and converting the AC utility electricity into DC, to charge the batteries. The Tesla Powerpack 2 Inverter uses a multi-level Silicon Carbide (SiC) switching topology, for high efficiency.

Tesla describes the switching frequency as non-audible resulting in lower acoustic noise (<70 dB at 50°C, typically <60 dB at STC), with no tonality. The higher switching frequency enables the Tesla inverter’s controls to run faster than most competitors. The higher switching frequency also allows for a smaller size filter, resulting in a higher power density.

The inverter size is configurable with one to ten rack-mounted modules, as shown in Figure 5-2. The inverter modules use blind-mate power connections for ease of installation. The non-isolated modules, referred to as Powerstages, are paralleled at the Powerpack 2 level, and the same paralleling capability can be continued at the system level, allowing multiple Powerpack 2s to operate together to form larger systems.

Figure 5-2 Internal view of Tesla Powerpack 2 Inverter

The circuit diagram in Figure 5-3 illustrates how multiple Powerpack batteries are paralleled to form a DC bus. The DC bus then feeds one to ten modular inverters known as Powerstages. Circuit protection for the batteries is provided by DC fuses.

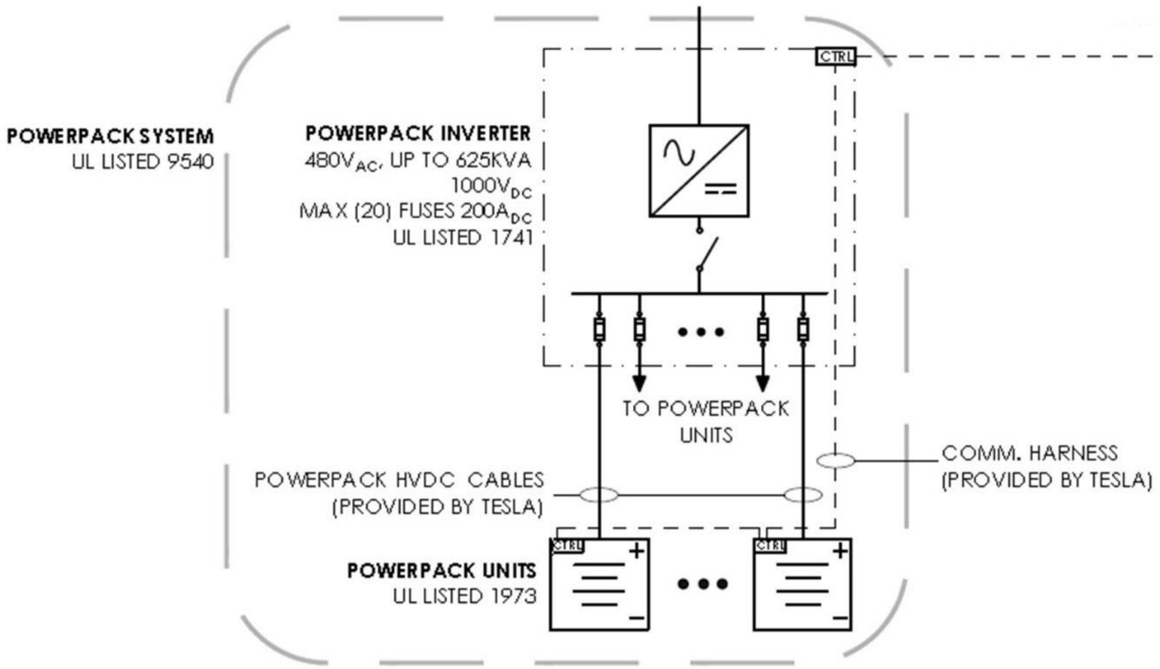


Figure 5-3 Powerpack 2 DC circuit diagram

The circuit diagram in Figure 5-4 provides additional details of the inverter design. Fuses for both the AC and DC circuits provide protection against short circuits. The AC contactor allows disconnection from the grid in the event of a fault condition. The dry-break coolant connections facilitate the field swap-out of inverter modules.

The system was designed to tolerate a failure of an inverter, by disabling the failed unit and distributing the load to the remaining inverters. Fault scenarios tested by Tesla include a short on the DC bus, where the battery modules respond by limiting the short circuit current. Additionally, inverters are protected by DC fuses to open in the event of a short circuit.

The ability to recover from the loss of an inverter provides redundancy in the power conversion stage, potentially increasing the availability of the system significantly.

Tesla describes the inverter's operational capabilities as follows:

> *Tesla's inverter can be operated in three main modes: current source mode, rotating machine mode, and a blended mode that is a combination of the first two modes. The current source mode enables ultra-fast response to commands and a full suite of smart inverter functions detailed by the California Public Utilities Commission Rule 21. The rotating machine mode emulates inertia, is grid forming, provide voltage and frequency stabilization as well as*

harmonics damping. The Inverter can seamlessly go back and forth between the 3 control modes while supporting the grid. The inverter is designed to be used for a broad range of applications with many grid-tied and microgrid functionalities including frequency response, voltage response, active/reactive power prioritization, fast ramping capabilities, a wide range of configurable voltage and frequency ride through, automatic reconnection after a grid fault, black start capability, and full operation in asymmetric grid conditions.

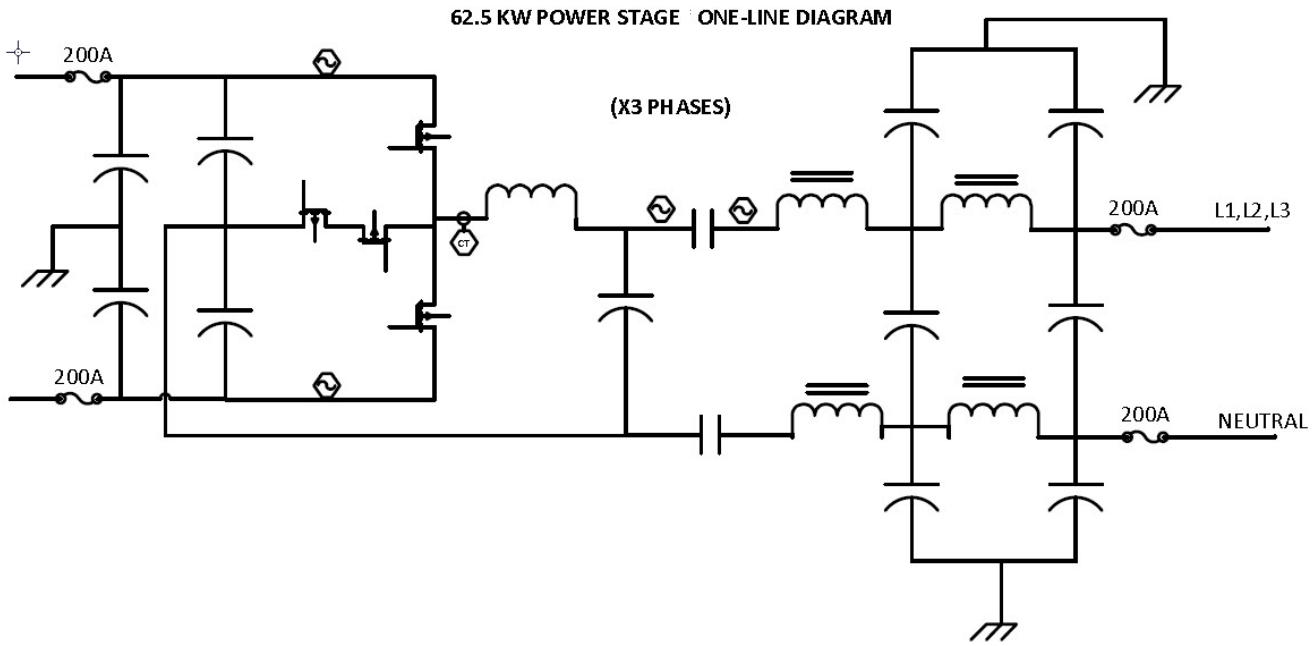


Figure 5-4 Powerpack 2 Inverter circuit diagram

5.2 Inverter technical specification

In Table 5-1, the electrical characteristics for the Tesla Powerpack 2 are listed. The system firmware allows for both 400 V AC and 480 V AC output with 3-phase, 4-wire, Wye grounded output configuration. The 4-wire configuration is required for back-up power applications where loads can be unbalanced. The inverter carries an overload capability of 120% of full load for a maximum of 10 seconds. Overload capability is generally associated with backup power and micro-grid applications where power surge conditions must be accommodated.

The 3-phase, 4-wire output configuration of the Powerpack 2 is necessary to provide backup and micro-grid power for unbalanced loads. This wiring configuration is not compatible with 3-phase, 3-wire ungrounded systems that exist in some manufacturing facilities. Tesla suggests that an isolation transformer will be required to interconnect the Powerpack 2 system to such ungrounded wiring configurations.

Table 5-1 Powerpack 2 electrical specification

Grid-Connected (Utility-Interactive) Mode

Default Voltage	400 VAC	420 VAC	440 VAC	450 VAC	480 VAC
65 kVA Rated Output Power (10 Powerstages)	540 kVA	568 kVA	595 kVA	609 kVA	650 kVA
Overload Capability	120% of rated power (10 sec max)				
Input Voltage Range	880-950 VDC				
Output Voltage Range (steady state voltage)	360-528 VAC (380-480 VAC grid)				
Nominal Frequency (configurable)	50 or 60 Hz				
Frequency Range	40-70 Hz				
Input Current	720 A				
Phases	3				
System configuration	4-wire, Wye grounded				
Max Output Current	65 kVA: 800 A (80 A per Powerstage)				
Peak Efficiency	> 98.9%				
Full Load Efficiency	98.5%				
CEC Weighted Efficiency	98.84%				
Power Factor at Full Load	> 99%				
Adjustable Power Factor (Controller Feature)	-1 to +1				
Total Current Harmonic Distortion (THD)	< 1.2%				
Power Regulation Accuracy	< 2%				
Overvoltage Category	Category III up to 3000 m				
Pollution Degree	III				

Supplemental Specifications for Grid-Forming (Islanding) Mode

Imbalanced Phase Load Power Output	100%

The mechanical specifications for the Tesla Powerpack 2 Inverter are shown in Table 5-2. Tesla notes that the inverter system's physical envelope does not change as the system grows in power rating; however, the inverter gets heavier as inverter modules are added.

Table 5-2 Tesla Powerpack 2 mechanical specifications

Equipment	Length: mm (in)	Width: mm (in)	Height: mm (in)	Weight: kg (lbs)
Powerpack, 2 Hour	1308 (51.5)	822 (32.4)*	2235 (88)**	2102 (4575)
Powerpack Inverter	1014 (39.9)	1254 (49.4)*	2242 (88.3)**	1120 (2470)
Tesla Site Controller	255 (10)	530 (20.9)	730 (28.7)	21.4 (47.2)

**Dimension does not include equipment anchor tabs*

***Dimension includes 2 in. lifting flanges in product height*

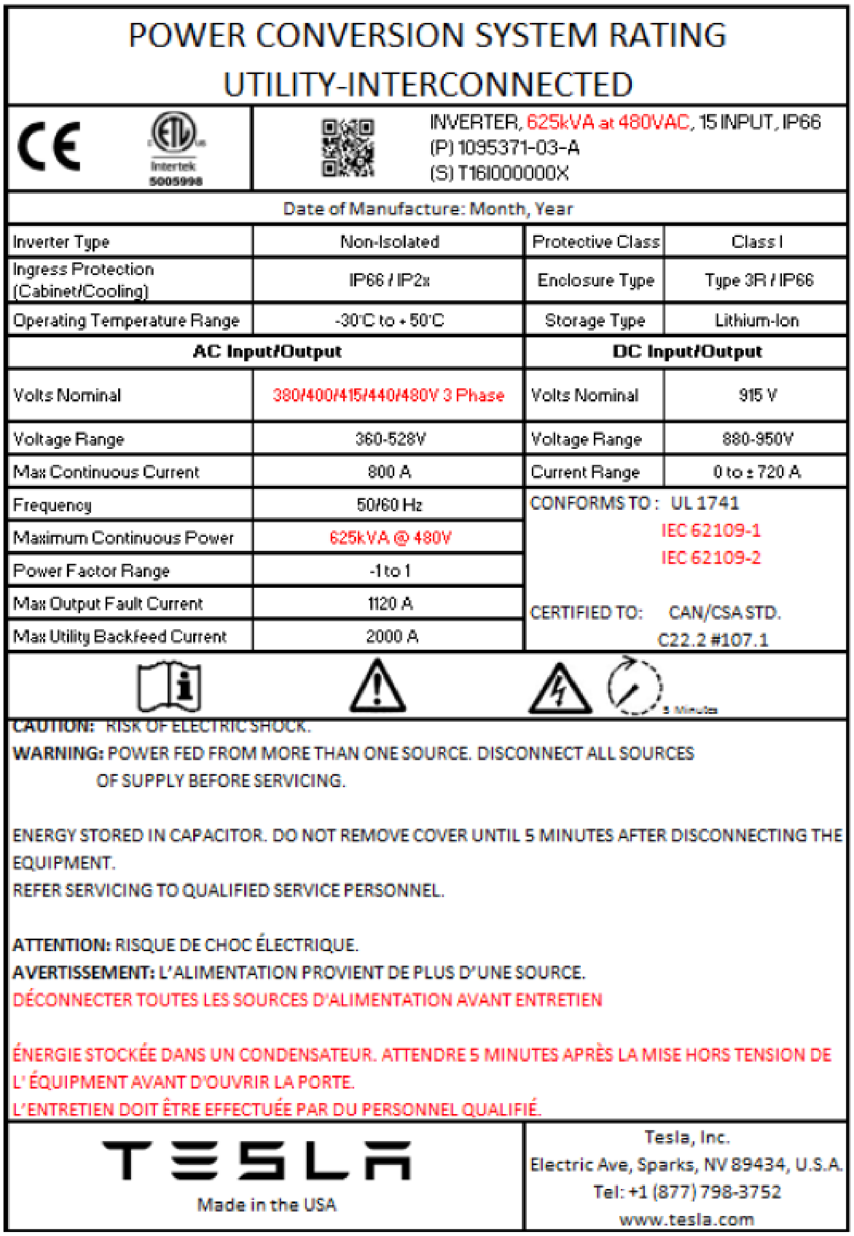
Equipment	Length: mm (in)	Width: mm (in)	Height: mm (in)	Weight: kg (lbs)
Powerpack Unit, 4 Hour	1308 (51.5)	822 (32.4)*	2235 (88)**	2175 (4795)
Powerpack Inverter	1014 (39.9)	1254 (49.4)*	2242 (88.3)**	1120 (2470)
Site Master Controller***	229 (9)	453 (17.8)	499 (19.6)	14 (30)
Tesla Site Controller	255 (10)	530 (20.9)	730 (28.7)	21.4 (47.2)

*Dimension does not include equipment anchor tabs.

**Dimension includes 2 in. lifting flanges in product height.

***The Site Master Controller is the first generation version of the Tesla Site Controller and was phased out in Q2 2018.

The power conversion system rating label for the Powerpack 2 Inverter, with ratings consistent with the output power rating available in August 2017, is shown in Figure 5-5. The label is marked with the Intertek (ETL) symbol, indicating compliance with the standards listed.



POWER CONVERSION SYSTEM RATING
UTILITY-INTERCONNECTED

Intertek 5005998

INVERTER, 625kVA at 480VAC, 15 INPUT, IP66
(P) 1095371-03-A
(S) T16I000000X

Date of Manufacture: Month, Year

Inverter Type	Non-Isolated	Protective Class	Class I
Ingress Protection (Cabinet/Cooling)	IP66 / IP2x	Enclosure Type	Type 3R / IP66
Operating Temperature Range	-30°C to +50°C	Storage Type	Lithium-Ion
AC Input/Output		**DC Input/Output**	
Volts Nominal	380/400/415/440/480V 3 Phase	Volts Nominal	915 V
Voltage Range	360-528V	Voltage Range	880-950V
Max Continuous Current	800 A	Current Range	0 to ± 720 A
Frequency	50/60 Hz	CONFORMS TO: UL 1741, IEC 62109-1, IEC 62109-2	
Maximum Continuous Power	625kVA @ 480V		
Power Factor Range	-1 to 1		
Max Output Fault Current	1120 A	CERTIFIED TO: CAN/CSA STD. C22.2 #107.1	
Max Utility Backfeed Current	2000 A		

5 Minutes

CAUTION: RISK OF ELECTRIC SHOCK.
WARNING: POWER FED FROM MORE THAN ONE SOURCE. DISCONNECT ALL SOURCES OF SUPPLY BEFORE SERVICING.

ENERGY STORED IN CAPACITOR. DO NOT REMOVE COVER UNTIL 5 MINUTES AFTER DISCONNECTING THE EQUIPMENT.
REFER SERVICING TO QUALIFIED SERVICE PERSONNEL.

ATTENTION: RISQUE DE CHOC ÉLECTRIQUE.
AVERTISSEMENT: L'ALIMENTATION PROVIENT DE PLUS D'UNE SOURCE.
DÉCONNECTER TOUTES LES SOURCES D'ALIMENTATION AVANT ENTRETIEN

ÉNERGIE STOCKÉE DANS UN CONDENSATEUR. ATTENDRE 5 MINUTES APRÈS LA MISE HORS TENSION DE L' ÉQUIPMENT AVANT D'OUVRIR LA PORTE.
L'ENTRETIEN DOIT ÊTRE EFFECTUÉE PAR DU PERSONNEL QUALIFIÉ.

TESLA
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Figure 5-5 Powerpack 2 Inverter label

5.3 Inverter environmental characteristics

Based on the information provided in Table 5-3, the Tesla Powerpack 2 Inverter is rated to +50°C, which is adequate for most locations in North America. The low temperature limit of -30°C is also adequate for most but not all locations in North America, and the system can tolerate short durations below this limit. However, for locations with prolonged exposure to temperatures significantly below -30°C, Tesla recommends installing the system in a building with environmental controls. The system will also self-protect when the ambient temperature exceeds +55°C, and not operate.

The installation manual does not limit exposure to sun nor rain and snow for potential installation sites. The inverter is also rated for operation up to an elevation of 3,000 meters without power derating. DNV GL finds the elevation rating of the Tesla Powerpack 2 Inverter also suitable for most locations in North America.

The liquid cooling equipment is described as "fully redundant" which allows the inverter to operate in the event of a failure in one of the fans or pumps, to the full rating of the system.

Table 5-3 **Tesla Powerpack 2 inverter's environmental specifications**

Operating Temperature	-30ºC to 50ºC (-22ºF to 122ºF)
Storage Temperature	-40ºC to 60ºC (-40ºF to 140ºF)
Humidity	Up to 100% condensing
Maximum Altitude	3000 m (9840 ft) above sea level
Noise	< 70 dBA at 1 meter
Ingress Rating	IP66, NEMA 3R
Impact Rating	IK09
Seismic Rating	High seismic level, 1.0g ZPA, 2% damping per IEEE 693-2005

The Tesla Inverter carries an Ingress Rating of IP 66, NEMA 3R which indicates the inverter is dust proof and protected against jets of water, one of the top ingress ratings in the inverter industry.

The impact and seismic ratings represent the efforts by Tesla to harden and protect the product against potential damage from shipping and earthquakes, making for a more reliable inverter.

5.4 Power quality and grid support

In Figure 5-6 the reactive and real power capacities of the Tesla Powerpack 2 Inverter are shown under operation at 400 V AC, however, Tesla claims that the data in Figure 5-6 are also applicable at 480 V AC. The chart shown represents the performance of a 10-Powerstage inverter system. The chart indicates that under all AC line voltage conditions shown, the inverter can deliver a combination of real and reactive power, up to the system's kVA limit. The inverter can supply any level of reactive power, up to the kVA limit; however, as shown in Figure 5-6, the real power output level will be reduced to provide reactive power. The capabilities described are typical for energy storage inverters designed, in part, with grid support features.

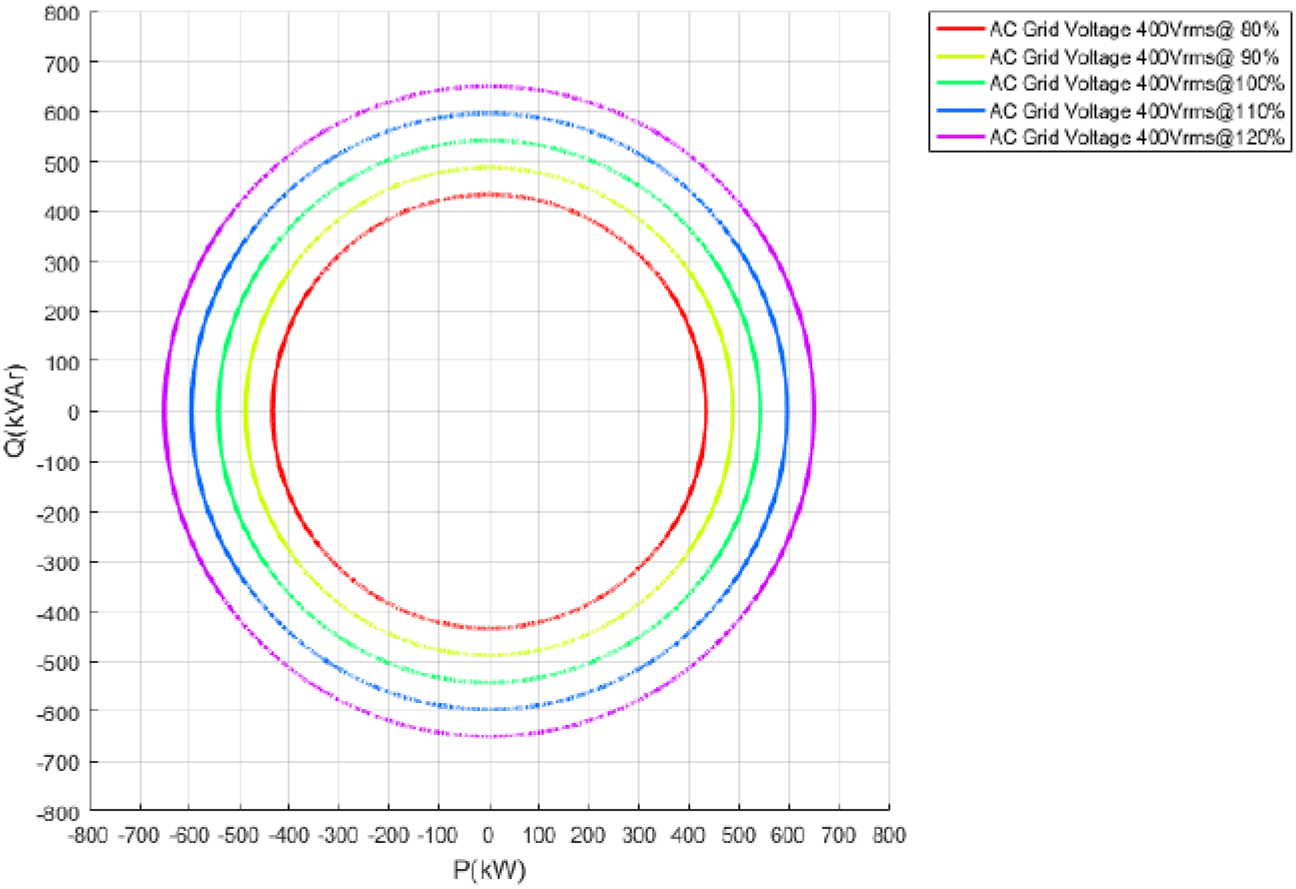


Figure 5-6 Powerpack 2 reactive power capacity

Grid support can also refer to the ability to survive short circuit conditions on the AC grid while providing AC current to clear fault conditions. The test waveforms in Figure 5-7 demonstrate that, when exposed to a single phase-to-neutral short circuit, the inverter provided current for approximately 174 ms before shutting down. The data demonstrates the basic functionality of a ride-through test. However, since the grid voltage did not recover during the 174 ms period, the inverter stopped operation rather than continue to ride-through. This aligns with expected performance based on a programmed ride-through response within the inverter.

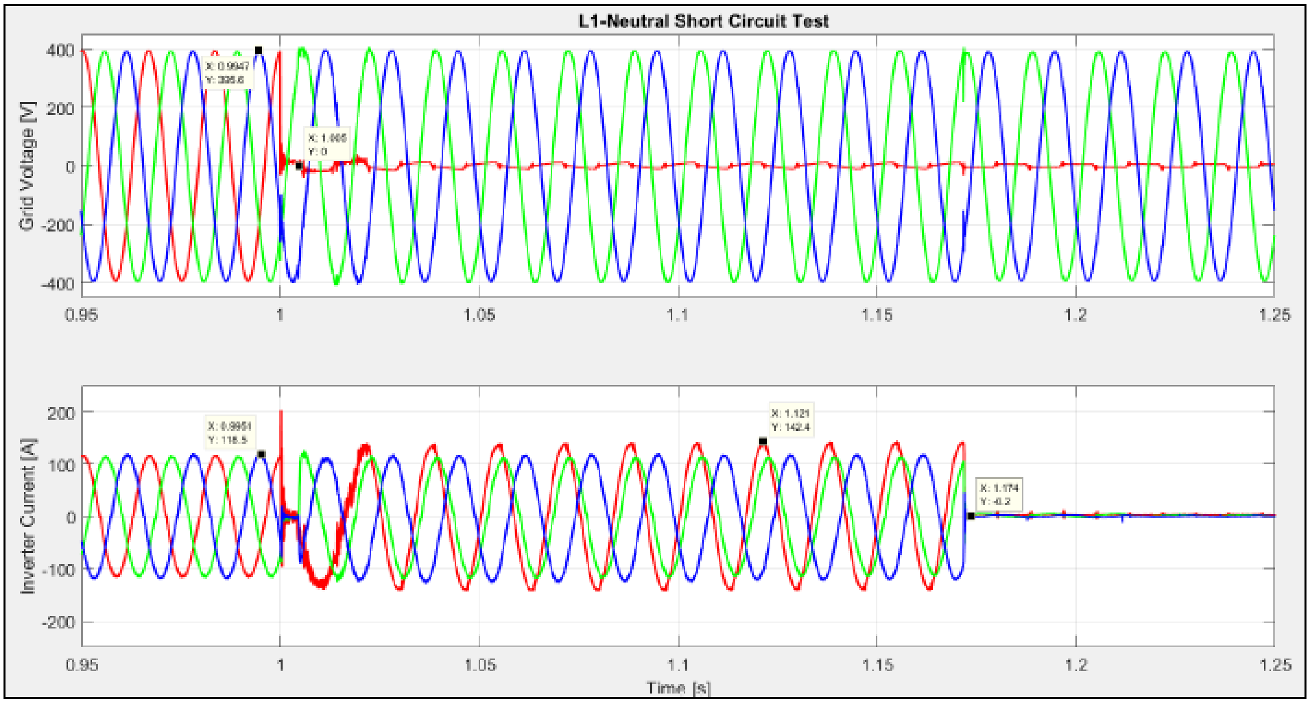


Figure 5-7 L1 to neutral short circuit test

Each Tesla Powerpack 2 Inverter is programmed with standard voltage ride-through limitations as shown in Figure 5-8. Low-voltage ride-through and high-voltage ride-through pairs of magnitude and time data are configurable, allowing the system operator to configure ride-through characteristics that meet local requirements.

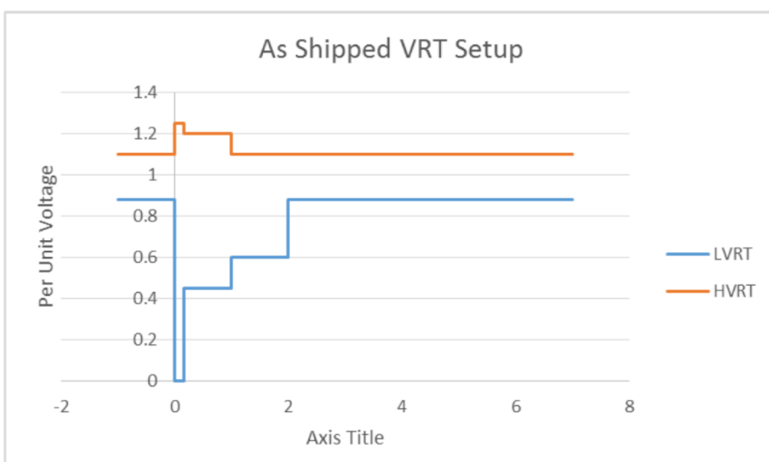


Figure 5-8 Voltage ride-through limitations

The Tesla Powerpack 2 Inverter also provides the following grid-support features:

- Frequency ride-through
- Adjustable output ramp rate control
- Frequency – Watt control
- Volt – VAR control
- Volt – Watt control
- Balanced power or current option
- Real or reactive power prioritization
- Anti-islanding and rate of change of the grid frequency anti-islanding
- Seamless island/grid transitions
- Inertia with rotating machine mode

DNV GL did not verify the functionality of the list of grid-support features as a part of this review.

Tesla provided high- and low-voltage and high- and low-frequency ride-through test reports that showed Powerpack 2 demonstrated the expected system response to out-of-range voltage and frequency conditions.

Tesla also provided test data verifying compliance with IEEE 1547 requirements for tolerance of abnormal voltage and frequency conditions. DNV GL found that the inverter’s performance demonstrated met the standard’s requirements.

DNV GL reviewed detailed harmonics data for a single Powerstage Powerpack 2 Inverter and found the inverter to meet IEEE 519 Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems, with measured harmonics well below the IEEE 519 recommendations. Additionally, DNV GL reviewed a full set of harmonics data for a complete Powerpack 2 Inverter operating at three power levels, including full load operation at 625 kW. All harmonic data reviewed were in magnitude well below the IEEE 519 limits.

5.5 Stand-alone operation

The Tesla Powerpack 2 Inverter has the capability to operate in an island or stand-alone configuration to power a local load, and to manage the load share among connected Powerpack 2 systems and solar PV inverters. The evaluation of the capabilities and the review of test data were outside of the scope of this review, due in part, to the magnitude of effort required to verify operation with the many possible system configurations, loads, and parallel sources.

5.6 Inverter efficiency

One of the key metrics for energy storage inverters is the operating efficiency. The Tesla Powerpack 2 Inverter was designed to operate over a narrow DC voltage range, allowing the design to be optimized for conversion efficiency at a relatively high DC input voltage. Tesla reports the peak efficiency at 98.9% and full load efficiency at 98.5%, which are among the best for power converters for similar applications.

DNV GL reviewed detailed efficiency data for the Tesla Powerpack Inverter and confirmed the peak and full load efficiencies reported. The data did not include details of the test and ambient conditions, therefore, the efficiency stated should be considered achievable at optimum test conditions rather than standard field conditions.

5.7 Quality and reliability

Tesla provided the document, "Test Reliability Program Overview", describing the 10-process program. The 10 individual processes that comprise the program are as follows:

- Reliability Allocation
- Supplier Selection
- Lessons Learned
- Design Failure Modes and Effects Analysis (DFMEA) and Production Failure Mode and Effects Analysis (PFMEA)
- Simulations
- Validation Testing
- Reliability Demonstration
- Risk Assessment
- Ongoing Reliability Testing (ORT) and Burn-in
- Field Reliability

The flowchart in Figure 5-9 shows how the steps in the Test Reliability Program interrelate.

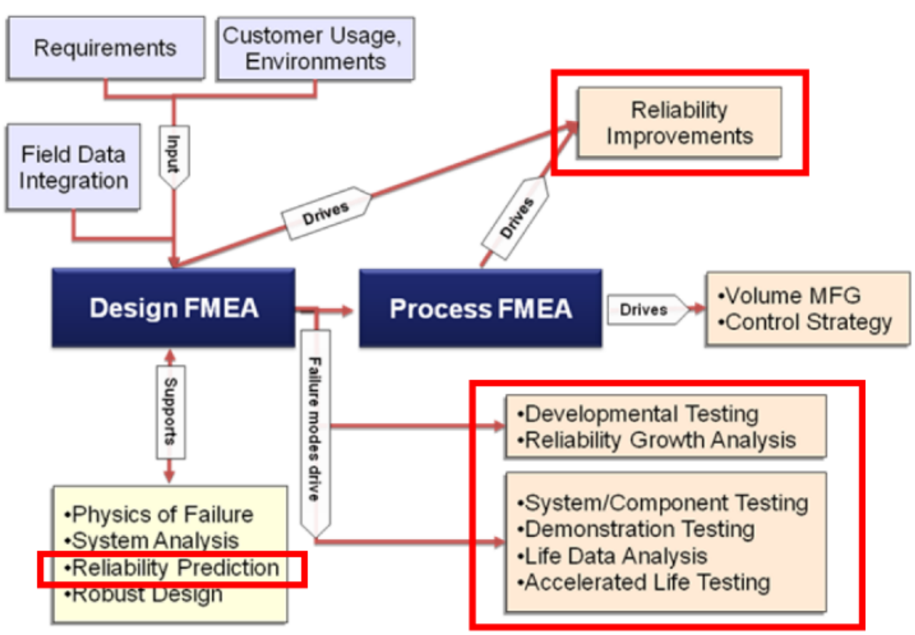


Figure 5-9 Flow chart of Test Reliability Program

5.8 Inverter reliability evaluation

Reliability is a key metric of the performance of all power inverters.

The three main areas that DNV GL reviews when evaluating inverter reliability are:

- Design for reliability
- Reliability testing
- Field reliability history

5.8.1 Design for reliability

Many elements go into design for reliability. These include component selection, derating, analytical reliability calculations, and failure mode analysis.

The Powerpack 2 inverter was designed for a 20-year life. System availability is the key metric tracked by Tesla to report progress in achieving reliability goals. Tesla allocates reliability requirements based on achieving system availability targets.

The Tesla Powerpack 2 Inverter provides redundancy in the form of multiple inverter modules, operating in parallel. With redundancy at the module level, the ability to meet the availability target is enhanced. Generally, an availability target can be met by providing a rapid service response to failures. However, with redundancy providing further support for availability, the importance of a rapid response is reduced. Circuit reliability remains an important metric of design quality; however, the redundancy design approach used by Tesla reduces its role in system availability.

Clearly, systems with redundant components can improve system availability. However, redundant components result in a higher total number of components, which is the case for the Powerpack 2 Inverter system. As a general guideline, systems with more components are less reliable, resulting in more field service calls. To summarize, redundant components tend to significantly enhance system availability, while at the same time, requiring more component replacements. Tesla has chosen to optimize availability in addition to other design objectives, which is consistent with the expectations of system owners.

5.8.1.1 Inverter component selection and derating

One important element of achieving high product reliability is the selection of quality parts and design for operation at appropriate stress levels which will allow the components to perform reliably for their service lifetimes.

It is common for electronic product manufacturers to implement in-house design guidelines for the levels of stress at which individual components can operate. This includes derating factors below the component specification limits for parameters such as semiconductor device junction temperature, capacitor ripple current, applied voltage, and ambient temperature.

DNV GL reviewed thermal data for inverter operation under extreme test conditions where the coolant temperature was elevated to +70°C; at least 10°C above worst case conditions in a +50°C ambient environment.

Analysis by Tesla indicates the DC capacitors have the smallest thermal design margin under high load, high ambient temperature conditions. Tesla has consulted with the capacitor manufacturer gaining assurances that the capacitors in use will tolerate the worst-case load conditions, while meeting the capacitor life requirements. DNV GL has reviewed the thermal design margins for the Powerpack 2 Inverter and found the margins to be adequate.

5.8.1.2 Inverter Mean Time Between Failure

DNV GL believes that an important analytical approach for evaluating the reliability of a power inverter is to calculate the product mean time between failure (MTBF). Tesla does not consider the MTBF calculation to provide useful reliability information beyond their component-level evaluations, and therefore did not perform the calculation. DNV GL recommends the inclusion of this information.

5.8.1.3 Inverter FMEA

Failure Mode and Effects Analysis (FMEA) was one of the first systematic techniques for failure analysis. It was developed by reliability engineers in the 1950s to study problems that might arise from malfunctions of military systems. An FMEA is often the first step of a system reliability study. It involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, and their causes and effects. For each component, the failure modes and their resulting effects on the rest of the system are recorded in a specific FMEA worksheet. There are numerous variations of such worksheets.

A successful FMEA activity helps to identify potential failure modes based on experience with similar products and processes—or based on common physics of failure logic. It is widely used in development and manufacturing industries in various phases of the product life cycle.

Tesla provided a 12-page FMEA Process Overview document with a thorough description of the process as performed internally by Tesla. A FMEA worksheet was provided showing a thorough and rigorous list of performance tests and recommendations and actions to be taken if failures of components have occurred. This demonstrates Tesla's standards for performance and reliability.

DNV GL reviewed an extensive Design FMEA for the Powerpack and associated inverter, which included an exhaustive study of failure modes, effects, and recommended actions to mitigate the failures. The Design FMEA represents a significant investment of effort by Tesla to understand the potential effects of failure modes of all types and origins.

DNV GL also reviewed a PFMEA focusing on production related failure modes, effects, and mitigating actions. The PFMEA was created applying a standard software package that Tesla uses for the vehicle production.

5.9 Inverter testing

Tesla provided a list of reliability tests performed on the Powerpack 2, which consisted of 198 individual tests applied to the inverter and battery module. A total of 74 tests were performed on inverters, or the entire system including the inverter, consisting of the following:

- PTCE – Power Temperature Cycling Endurance
- HTOE – High Temperature Operational Endurance
- HTHE – High Temperature Humidity Endurance
- CTS – Coolant Thermal Shock
- Pressure Cycle – Test of cooling system

- LTOE & PTCE – Low Temperature Operational Endurance and Powered Temperature Cycling Endurance
- Shipping Vibration and Seismic – Test of the system's ability to withstand shipping and seismic events

The test results are recorded in Tesla's online system of reliability test data. DNV GL has reviewed samples of the data records where actions, dates and the names of test personnel are recorded.

5.9.1 Inverter Design Verification Testing

The design verification testing (DVT) is generally the first group of verification tests performed on a new design. The tests range from simple verifications of power supply voltages to extensive tests of full-load operation, based on the test protocol applied.

DNV GL observes that the tests performed by Tesla are recorded directly into their online data system, and do not result in hardcopy test reports that would facilitate review by external third-party engineers. This process of data gathering and storage is growing in the industry. As such, while DNV GL viewed the processes on screens during a site visit (described in Section 12), details of these screens were not provided for desktop review, and thus DNV GL cannot comment on them in detail.

The DVT falls into the category of tests that were certainly performed at some point by Tesla. The entire reliability test program cannot be performed unless the unit complies to the basic functionality described in the specification. DNV GL, however, was not able to perform a desktop review of these tests and cannot comment on them further.

5.9.2 Inverter highly accelerated lifetime testing

Highly accelerated lifetime testing (HALT) is a method of testing electronic equipment in a relatively short period to determine whether it will have reliable performance over its expected operating life. This is done using test chambers and techniques to apply stresses on the components that are beyond those that it is expected to normally encounter. This typically includes high and low temperatures, temperature ramping, and vibration. The equipment is exposed to the high levels of stress and then issues are addressed as they are found. DNV GL believes that HALT is a critical part of the developmental process for a highly reliable product.

HALT is unlike tests performed within the limits of the specification; it is designed to take the equipment to failure. Some reliability engineers believe that HALT only creates failure modes that will not occur during operation under typical conditions. Additionally, as the products grow in size and weight, HALT becomes increasingly difficult to perform. For large systems, often critical printed circuit board assemblies are tested individually.

Tesla did not provide HALT data. Some of the system-level reliability tests performed by Tesla are similar to HALT, however, are not designed specifically to induce failures. Additionally, Tesla states that component-level statistical reliability testing of components is performed in the place of HALT.

5.9.3 Summary of inverter testing

The inverter tests performed by Tesla are typical of those performed by the well-established central inverter manufacturers for solar PV. Tesla tested more modules when compared to central inverter tests, taking advantage of the smaller inverter modules that make testing easier. Comparisons are made between the Tesla energy storage inverter and the solar PV central inverters because of the similarities in functionality, and the general lack of energy storage inverters on the market with which to compare. In some cases, Tesla has not provided test data; in these areas, DNV GL has noted that it cannot comment on such claims.

5.10 Regulatory and standards

5.10.1 Applicable standards

For the North American markets, the UL 1741 Standard is the "Standard for Safety - Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources." It is based on the IEEE 1547 "Standard for Interconnecting Distributed Resources with Electric Power Systems." A UL 1741 listing is generally required for all inverters that connect to the utility grid in North America and employed in residential or commercial sized systems. Certification to this standard involves a series of design inspections and tests. Especially challenging are the anti-islanding, grid protection, surge, and EMI testing requirements. Further, UL 1741 SA "Supplement for Grid Support Utility Interactive Inverters and Converters" is intended to be an additional standard, demonstrating compliance with Hawaiian and Californian grid requirements, preventing unintentional discharge to the grid.

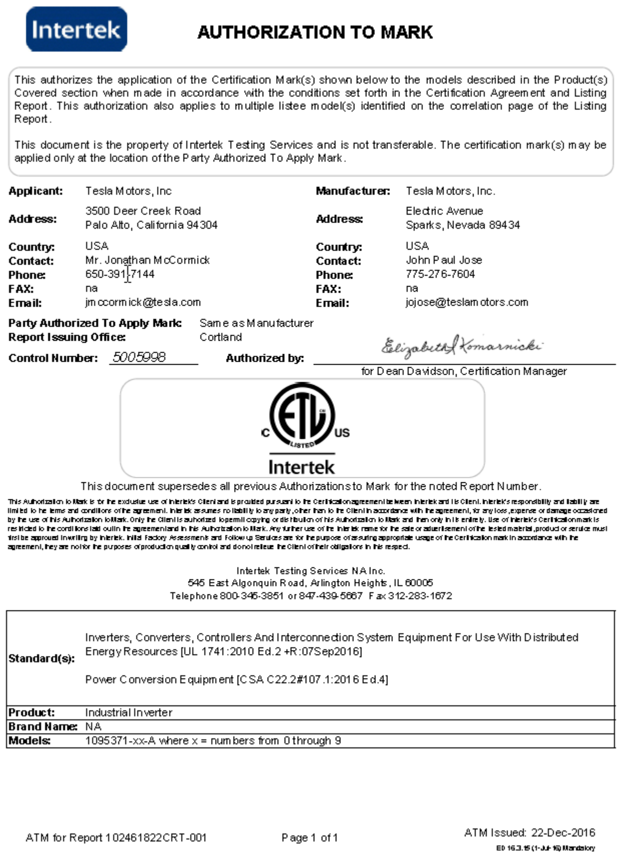
Below in Table 5-4 are the major testing standards for North America.

Table 5-4 Testing Standards for North America

Standard	Title
UL 1741	Standard for Safety Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
IEEE 1547	Standard for Interconnecting Distributed Resources with Electric Power Systems
CSA 22.2N. 107.1-01	Safety Requirements for General Use Power Supplies (Canada)

5.10.2 Regulatory test reports and certifications

In Figure 5-10, the letter of Authorization to Mark the Powerpack 2 system with Intertek's ETL symbol for certification to both U.S. and Canadian standards is shown.



AUTHORIZATION TO MARK

This authorizes the application of the Certification Mark(s) shown below to the models described in the Product(s) Covered section when made in accordance with the conditions set forth in the Certification Agreement and Listing Report. This authorization also applies to multiple listee model(s) identified on the correlation page of the Listing Report.

This document is the property of Intertek Testing Services and is not transferable. The certification mark(s) may be applied only at the location of the Party Authorized To Apply Mark.

Applicant:	Tesla Motors, Inc	**Manufacturer:**	Tesla Motors, Inc.
Address:	3500 Deer Creek Road Palo Alto, California 94304	**Address:**	Electric Avenue Sparks, Nevada 89434
Country:	USA	**Country:**	USA
Contact:	Mr. Jonathan McCormick	**Contact:**	John Paul Jose
Phone:	650-391-7144	**Phone:**	775-276-7604
FAX:	na	**FAX:**	na
Email:	jmccormick@tesla.com	**Email:**	jojose@teslamotors.com

Party Authorized To Apply Mark: Same as Manufacturer
Report Issuing Office: Cortland
Control Number: 5005998 **Authorized by:** Elizabeth A Komarnicki
for Dean Davidson, Certification Manager

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Intertek

This document supersedes all previous Authorizations to Mark for the noted Report Number.

This Authorization to Mark is for the exclusive use of Intertek's Client and is provided pursuant to the Certification agreement between Intertek and its Client. Intertek's responsibility and liability are limited to the terms and conditions of the agreement. Intertek assumes no liability to any party, other than to the Client in accordance with the agreement, for any loss, expense or damage occasioned by the use of this Authorization to Mark. Only the Client is authorized to permit copying or distribution of this Authorization to Mark and then only in its entirety. Use of Intertek's Certification mark is restricted to the conditions laid out in the agreement and in this Authorization to Mark. Any further use of the Intertek name for the sale or advertisement of the tested material, product or service must first be approved in writing by Intertek. Initial Factory Assessments and Follow up Services are for the purpose of assuring appropriate usage of the Certification mark in accordance with the agreement, they are not for the purposes of production quality control and do not relieve the Client of their obligations in this respect.

Intertek Testing Services NA Inc.
545 East Algonquin Road, Arlington Heights, IL 60005
Telephone 800-345-3851 or 847-439-5667 Fax 312-283-1672

Standard(s):	Inverters, Converters, Controllers And Interconnection System Equipment For Use With Distributed Energy Resources [UL 1741:2010 Ed.2 +R:07Sep2016] Power Conversion Equipment [CSA C22.2#107.1:2016 Ed.4]
Product:	Industrial Inverter
Brand Name:	NA
Models:	1095371-xx-A where x = numbers from 0 through 9

ATM for Report 102461822CRT-001 Page 1 of 1 ATM Issued: 22-Dec-2016
ED 16.3.15 (1-Jul-16) Mandatory

Figure 5-10 Authorization to apply UL 1741 mark from Intertek

DNV GL reviewed the initial factory assessment report and the follow-up service report created by Intertek during visits to the Tesla Gigafactory. All items reviewed by Intertek were reported as in-order, with no non-compliances requiring Tesla's response noted.

Additional inverter certifications for Tesla Powerpack 2 Inverter verified by DNV GL include:

- AS/NZS 4777.2:2015 Grid connection of energy systems via inverters, Part 2: individual requirements
- TROV2 Transient Over-Voltage and Frequency & Ride-Through Requirements for Inverter-Based Distributed Energy Resources, Full Frequency and Voltage Ride-through Settings of Oahu, Hawaii, Maui, Molokai, and Lanai

5.11 Inverter field history

As part of the initial report, Tesla provided a summary of fleet performance for the Powerpack, covering 76 customer sites in 8 countries. Additionally, Tesla provided a fleet summary listing approximately 300 systems consisting of Powerpack 1, Powerpack 1.5, and Powerpack 2 systems. Approximately 10% of these systems were Powerpack 2, the subject of this report.

To update the report, an auto-generated summary of the Industrial Storage Component Replacements for one week, with total replacements for the last one-year period, was provided to DNV GL. The Powerstage accounted for 175 replacements over the one-year period, which represents approximately a 4.7% annual failure rate. Of the seven subcategories under the Powerstage heading, the “Cascading Failure” and “SiC Failure” were the top two subcategories reported. While both subcategories are associated with the power conversion, silicon-carbide switching devices, the cascading failure is an effect of the SiC failure and mitigated separately. Tesla claims that cascading failure can be eliminated independently from the SiC failure. As indicated in this report, with over 450 Powerpack systems installed, consisting of multiple Powerstages, the number of operational Powerstages is adequate to view failure data as statistically significant. Based on the data presented, it was not clear whether the failure trend was increasing or decreasing; however, with 3 of the 175 replacements in the latest week reported, the failure rate for the latest week was near the average, indicating a steady-state failure rate.

Tesla performed a detailed analysis of the Powerstage failures and reported that >80% of the failure modes have been identified and addressed, with corrective actions pending verification. Following comprehensive lab tests, Tesla intends to release a Powerstage variant to prevent the reoccurrence of the failures. Given these corrective actions are effective, DNV GL anticipates increasing inverter reliability in the future.

Even given the 4.7% failure rate, the Powerpack configuration utilizes multiple Powerstages operating in parallel, resulting in a limited impact on system availability. DNV GL has reviewed the way the inverter isolates a faulted Powerstage and continues to operate while that single Powerstage remains in the faulted state. The inverter hardware configuration includes a separate AC contactor for each Powerstage, allowing the inverter to disconnect a faulted unit on the AC side. The inverter’s firmware then automatically adjusts operation based on the reduced number of operational Powerstages and resumes operation. The multi-Powerstage configuration of the inverter also facilitates the rapid exchange of Powerstages, in the event of a failure.

5.12 Summary of the Tesla Powerpack 2 Inverter

This section of the Technology Review focuses primarily on the technological aspects of the Powerpack 2 Inverter, designed and manufactured by Tesla. The topology consists of multiple Powerstages, creating a scalable inverter platform with power circuit redundancy. The Powerstages consist of a multi-level SiC switching topology, for high efficiency.

The inverter is certified to UL 1741 by Intertek and is actively being deployed in North America as well as internationally. The inverters are provided with enclosures suitable for outdoor use, with temperature and elevation ratings adequate for most locations in North America.

The use of multiple Powerstages should result in higher availability, because a Powerstage failure can be isolated, allowing the remaining Powerstages to carry the load. The use of the Tesla-designed inverter in the Powerpack 2 system started relatively recently. DNV GL anticipates increasing Powerstage reliability as Tesla implements improvements in the Powerstage design.

6 TESLA SITE CONTROLLER AND OPTICASTER SOFTWARE REVIEW

6.1 Controller overview

The Tesla Site Controller serves as the controller and hosts the hardware and software applications that command the charge and discharge functions, monitoring, and control of the Powerpack 2 system. It is the single point of interaction with third-party interfaces, customer supervisory control and data acquisition (SCADA) systems, and Tesla servers. The Tesla Site Controller collects on-site telemetry data from individual Powerpack units, inverters, and meters and passes relevant logs and alerts to Tesla for remote diagnostic and maintenance. It is also responsible for collecting feedback data from each of the individual inverter units, running algorithms to optimize the system operation, and providing commands to inverter units. Users can access and update the energy storage operational status and control interface locally through Tesla's REST API (Representational State Transfer Application Program Interface).

The Tesla Site Controller communicates using the following protocols:

- With external interfaces: Modbus over TCP/IP over Ethernet or DNP3 to external interfaces
- With Tesla servers: cellular GSM (default) or a wired interconnection (optional)
- With each inverter block: private TCP over Ethernet network, physically separate from other communications

One Tesla Site Controller is required per point of interconnection and is provided pre-assembled and configured for each site in a NEMA 3R enclosure. The Tesla Site Controller is seen relative to the other major components in the Powerpack 2 System in the block diagram in Figure 6-1, notated within that image as "Powerpack Controller".

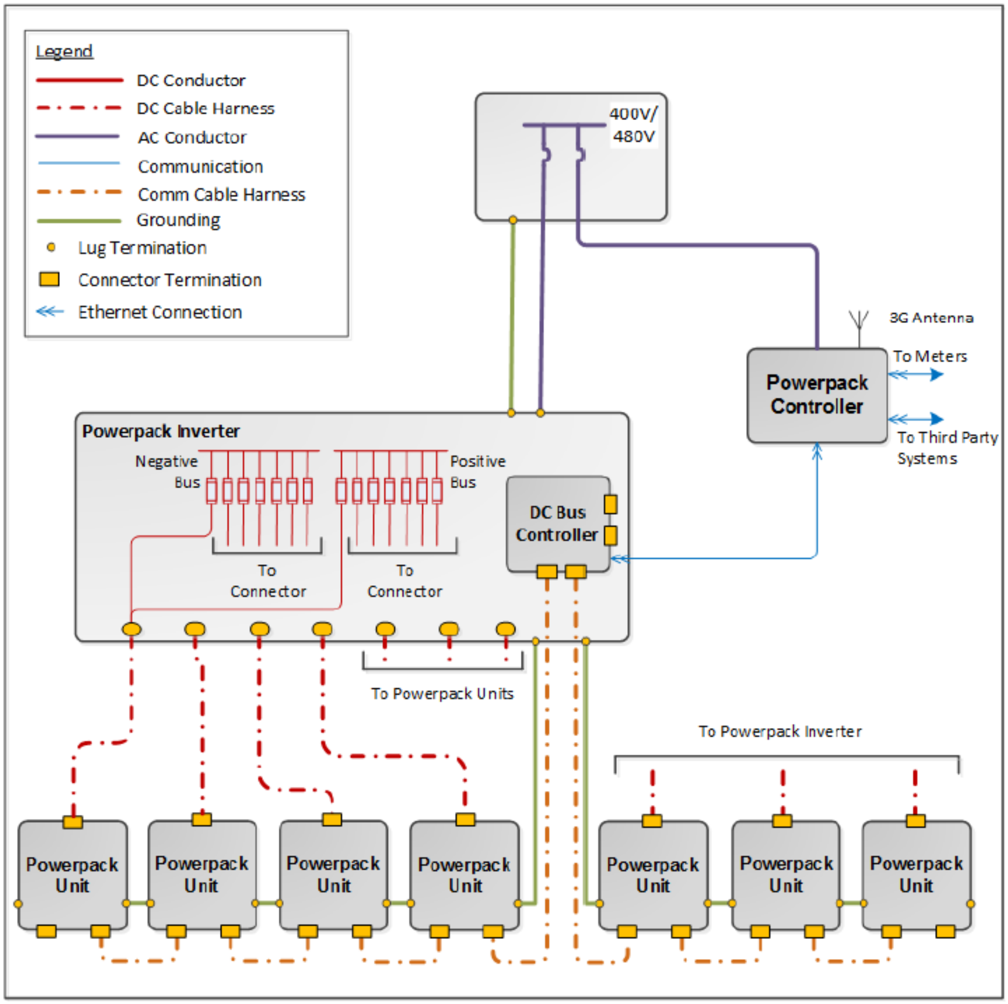


Figure 6-1 Powerpack 2 system block diagram

6.2 Controller hardware description

The Tesla Site Controller communicates to each inverter block over a private TCP network. Each inverter block receives a charge or discharge command from the Controller, which will then trigger a command to the DC bus to activate the Pods, while simultaneously sending a power command to the inverter, controlling its block of Powerpacks. If more than four Powerpack inverters are required for the site, multiple inverter blocks are aggregated via Ethernet to a network switch typically sized to 2.5 MW blocks. Each network switch is connected via a fiber ring to the Tesla Site Controller, as shown in Figure 6-2 below (labeled as "Tesla Site Master Controller").

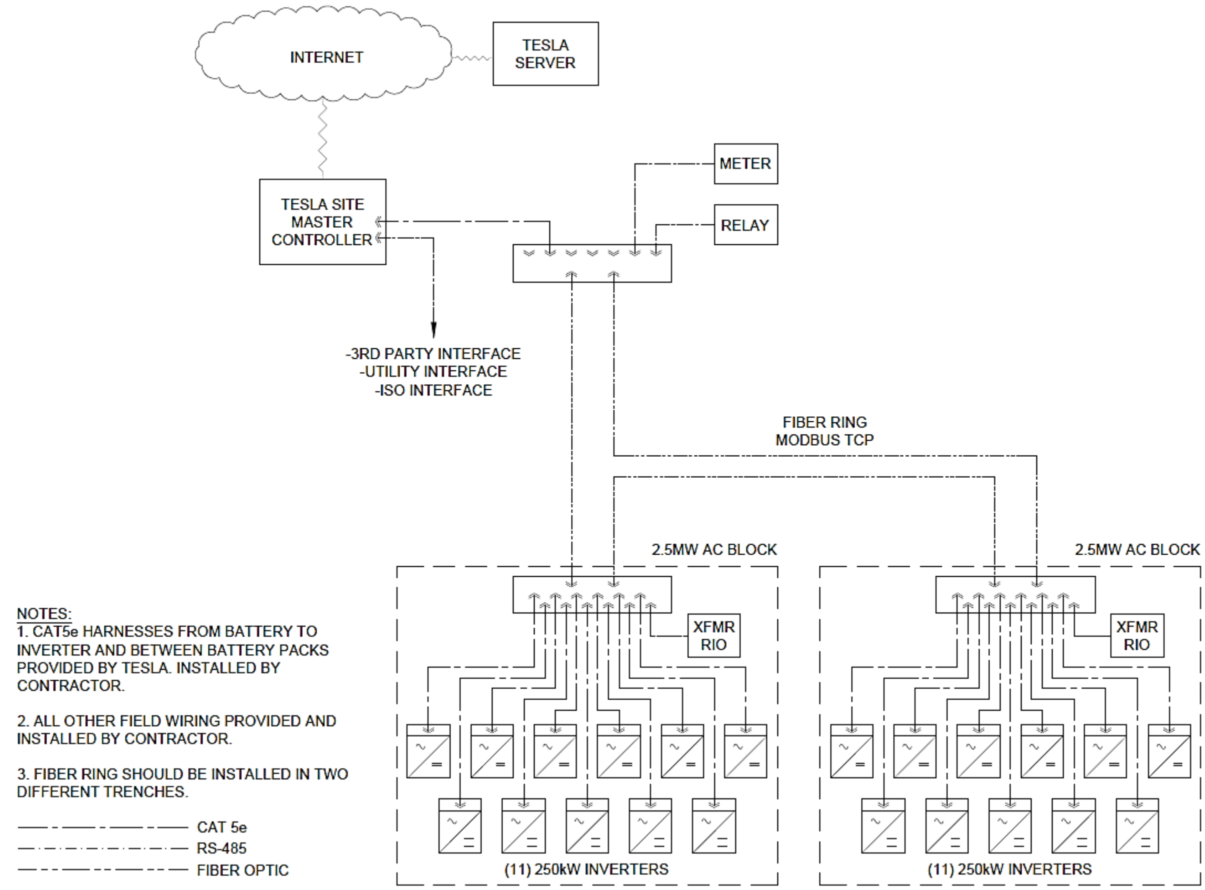


Figure 6-2 Powerpack 2 System AC block connections

The Tesla Site Controller resides inside the Site Master Assembly, which is a collection of equipment housed in an UL Recognized NEMA 3R enclosure, rated for outdoor installation. The complete Site Master Assembly is typically installed on a stand-alone, site specific structure as described in the installation manual, such as a frame constructed of Unistrut. Multiple conduits enter the bottom of the enclosure, routing the communications cables necessary to link all the inverters and DC bus controllers. Currently, although the hardware within the enclosure may vary slightly based on the communication and control needs of the individual sites, typically this enclosure houses the following:

- Site controller (computer)
- Site specific data communications equipment
- DC power supply
- AC fuses
- Control transformer
- Surge arrestors

6.3 Controls software review

This section focuses on a review of the conceptual design, performance, reliability, and security features of the Tesla Opticaster software in the Tesla Site Controller for behind-the-meter Powerpack applications. The Opticaster software is used for both optimizing the Powerpack 2 System size during design and optimizing storage dispatch during operations through forecasting and real-time control.

Tesla has modeled, simulated, and written controls for grid-connected battery systems since 2011. The first algorithms were implemented in 2012, and Tesla claims that they have improved over time through the utilization of actual customer load data for installed systems. The Tesla development team includes individuals with modeling, optimization, controls, software, and embedded firmware experience both at Tesla and prior to Tesla. As of Q4 2018, Tesla reports that the Opticaster product is fully deployed, operated, and maintained on over 180 commercial and industrial systems and for over 2,600 residential units across 16 countries.

6.3.1 Powerpack operational states, modes, and uses

The Powerpacks can be controlled to operate in a variety of modes. These modes of operation are applicable to both grid-tied and behind-the-meter uses and can also be used to provide ancillary services to the grid. These control modes can ultimately be used to provide emergency backup power, peak shaving, demand response, transmission & distribution support, capacity firm, and frequency response. The system has three inherent states, based on commands provided:

- Active – System is charging or discharging.
- Ready – System has no output, but is ready to receive a command to charge or discharge. System will maintain batteries in optimal battery state.
- Off – System has zero output, with DC bus and thermal management shut off.

The user can control the system behavior by selecting the appropriate operational mode and enabling the desired features, identified in Table 6-1. Real and reactive power modes can be operated together, selecting set points or ranges within which the system must operate, while simultaneously controlling for additional applications highlighted under "Add-On", commonly the Frequency Support or Frequency Response Mode. Islanded operation does not impact the operation of the other modes shown in Table 6-1. The mode noted in the figure under Real Power Mode as "Autonomous" refers to Tesla's Opticaster. The Tesla Site Controller operates the battery based on these states.

Table 6-1 Operational modes and states

Real Power Mode	Reactive Power Mode	Islanding	Add-On
Off	Off	Auto Active	Always Active
Direct	Direct	Island Ready	Frequency Support
Site	Power Factor	Intentional Island	Volt-Var
Go To Energy	Voltage Control	PQ Island	Ramp Rate
Autonomous			Heat Mode
Scheduler			Peak Power

In addition to the above, as previously noted, the 2-hour system can be operated in Peak Power Mode.

6.3.2 Opticaster control methodologies

Within this section, DNV GL provides a review of the overall architecture and control methods for Tesla's Opticaster software. Opticaster is designed to autonomously maximize economic benefits of the Powerpack 2 through its functions, including forecasting, optimization, and real-time control, discussed in detail in this section. A high-level overview of these functions and their inputs and outputs are shown in Figure 6-3.

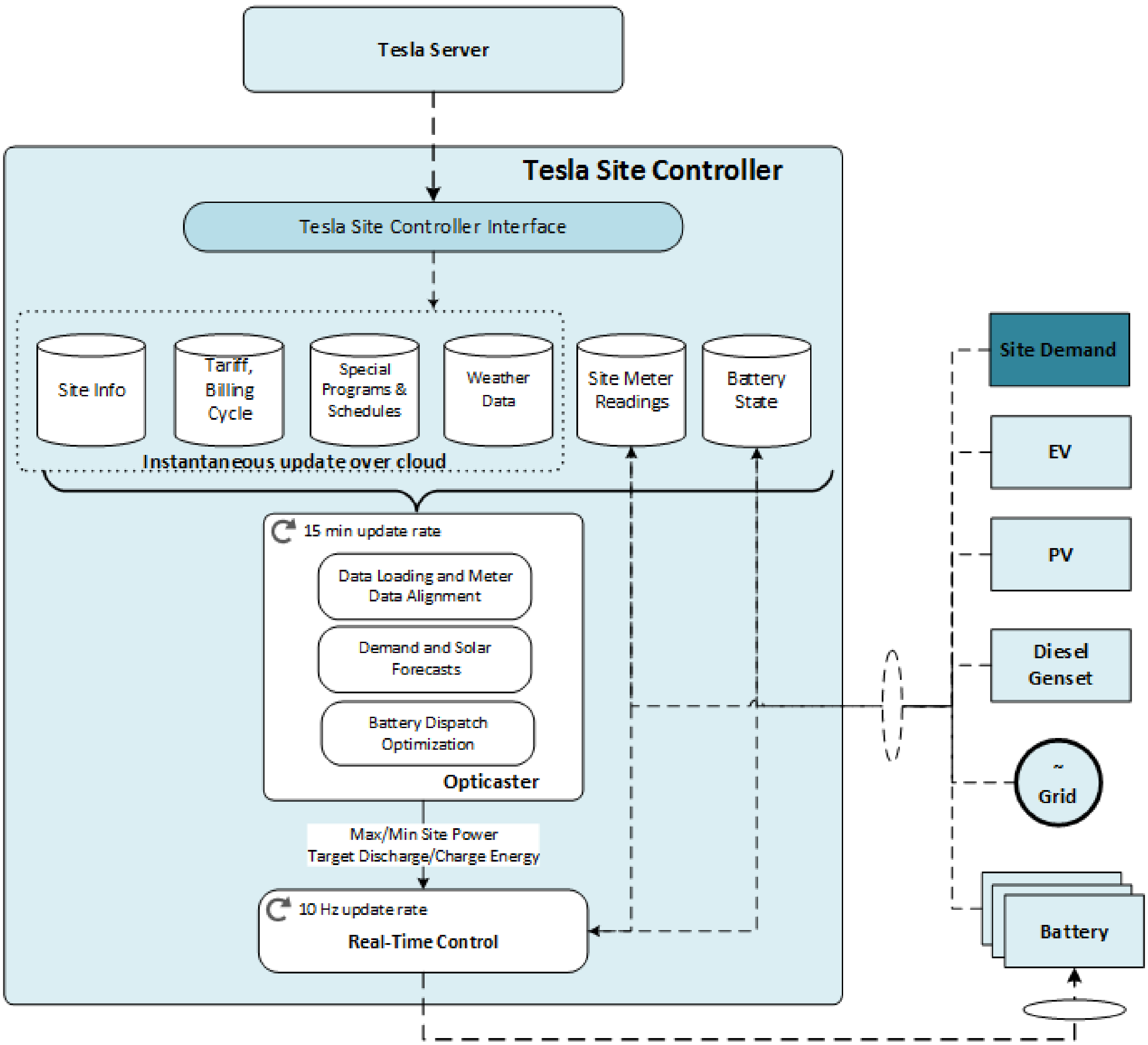


Figure 6-3 Control diagram for Opticaster software

Tesla uses a hybrid approach for its Opticaster control. Opticaster's functionality is divided between both on-site software inside the Tesla Site Controller and cloud-based support to update algorithm and optimization parameters. As shown in Figure 6-3, forecasting and optimization occur locally, developing a controls schedule based on data received from the local systems and signals from the cloud, such as schedules, price events, and customer preferences. The on-site controller provides commands to the battery based on this optimized charge and discharge schedule, monitoring the system to confirm operation per the commands provided. As such, a temporary loss in network connection will not adversely affect site performance. While longer term communications outages may impact performance, the autonomous continuing functionality of Opticaster provides a benefit for system owners regardless.

This section will address three facets of this process: system sizing, forecast development, and controls for various applications. In general, the achieved value of optimized system dispatch, especially in the case of balancing multiple applications, will always be affected by forecast uncertainties. Although DNV GL has not reviewed the algorithms themselves, DNV GL is of the opinion that the following description of Tesla's Opticaster software makes achievable claims and rationally addresses the known challenges of energy storage optimization and forecasting.

6.3.2.1 System sizing

To ensure the Tesla Powerpack 2 System is appropriate for a particular site and application, an initial site assessment is performed. This site assessment uses the Opticaster optimization and forecasting software for system sizing. For peak shaving and time-of-use load shifting, Tesla requires historical data, including at least a year of 15-minute load profiles, a recent utility bill, and any on-site generation data. This information is processed through the same model as utilized during operation. Based on customer's historical load, utility structure, generator settings, and other site requirements, Opticaster performs simulations over the lifespan of each project. Each set of simulations provide an estimated avoided cost savings by testing various customer load behaviors and renewable generation scenarios against an array of Powerpack sizes and applications. A high-level visualization of this process is shown in Figure 6-4.

Figure 6-4 Design and analytics sizing workflow

DNV GL notes that this approach of integrated planning/design models and operation controls is emerging as an industry standard approach and is logical for optimizing for projected vs. realized application performance.

6.3.2.2 Forecasting

Once the site is active, forecasts of the electric demand for the site are updated every 15 minutes. Opticaster's forecasting functionality requires input data from a variety of sources. This data includes historic customer load profiles, solar profiles, holiday schedules, and temperature data, as well as on-site metering to provide current load and generation. This allows Opticaster to produce customer demand forecasts, updated every two minutes. Based on this input, control settings are re-evaluated, continuously optimizing the system's operation at 15-minute increments. Tesla claims that, because of the constant input of new data available to contrast with previous forecasts, the forecasts increase in accuracy as the system learns. An illustration of increasing forecasting accuracy over time is shown in Figure 6-5.

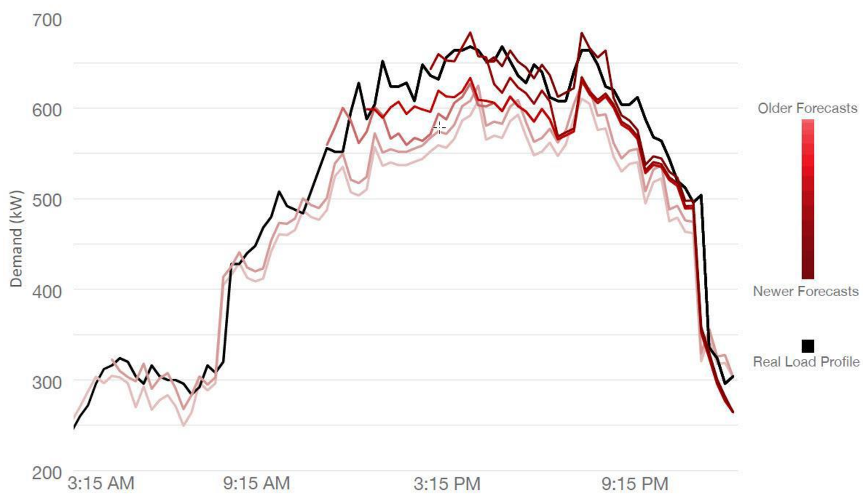


Figure 6-5 Illustration of Opticaster continuous forecasting

Tesla previously reported that multiple methodologies were developed to predict future demand at a given site and increase the peak demand reductions. Although a forecast strategy is generally appropriate for most sites, based on Tesla's high volume of simulations, this strategy may not be appropriate for every billing cycle. Tesla therefore has developed a variety of benchmarks to improve strategy selection per site and inform algorithm development. Tesla has conducted this development in the context of total "system savings", defined as a combination of peak reduction, energy arbitrage, and other revenue streams, as follows:

- Perfect case: Simulated maximum achievable system savings with perfect knowledge of demand for the next 24 hours at each 15-minute time interval.
- Best Strategy for a billing cycle: Simulated system savings achieved using the best forecasting strategy for a specific billing cycle. The best strategy is found by running the calculation over all the strategies for a specific billing cycle.
- Best Strategy overall: Simulated system savings achieved using the best forecasting strategy for all the billing cycles. The best strategy is found by running the calculation over all the strategies for all available billing cycles.

- Actual Strategy: Simulated system savings achieved using the forecasting strategy that runs on the site. These results should be the same as the best strategy results; otherwise the forecasting strategy should be updated.
- Actual: Peak system savings achieved by playing back the actual dispatch of the storage system after the fact.

Tesla uses a metric called percentage of perfect, which measures the performance relative to the perfect information, to rank different forecasting strategies for each site and provide a benchmark to test new strategies being developed. This metric can be used to select the actual strategy that runs on each site. However, Tesla reports that the optimization has been improved to handle multiple forecast curves with various probabilities, to best attune the forecast strategy to the site conditions. Regardless of the selected strategy, Tesla adjusts the forecasting model continually based on precise modeling of capacity degradation sent from the on-site BMS for the Powerpack 2s.

6.3.2.3 Operations and real-time control

At its core, Tesla's Opticaster software platform dispatches the battery with the goal of optimizing the combined value of storage applications, while also meeting other objectives specific to the site, such as local interconnection requirements or performance based incentive requirement. The objective of the optimization is to achieve reductions in net energy cost, demand charges, and diesel consumption while maximizing the value of various grid services. To support this, and as shown previously in Figure 6-3, Opticaster takes as input tariff and billing cycle information for the site, savings/incentive programs, contractual commitments, and grid rules, as well as battery and site information, including all meter readings, battery full pack energy, current energy remaining, max charge power, max discharge power, preferred charge power, preferred discharge power, and battery health information (such as temperature). These variables are fed into the controller to produce an optimized battery dispatch schedule that charges and discharges the battery to maximize customer savings.

In all cases, the objectives are configurable according to customer preference. Figure 6-6 illustrates commonly used applications that Opticaster supports.

Figure 6-6 Common Powerpack 2 applications

For commercial or industrial customers, electricity is typically billed by the utility in two ways: by total monthly energy consumption and by peak power demand during the given billing period. To address this, Opticaster is designed to optimize both energy and demand charges weighted by their respective costs. Figure 6-7 depicts a simulation of the Powerpack 2 providing tariff optimization, a combination of peak shaving and load shifting/energy arbitrage. The example demonstrates the system taking advantage of low energy prices to fully charge the battery early in the day and discharging during a forecasted peak period later in the day.

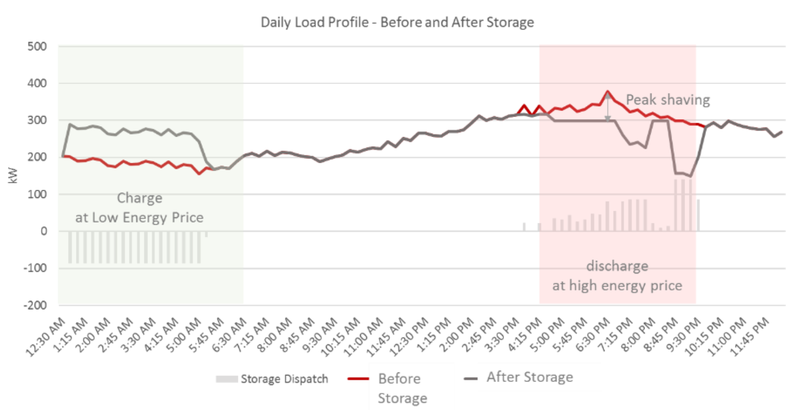


Figure 6-7 Example of tariff optimization

Customers may also use solar to offset the electricity their site consumes from the local grid. For these customers, an on-site Powerpack system charges from unused solar electricity generated during the day for later use when solar power is not available, through an application called solar self-consumption. To ensure economic performance while maximizing solar self-consumption, Opticaster maintains a wide range of system parameters: maximum solar export power, charge constraints for Investment Tax Credits (ITC), site demand, utility interconnection rules, and other cycling and emission requirements that qualify the customer for state incentives, such as SGIP in California. Figure 6-8 shows an example of Opticaster commanding Powerpacks to charge from solar during the day, then discharge to shave the customer's evening peak.

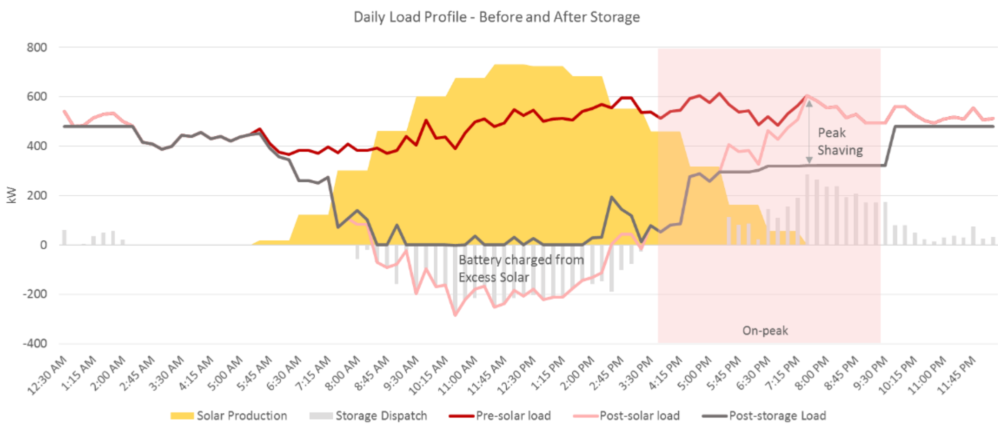


Figure 6-8 Renewable self-consumption and peak-shaving

Opticaster can also support demand response (DR) programs, wholesale market grid services, and other special price events, such as the CAISO day-ahead market through DRAM (Demand Response Auction Mechanism) as well as for Critical Peak Pricing in PG&E. Figure 6-9 shows an example of a DR event, during which the algorithm commands the Powerpack system to precisely meet the DR commitment below the baseline. Ensuring sufficient battery capacity is available during these events is dependent upon appropriate sizing and forecasting, as previously outlined in this section. Similarly, forecasting is key to providing grid services. As shown in Figure 6-10, Tesla dispatched the storage system at a site to clear a 0.45 MW DRAM event during a solar eclipse, demonstrating the system's grid service support.

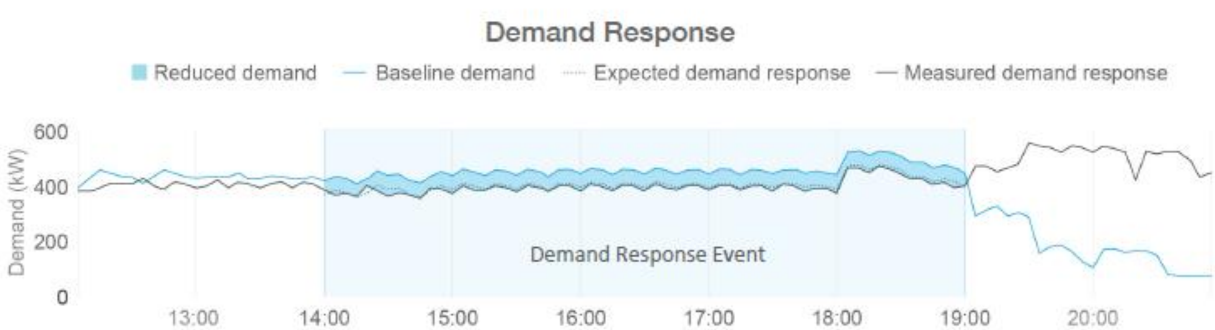


Figure 6-9 Illustration of load behavior during demand response event from a real site

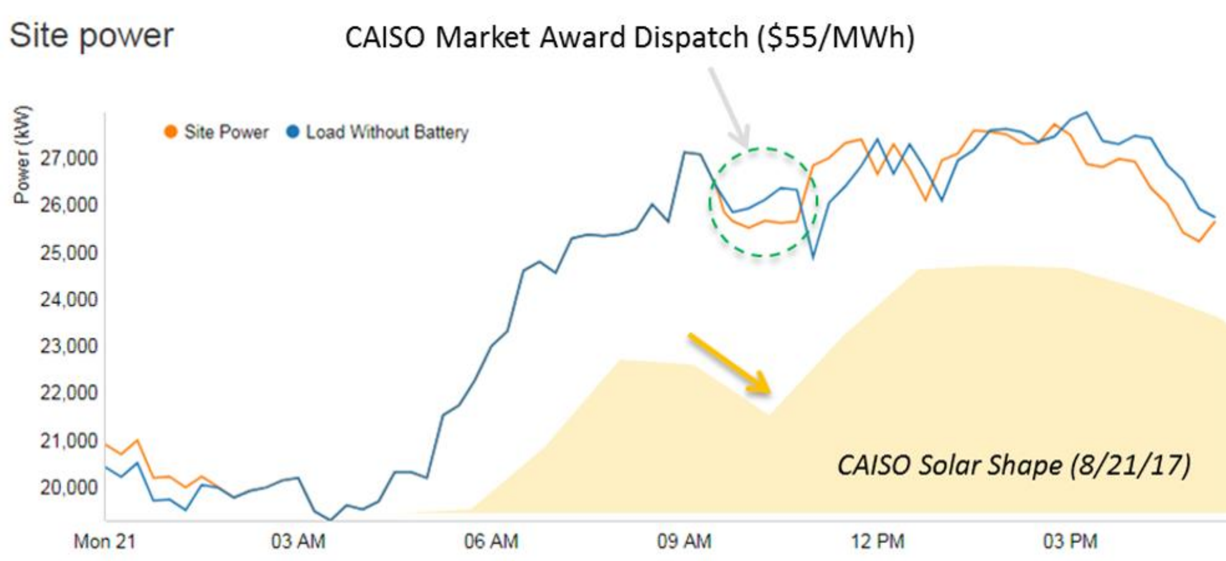


Figure 6-10 CAISO DRAM response for a site on 21 August 2017

For systems intended to allow disconnection from the grid, Tesla's Opticaster-powered microgrid solution manages power and energy flow of load and any power generation assets, while balancing demand needs and customer preferences and maximizing economic benefit over the life of the microgrid. The reason for the microgrid may be based on energy security (ensuring a key facility has zero downtime), unreliable grid connections, or isolated communities in need of power sources. While diesel based generators have historically been the standard source to serve these power needs, Tesla's Opticaster-powered microgrid solution can either reduce reliance on diesel generators or, in some cases, eliminate the need for it.

Due to their design, microgrids are often required to transition between islanded (off grid) and grid-connected configurations. Opticaster is designed to adapt to changes in grid connectivity and alternate optimization strategies accordingly. When connected to the grid, Opticaster considers all standard commercial applications to maximize savings. When off-grid, due to outages or otherwise, the Powerpack can serve as backup power to mitigate short interruptions from grid blackouts. In the transitional states, the battery will be used to ensure matching of power levels and a theoretically seamless change between sources.

In both on and off grid modes, where applicable, the system can reduce diesel generator use down to the lowest efficient levels and increase renewable self-consumption in its stead, optimizing the system as a whole. This is enabled by forecasting times when site demand is high and commanding diesel generators to run at a high fuel efficiency point during those peak demand periods. Opticaster also predicts the onset of solar generation and intentionally empties the battery to charge from solar as much as possible. The figures below compare conventional rule-based methods (Figure 6-11) to Opticaster-based dispatch (Figure 6-12).

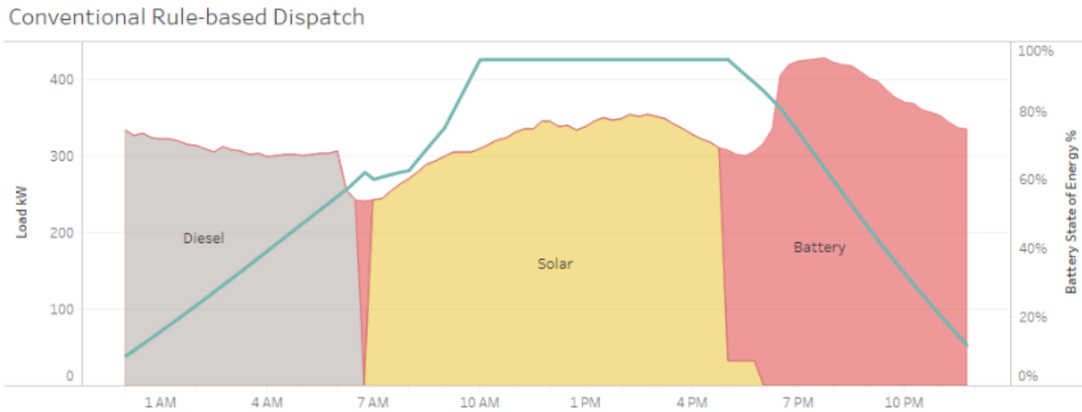


Figure 6-11 Conventional microgrid approach

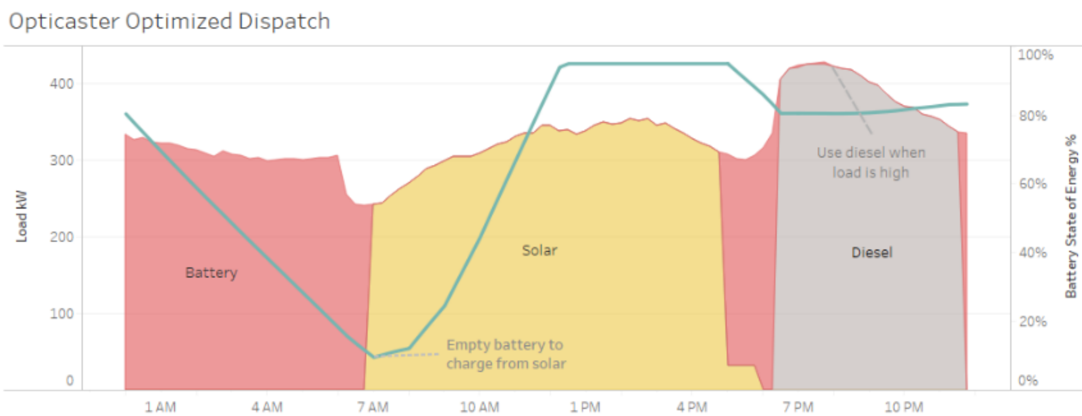


Figure 6-12 Opticaster microgrid approach

Through peak shaving and load shifting, customers reduce their utility bills. By participating in a DR program and other grid services, Powerpack systems stack multiple revenue streams that further benefits end customers.

Finally, Opticaster can support operational constraints for incentive programs, such as meeting minimum cycling requirements for SGIP. Such requirements are, Tesla notes, a part of the core Opticaster algorithm. Based on each site characteristics and incentive requirements, the battery is automatically dispatched to maximize the combination of utility bill savings and incentive payment to the customers. In some cases, this does mean that the algorithm will prioritize compliance with incentive requirements if the marginal benefits of achieving incentive targets is more lucrative than tariff optimization.

In addition to each of the previously listed individual applications, Opticaster is capable of combining grid services, incentive compliance, and peak shaving/load shifting, resulting in a system that maximizes customer savings through stacking of multiple value streams. DNV GL did not review data demonstrating multiple applications optimized simultaneously. The overall structure of Opticaster and stacking of multiple value streams represents an emerging industry norm. DNV GL finds the cited inputs to be necessary and sufficient for achieving acceptable performance for Opticaster, and DNV GL believes the utilization of Opticaster for both system sizing and operations is advantageous for reducing error in economic savings estimations. Actual performance of systems utilizing this control platform is reviewed in Section 6.4.

6.3.3 Reliability and resiliency

DNV GL assessed the reliability and resiliency of the Tesla software for forecasting, optimization, and control. This assessment includes a review of the software development lifecycle, update strategies, historical downtime, and outage mitigation strategies.

6.3.3.1 Software development lifecycle

Tesla utilizes a variety of languages and platforms to expeditiously program the Tesla Site Controller firmware and develop or update the control algorithms. This development is conducted via a modified Agile development lifecycle, based on 2-week sprints. First, the requirements are documented in a specification tracker. These requirements are then itemized as tasks within a ticketing system and grouped by planned firmware releases. These ticket groups are addressed within a sprint and, to ensure the quality of the development, the results are run through at least hardware-in-the-loop simulations and system testing by a dedicated validation engineer for approval. Finally, the code must pass full system validation, wherein the systems team will conduct testing specific both to the features being added or updated and as entire system, on beta systems identical to those installed in the field. Once system validation receives sign-off, the firmware is released to manufacturing for deployment to the new systems and service production line, who is responsible for remotely updating active sites. Any change to the Tesla Site Controller code for those active sites will further automatically trigger software-based unit and integration tests. Changes that do not pass these tests are not merged. DNV GL feels that this testing system, especially the inclusion of dedicated personnel to handle the validation is critical and will help to avoid unexpected outages and/or under-performance.

These measures are taken to ensure Powerpack 2 system stability. Tesla has reported one system-wide outage, wherein a software issue caused the duplication of an optimization cycle and a system crash. This issue was identified and addressed the following day, and, to prevent similar issues in the future, all meter data is now sanitized prior to input. This example further reinforces the need for thorough testing and quality control in software rollouts.

6.3.3.2 Update strategies

All code updates to both the site firmware and software are managed through an over-the-air update mechanism and go through the validation process as described above. Where hot updates are not feasible, the customer will experience some downtime, which can be variable based on the updates being performed. If an update is exclusive to the Tesla Site Controller, outages will average 15 minutes. If other system components require updates, depending on the size and configuration of the site, those components may be offline upwards of 45 minutes. These outages on a single Powerpack block system would cause a complete system outage. However, in a system with more than one Powerpack block, the full Powerpack 2 System would still be able to run with reduced capability.

Control parameters can be updated without disruption to the system. The new configuration can be updated remotely and will be accepted into the system the next time the optimization algorithm is invoked on site, which occurs every 15 minutes.

System quality for field units continues to be maintained through updates and testing. After released through full validation from the Tesla Systems team, the Fleet Management team handles deployment. All systems are continuously monitored to confirm appropriate functionality. Tesla evaluates fleet performance on a weekly basis and Opticaster performance monthly. Performance is compared to the optimal case, as well as to potential but not-pursued cases, and updates are rolled out to forecasting strategies as appropriate.

Tesla informed DNV GL that it is developing a number of strategies for algorithm improvement. These include:

- Using stochastic optimization methods to capture forecast uncertainty
- Adding multi-linear regression forecast strategy in Opticaster operation
- Considering a more comprehensive set of weather parameters in forecasts

DNV GL has a positive opinion of these proposed improvements and recommends updating this report if they are enacted.

6.3.3.3 Outage mitigation strategies

To confirm the suitability of a system to avoid disruption, DNV GL reviewed Tesla's outage mitigation strategies. These include review of system redundancy and potential points of failure, communication channels, system diagnostics, and disaster recovery plans.

While the Tesla Powerpack 2 System currently has no redundancy built into its control platform, Tesla has added this functionality into their product roadmap as an optional add-on for future deployed systems. Currently, there are three single points of failure in the current system: the Tesla Site Controller, the meters, and the communication network (e.g., switches, cables). The system can be equipped with these items redundantly, where requested. In the case of the Tesla Site Controller's planned redundancy, a stand-by Tesla Site Controller would be provided; Tesla is currently working on the detailed design, including switch-over methodology for roll out in 2018. Additionally, although server connectivity/communication is a single point of failure, the system does not depend on this connectivity to operate. Opticaster computes optimal battery commands for every 15-minute interval and the site controller can use an optimized dispatch in the event of a communication loss. Failure of this portion of the system would then only result in a loss of external data logging.

All communications, including dispatch commands and data, will be managed via a 3G cellular link with a built-in modem. In cases where a cellular connection is not available, Ethernet may be used instead. Connections and integration with other systems, (e.g., building management applications), will be conducted primarily via Ethernet, as shown in Figure 6-13.

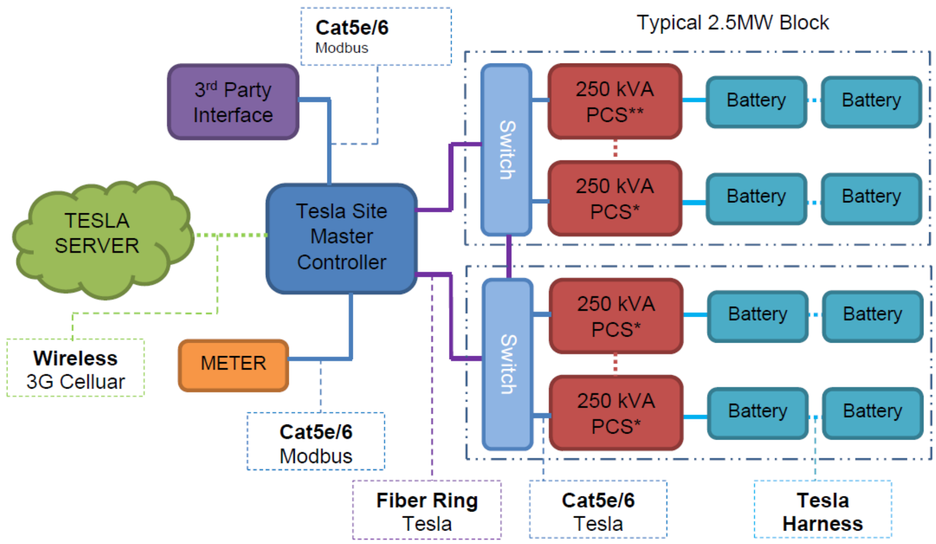


Figure 6-13 Diagram of communication paths

Tesla employs the following communication protocols:

- SSH
- Modbus/TCP for direct customer commands
- Modbus/TCP and Modbus/RTU for meter communication
- https for inbound and outbound communication
- OpenVPN (TLS) for VPN connectivity
- Proprietary Tesla protocol for internal communication

The Tesla Site Controller provides Tesla access to monitor data in real time. That data generates alerts in the ticketing system. The operational state is continually monitored and communicated, including online status, faulted status, power in/out, and state of charge.

Alarms are similarly monitored via all communication protocols and are also displayed at the kiosk itself. The system is monitored for runtime faults; a troubleshooting ticket will be filed in the maintenance scheduling system within an hour of the fault occurring. If site communications are down, a notification to that effect will be generated within an hour. The customer can also elect to be notified of operational status changes by Tesla's automated alert system. Alarms will be sounded for:

- Loss of battery meter
- Loss of site meter
- Loss of generation meter
- Loss of load meter
- Number of operational AC blocks

In case of a communications outage between the site and Tesla, the Tesla Site Controller and thus the system can continue to function autonomously indefinitely. However, while Opticaster will run without communication to receive updated data such as weather forecasts, the optimizer may not produce peak results. Therefore, if the Tesla Site Controller cannot connect to Tesla's servers for 24 hours, it will reboot to reset the cellular modem hardware. Within 60 seconds of that reboot, Tesla asserts that the system should return to full functionality.

The Tesla Site Controller logs signals locally at 10-second intervals for up to 6 months/10 million entries, for diagnostics and long term monitoring. During standard operation, with active communication available, that data will be periodically synced to the Tesla servers. However, in the case of a communication outage, the local data storage allows for at least two weeks of data to be stored. Further, Opticaster continuously captures 15-minute interval information (amassing data at a rate of 1MB/year). This redundant log includes energy import and export readings for the site interconnection meter and battery meter.

Conversely, if the Tesla Site Controller loses communication between the meters or over the internal Ethernet network, the system will curtail system output, dropping to 0 power within 2 seconds. DNV GL believes that these diagnostics, alarm system, and signal logging are sufficient and in-line with industry standards.

Faults are auto detected and generate troubleshooting tickets in the Tesla monitoring system. Those tickets are triaged for remote investigation within 1 business day, and tickets promoted to field service are queued for the field service team. In cases where Tesla owns the system and/or all operations, Tesla will monitor the system for both full system faults and performance related faults.

Tesla maintains a master copy of all installed system's configuration parameters for the Tesla Site Controller. In the event of a disaster, Tesla can thus deploy a replacement system. The input data for autonomous operation is also captured. The latest 15-minute interval data, however, would be unavailable, unless requested from the customer. Notably, retrieval of this missing data point is not necessary, as the system can operate without it with no loss of functionality, demonstrating the robust nature of the program. Communication will be restored as described in the previous section.

6.3.4 Security

DNV GL assessed the security and resiliency of the Tesla software and interfaces from the customer-sited storage system, within the context of energy management systems and cyber security seen in the industry. Further, DNV GL will discuss potential future security compliance issues.

Communications between the Tesla Site Controller and Tesla's servers are over a VPN tunnel via or https for logs and alerts based on a fully standard TLS implementation with authentication and authorization managed through a unique X.509 certificate. Authorized Tesla personnel can connect to a Tesla Site Controller and transfer files using a point to point tunneling VPN with SSH key encryption, with defined role-based access levels. The customer can both monitor and control the Powerpack 2 on the Tesla Site Controller's external Ethernet interface over Modbus/TCP on port 502 or DNP3. The customer is responsible for providing secure authentication to both Modbus and DNP3 as well as not routing beyond the local requirements. Local communication between the Tesla Site Controller and inverter blocks is on the internal Ethernet network over a private TCP network. Tesla also provides programmatic customer access to the Tesla Site Controller through a REST API over Ethernet that provides additional data points and control modes not available over Modbus and DNP3.

The Powerpack 2 System has a secure network which limits the traffic to and from site and within the site using a whitelist strategy. The Powerpack 2 System is capable of tracking and storing configuration files and firmware versions used on site.

Tesla utilizes a compliance team to develop and implement security features which ensure alignment with local interconnection requirements. Tesla has noted that, to this end, it is pursuing compliance with IEEE 2030.5 as mandated by CA Rule 21 and grid codes for Type A - D.

Regarding physical security to support its cyber security, the Tesla Site Controller is installed in a lockable enclosure, co-located with the Powerpacks. The customer is expected to provide on-site physical security. If physical security is compromised, a sophisticated attacker would be able to control the battery system and examine historical logs for that particular site.

6.4 Historical application performance evaluation

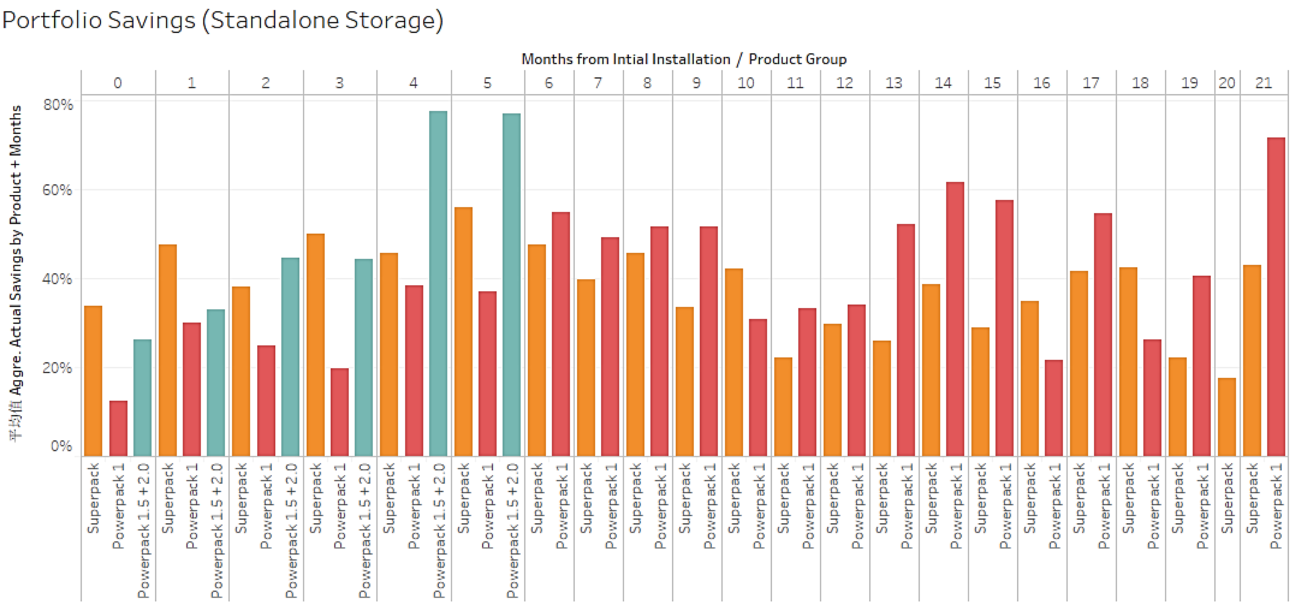
Tesla provided both simulated and field performance results from fully operational sites, including those performing applications now incorporated into Opticaster. Data was provided at both a fleet level and for individual sites. The following section provides a summary of a sampling of these performance results, as well as a summary of the installed sites in terms of system size and battery energy throughput.

6.4.1 Historical controls performance

Tesla has deployed Powerpack projects in 30 countries with a total of over 390 MW with 800 MWh of energy storage at over 450 customer sites as of Q3 2018. The systems' use cases include off-grid applications, back-up, and demand charge reduction. Tesla has integrated these systems as stand-alone systems or with other on-site generation such as solar or diesel gen-set. Tesla provided DNV GL with a full fleet list of systems commissioned by Q3 2018, including the Powerpack 1, the transitionary Powerpack 1.5, and Powerpack 2, which is reviewed here.

First, in Figure 6-14, Tesla provided DNV GL with high level performance data, in the form of a bar graph, demonstrating aggregated fleet performance of 156 sites running Opticaster. The portfolio savings are shown according to standalone storage and solar + storage sites and are further distinguished based on the version of Opticaster used. Superpack and Powerpack 1 sites were equipped with an older version of Opticaster, whereas Powerpack 1.5 and 2.0 sites are using the same updated version including similar hardware infrastructure. Tesla informed DNV GL that, while only a small percentage of Powerpack 1 and 1.5 sites opted to utilize Opticaster, all Powerpack 2 systems will have Opticaster as a standard offering, although the client does have the flexibility not to utilize it. The fleet list, as of Q3 2018, lists 154 Opticaster-controlled systems, 21 of which are Powerpack 2 sites. As possible, DNV GL has assessed the performance of Opticaster for the Powerpack 2 specifically, to demonstrate general controls performance, as well as the robustness of Tesla's controls design process. System level performance is discussed in further detail in Section 9.

The data provided in Figure 6-14 demonstrates average aggregated monthly performance by product type since initial installation. The vertical axis represents the percentage of actual savings compared to the theoretical maximum savings for each month. As mentioned earlier, Powerpack 1.5 and 2 are grouped together to since they are equipped with the newer version of Opticaster. In both standalone and solar + storage portfolios, Powerpack 1.5 and 2 generally performed better than their predecessors over the same time period and also show an improvement in savings with longer Opticaster runtime.



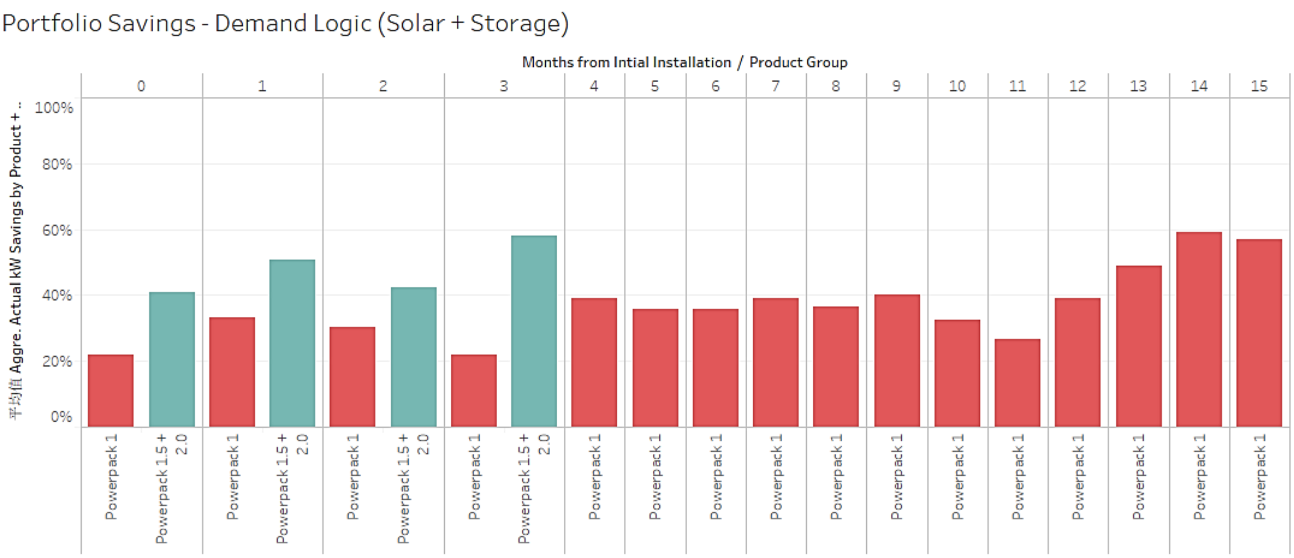


Figure 6-14 Aggregated actual savings versus months since installation

Tesla provided another comparison of performance for each product type as shown in Figure 6-15 below. The figure illustrates that, on average, Opticaster-enabled Powerpack 1.5 and 2 systems conducting peak shaving and load shifting achieve 55% of their theoretical maximum total savings, an increase of 14% from the previous generation of Powerpack. As previously noted in Section 6.3.2.2, the higher this percentage is, the better aligned the forecast and related strategy is to the actual performance.

Additionally, Tesla provided in this same figure planned improvements to achieve performance closer to that which is forecasted by the best annual controls strategy. These improvements include both hardware and controls or algorithm improvements. While proposed hardware upgrades on average account for an improvement of approximately 6% for Powerpack 1.5 and 2, Tesla has determined that an additional 38%

average improvement could be made if controls strategies and the forecasts they depend on were upgraded. DNV GL was not provided with the methodology by which these controls improvements would be made, but surmises that a portion is related to the iterative improvement of forecasts and optimization.

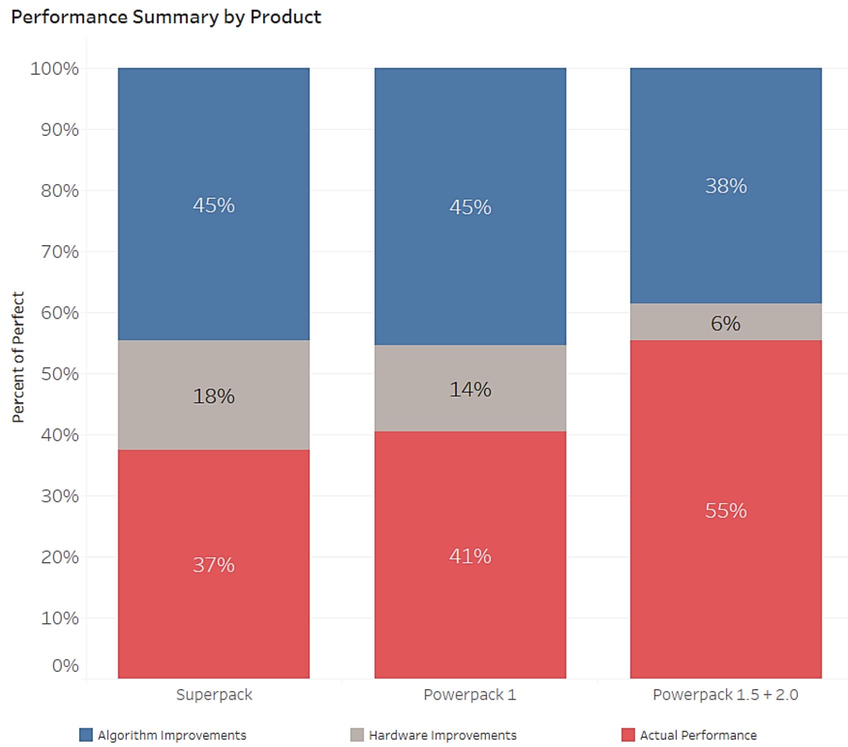


Figure 6-15 Actual performance comparison by product

Tesla further provided a week of load and forecast data for a small commercial site, to demonstrate active forecast optimization as well as the Opticaster controls enacting the selected applications. Although this is a very small sample size, the data provided aligns with Tesla's claims. DNV GL compared these actual loads with each subsequent forecast, which was updated every 15 minutes. The resultant assessment aligned with the process described by Tesla's documentation (as illustrated previously in Figure 6-5) and appears to provide a fair forecast, improving iteratively over time.

Tesla also provided data demonstrating Opticaster performing peak shaving, one with standalone storage and one with solar + storage shown in Figure 6-16 and Figure 6-17, respectively. The blue shaded areas in the figures represent the site demand, while the green line shows the net load, after the utilization of Tesla's Powerpack, both in kW. The standalone storage site clearly displays its ability to shave peak loads over a month as represented in Figure 6-16. According to Tesla, this site was able to reduce peak loads while also meeting battery cycling requirements of a utility incentive program and achieved 87% of its theoretical maximum savings for the month. The solar + storage site equipped with Powerpack 2 also shows peak demand reduction capability in conjunction with self-consumption of excess solar energy in Figure 6-17. The resultant graphs provide a standard profile for this type of application, lending some support to Tesla's claims.

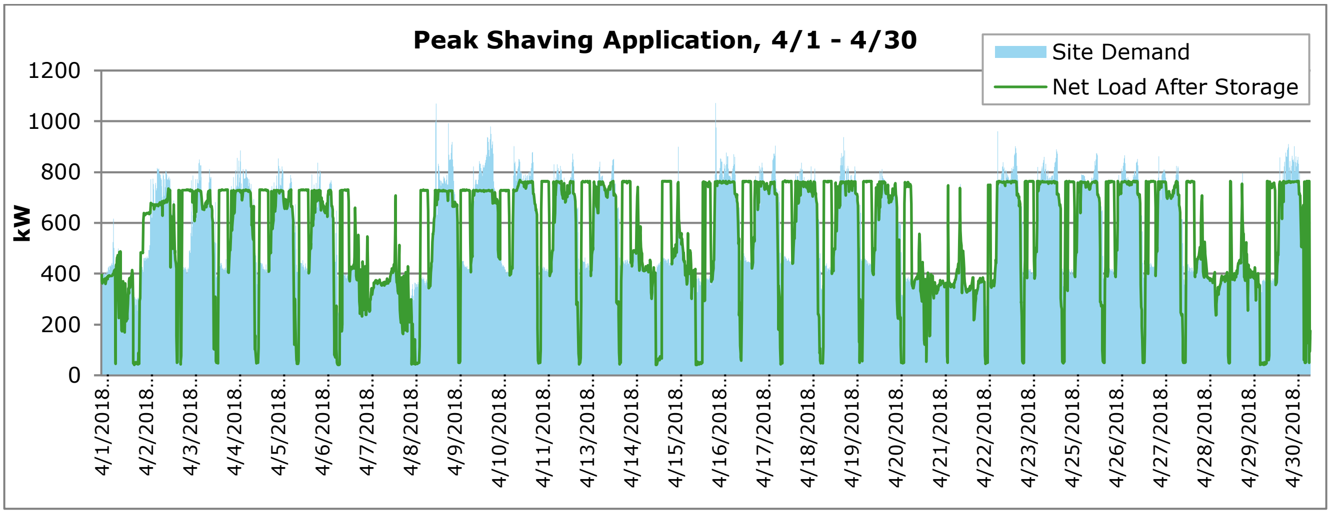


Figure 6-16 Standalone storage Opticaster peak shaving example, government facility (750 kW/1,425 kW battery)

DNV GL examined the interval data of the solar + storage site for a week in June 2018 to highlight the ability of the battery in reducing peak demand. In Figure 6-17, as solar production diminishes, net load begins to increase and reaches its peak in the evening, shown by the yellow lines on the positive axis. The battery is discharged during this period to reduce peak demand as highlighted by the green line (net load after storage). This effect is also shown by the red dotted circles on each day of the week. The negative net load values correlate to electricity sold to the grid and may be contingent upon applicable local interconnection agreements.

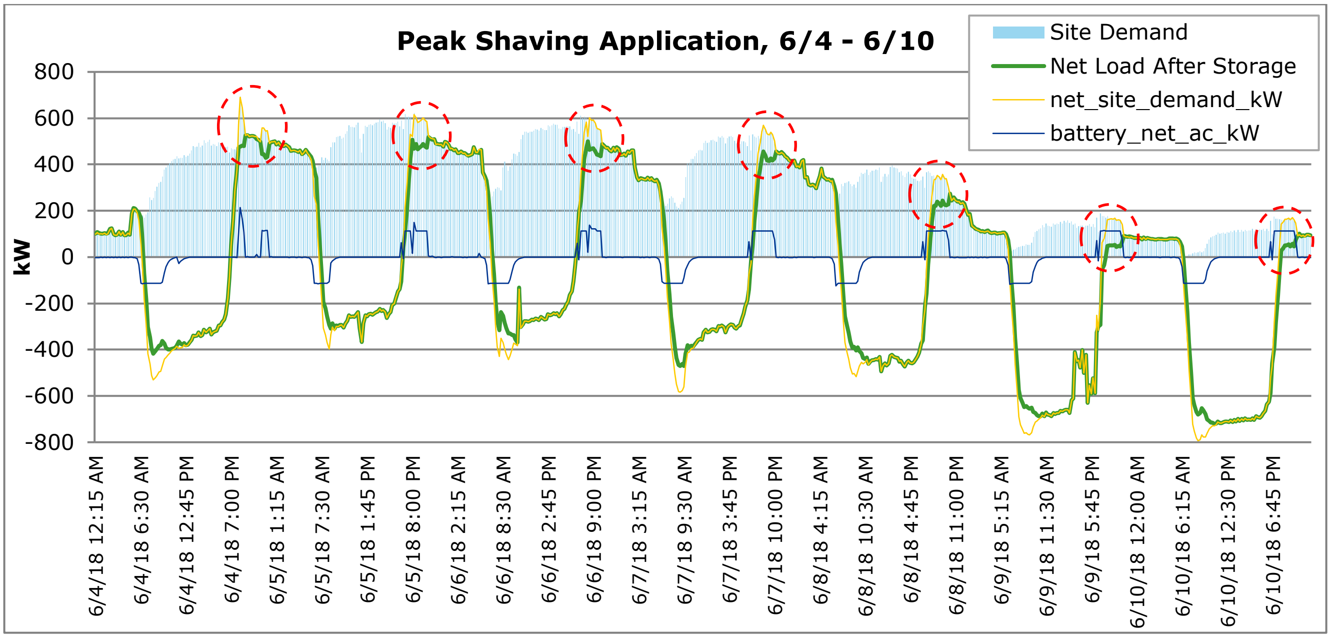


Figure 6-17 Solar + storage Opticaster peak shaving example, food processing facility (100 kW/420 kWh battery)

In terms of required functionality, DNV GL is confident that the Opticaster system can command a Powerpack 2 to respond to a DR event, wholesale market grid service needs, and other special price events. Figure 6-9 and Figure 6-10, shown earlier within Section 6, illustrates real systems operating in response to such events. DNV GL, however, did not receive further data to validate these functions over an extended period of time or in concert with other applications.

Finally, Tesla provided a list of 37 Opticaster-controlled sites participating in an incentive program, specifically SGIP, with greater than 10 months of operation. SGIP currently requires a minimum of 130 cycles per year, and had previously required 250 cycles annually. The data provided demonstrates that, based on current cycling requirements and average annual cycling rates, 34 of the 37 systems (nearly 92%) are assumed to be in compliance with SGIP. DNV GL did not review the relative benefit of prioritizing tariff-driven cycling in the 3 cases where the systems appear to not be in compliance.

6.5 Software and controls summary

DNV GL has performed an assessment of the conceptual design, performance, reliability, and security features of the Opticaster software and Tesla Site Controller components of the Powerpack 2 System for commercial applications. DNV GL finds the cited inputs and design logic to be sufficient for achieving acceptable performance for optimized economic dispatch.

To this end, Tesla provided historical performance data to demonstrate these capabilities in the field. Tesla provided DNV GL with a full fleet list of systems commissioned as of Q3 2018, including the Powerpack 1, the transitionary Powerpack 1.5, and Powerpack 2, which was the focus of the review. In both standalone and solar + storage portfolios, Powerpack 1.5 and 2 (which both leverage the most recent version of Opticaster) performed better on average than the previous Tesla generations over the same time period.

Tesla has integrated these systems as stand-alone systems or with other on-site generation such as solar or diesel gen-set. On average, Opticaster-enabled Powerpack 1.5 and 2 systems conducting peak shaving and load shifting achieve 55% of their theoretical maximum total savings, an increase of 14% from the previous generation of Powerpack. Beyond these fleet level statistics, DNV GL received data demonstrating the ability of the Opticaster to improve forecasts over time and implement peak shaving and load shifting applications, for both standalone storage devices and solar + storage installations. DNV GL additionally was provided with cycling counts for SGIP compliance. Although Tesla did not provide detailed data for demand response or wholesale grid services, sample operation for single instances of such events at operating sites was provided. DNV GL did not receive data explicitly demonstrating microgrid controls or stacking of applications. DNV GL recommends that this report be updated when detailed data demonstrating all these applications is available.

Finally, DNV GL assessed the reliability and security features of Opticaster and the associated system. DNV GL has a positive opinion of the reliability of the software and the processes that ensure the maintenance of the same. DNV GL finds the cyber security described to be aligned with industry norms, with on-going efforts to continue compliance with local interconnection requirements.

7 TESLA MANUFACTURING EVALUATION

As part of the evaluation for previous reports, DNV GL toured the new Tesla Gigafactory facility located in Sparks, Nevada on 21 March 2016. This visit was primarily focused on the battery manufacturing. DNV GL again visited the Gigafactory on 26 May 2017, as part of the evaluation for this report. A photo of the facility at the time of the first inspection is shown in Figure 7-1. The second visit was focused mostly on the inverter manufacturing, but the following section also includes updates to the battery manufacturing as provided. For this second visit DNV GL was accompanied by Tesla Powerpack 2 Engineering Team Manager AJ Booth.

Figure 7-1 Photos of Tesla Gigafactory manufacturing facility in Sparks, Nevada

Tesla is currently manufacturing its full line of stationary energy storage products, including their new line of inverters, energy storage systems and electric vehicles, at this facility. At the time of factory visit, a full-production assembly of the Powerpack 2 was underway; photos of the assembly process are included herein.

Tesla's manufacturing process is managed by a Product Excellence team: Purchasing, Design Engineering, and Quality departments. All three departments report to the VP of Infrastructure Development, Kevin Kassekert. An organization chart for the upper management at the Gigafactory is provided below.

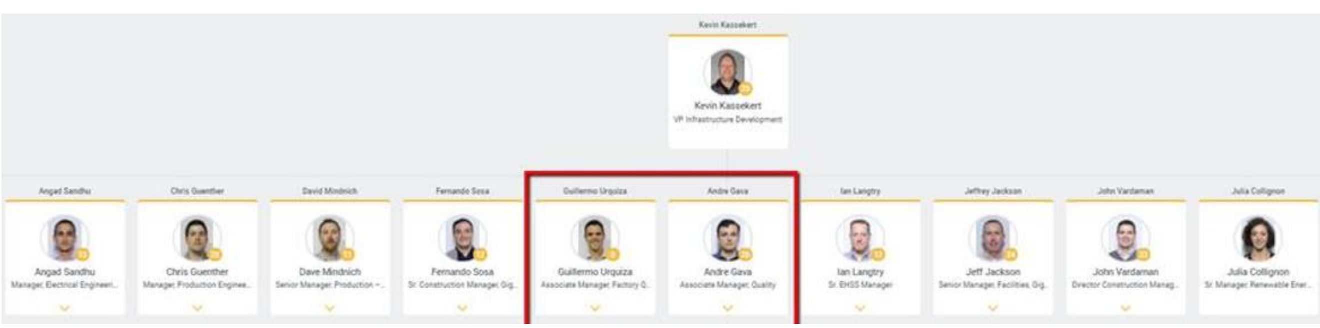


Figure 7-2 Gigafactory organization chart

7.1 Quality systems evaluation

As a precursor to a detailed review of the Tesla Manufacturing processes for both the inverters and the Powerpack 2 storage elements, DNV GL had evaluated the full quality systems approach deployed by Tesla through the product design and build cycle. Gigafactory Operations are currently certified to ISO 9001:2008 by National Quality Assurance (NQA) USA, a ANAB accredited certification body, with certification valid until 14 September 2018. Additionally, Tesla has partnered with NQA to complete 14001:2015 Environmental Management Systems registration, with audits schedules in place. DNV GL has assessed the reliability program and the Failure Mode and Effects Analysis (FMEA) process from a design perspective in detail.

The manufacturing line includes the quality functions of end of line testing, pass/fail testing, to discover issues, determine the root cause and take appropriate corrective actions. This is submitted to the cross-function review by Quality and Engineering. Quality performance is checked from when the components are received from shipping and a known-risk sampling is performed from performance recommendations. Test failures are tracked in weekly yield meetings, reviewed for quality issues, and feedback is provided to Tesla management.

Tesla's documented Reliability Program is integrated into their overall system development process and tracked in a software tool developed by ReliaSoft.

The Reliability Program consists of the following steps, discussed in further detail below:

- Reliability Allocation
- Supplier Selection
- Lessons Learned
- Design and Process FMEA
- Simulations
- Validation Testing
- Reliability Demonstration
- Risk Assessment
- Ongoing Reliability Testing (ORG) and Burn-In
- Field Reliability

Tesla's reliability program is a comprehensive process which includes running reliability and durability tests in parallel. The process begins with the product warranty goals, which are focused on the customer expectations of availability. The overall goal is to track the reliability of the major components in regard to the severity, frequency, serviceability, design complexity, and costs. The suppliers are selected based on their ability to manufacture quality products, and the resulting reliability of their components. If necessary, they must be willing to adjust their testing requirements to meet Tesla's standards. FMEAs for both design and processes are conducted to discover weaknesses and implement corrective actions.

Prior to testing, all parts go through a simulation in a variety of environmental conditions; those that fail will be exchanged or monitored closely during testing. Tesla then runs validation testing, with a pass/fail metric for units placed under stresses representative of a full design life. These results are matched with initially determined targets. In cases where the target is not met, a risk assessment is conducted to determine what the impacts of a failure would be. Once production has begun, reliability testing continues periodically, and burn-in testing targets potential early-life failures for each component.

The below photo in Figure 7-3 shows the burn-in testing equipment area for the Powerpack 2 Inverter. Cooling liquid at +70°C is supplied to the unit-under-test, simulating high ambient temperature conditions. The inverter under test is then cycled through a test algorithm that applies heavy loads while testing the corners of the operational envelope. The inverter operates under these high-stress conditions for 45-50 minutes.

In Figure 7-4, an automated fixture for the application of thermal grease is shown. Applying the correct thickness of grease has historically been problematic in the power conversion industry, resulting in power device failures. The automation of this process is viewed positively by DNV GL as a means of reducing variability in the manufacturing process. Tesla has made good use of their manufacturing experiences to reduce the potential for human error.

Figure 7-3 Inverter burn-in equipment test area

Figure 7-4 Automated application of thermal grease

In regard to field reliability, an ongoing process of tracking and monitoring the health of its installed base includes acquiring pertinent information, such as battery energy storage system degradation, which enables Tesla's preventive maintenance program and proactive replacement plans. Tesla maintains a repository of information on failures of all components, banning usage of parts that have not met Tesla standards.

Tesla has a documented FMEA process that is applied to all development projects. FMEA is a defined process for identifying all possible failures in a product design or manufacturing process. This process also documents and prioritizes the risks associated with the failures. Once failures and risks have been documented, corrective action plans can be developed.

The review of the FMEA process included the Product Excellence-Quality Inspection Key Points document, which highlighted the construction of the internal components of the enclosure and the installation of the fasteners and connectors as well as the printed circuit board (PCB) and wire harness installation. This document also included the Inspection Elements along with the Reject Criterion which noted the potential effects of failure and the severity rankings. A process for evaluating risks was further included in the FMEA process document. Risk evaluation includes the use of severity tables for determining the severity of a failure effect; the likelihood of occurrence using Tesla Motors' proprietary occurrence tables based upon historical data, including the service history, warranty data, and maintenance experience with similar or surrogate parts; and detection tables are based upon historical data for existing design controls, including the service history, warranty data, as well as test results and statistical analysis. The process includes generation of a Risk Priority Number, or RPN, to guide the decision-making process of what issues generated by an FMEA should be addressed.

DNV GL notes that Tesla's reliability program and FMEA processes are comprehensive and meet or exceed industry standards. The processes are well documented and integrated into their overall system development processes.

7.1.1 Incoming material inspection

Tesla provided their standard receiving and inspection document for review by DNV GL. The document details the guidelines for required activities relating to the inspection of incoming material to their manufacturing facility.

Incoming material inspection responsibilities are delineated between the clearly defined roles which include the inspectors, supplier quality assurance technicians, and the quality engineers. Inspectors inspect materials to design specifications as documented by mechanical drawings, internal documents, and national standards. The supplier quality assurance technicians examine the detection of non-conforming material and engage suppliers to resolve issues relating to non-conforming material. Finally, the quality engineers develop inspection standards, and collaborate with suppliers to drive root-cause analysis, temporary countermeasures, and permanent solutions. General training related to these roles is covered in the following section.

Figure 7-5 shows the flow of materials incoming to the manufacturing facility. Acceptable Quality Level (AQL) Sampling is implemented with tighter AQL levels based on history of shipments from the supplier, while all material is subject to a general visual inspection for any defects or abnormalities. The result of the acceptance sampling determines whether the lot is accepted or rejected. For some critical parts, Tesla has instituted a 100% check procedure. All materials in the facility are labeled with color coded stickers indicating status of inspection: a yellow "quarantine" sticker denotes material held in receiving inspection that is pending inspection, a green "approved" sticker denotes material that has passed inspection, and a red "reject" sticker denotes material that has failed inspection.

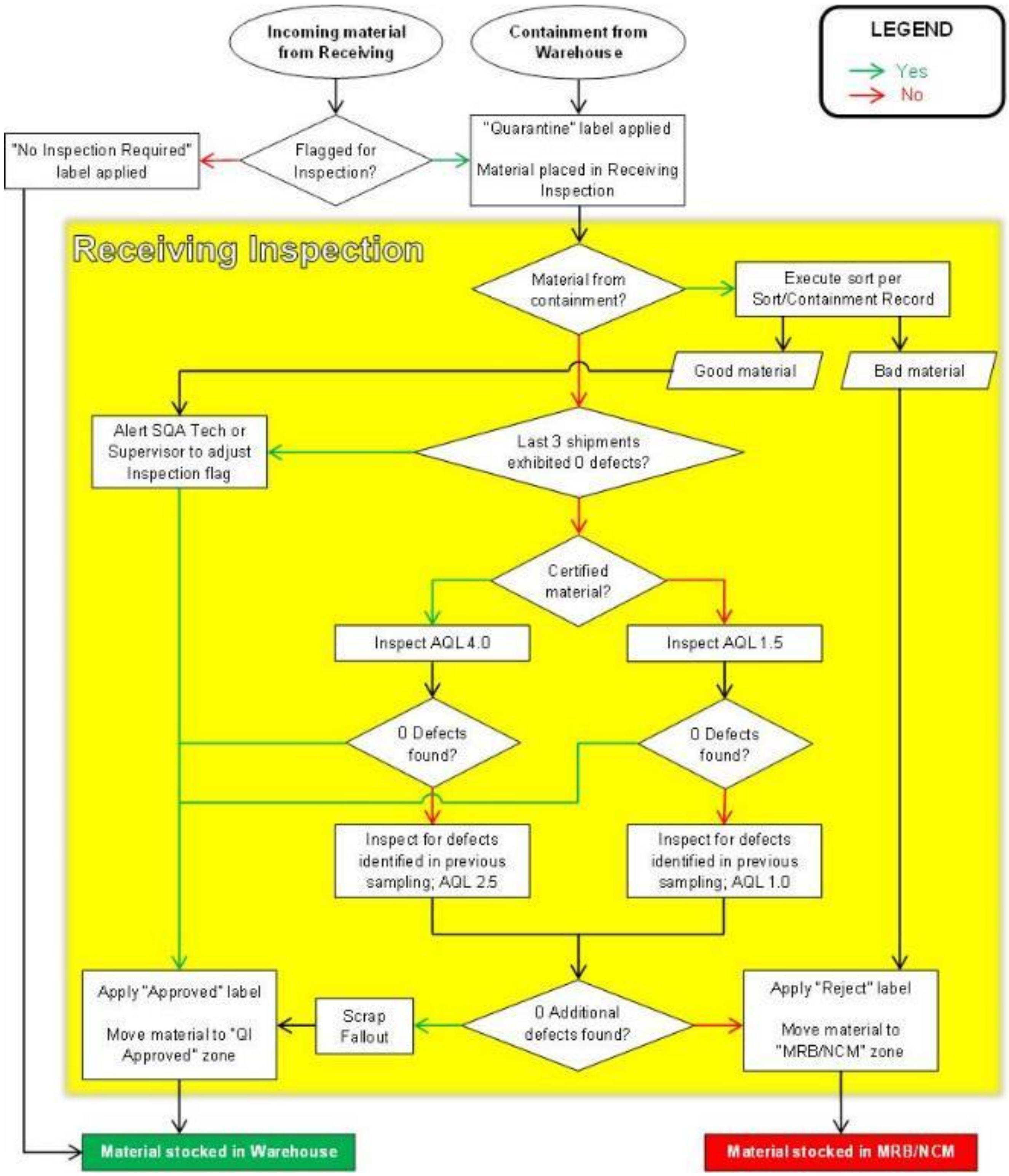


Figure 7-5 Incoming materials inspection flow

During the initial factory visit in the support of the Powerpack 1 technology review, DNV GL observed and witnessed the incoming material inspection process. DNV GL witnessed a Tesla technician performing incoming material inspection using a caliper to measure the thickness of an incoming part to compare against the specification. All parts are inspected against up-to-date specifications which Tesla maintains on all parts in their Enovia database. DNV GL also observed incoming materials stored in a designated quarantine area with clear labels indicating inspection status.

DNV GL looks very favorably on the rigor, quality, and documentation of Tesla's incoming material inspection processes.

7.1.2 Manufacturing quality management and training

Tesla maintains a complete genealogy and manufacturing history for every product manufactured at their facility. Their Data Analyzer tool can pull data on a specific product serial number from the Manufacturing Execution Systems. On a previous site visit, a live demonstration of this tracking system was performed where the data analyzer program was used to pull up the serial number of a Powerpack 2 being manufactured. A complete genealogy of the product was available that included all parts installed along with the station number, installation time, and the name of technician who installed it. The history of every operation and test performed was also available, with the results of those tests included along with the history.

Tracking this large database of well-organized and well-maintained data further allows Tesla to observe and investigate trends over all manufactured products. DNV GL notes this as highly favorable for tracking and improving product quality over time.

Every station in the facility has an instruction manual telling the factory associate what task to complete and what safety measures are required. A photo of the instruction manual is shown below in Figure 7-6.

Figure 7-6 Instruction Manual in hardcopy at assembly station

For qualifying manufacturing associates, Tesla is currently implementing a 4-star rating system for each manufacturing station. In this scheme, every associate working at the facility is assigned a 4-star metric for each station which designates their proficiency at the task based on tested metrics of quality and Takt (in-process manufacturing) time.

The star rating corresponds to an entry level technician at 1-star which has the ability to build quality production and can achieve certain Takt time, through an experienced 4-star rated associate who is qualified to train others on the station tasks. An associate can be certified to every station on each line. DNV GL was shown a versatility matrix which demonstrated the star rating for each associate on each station in the facility. Currently, stations cannot be started until an appropriately graded associate logs-in. Tesla is moving toward a badge control system which is integrated with the training database. The training level of each associate will then be tracked to the badging system.

Finally, on calibration, Tesla is using a system called Dispatch, developed by Leading2Lean. All tools and testers at the Gigafactory are currently calibrated, and those in-use are operating within their one-year calibration window. All calibration will be done by a NIST certified laboratory. A label of the calibrated tool is shown below in Figure 7-7 and Figure 7-8.

Figure 7-7 Calibrated tool

Figure 7-8 Label of calibrated tool

DNV GL notes that the manufacturing quality management and personnel training systems in place at Tesla Gigafactory meet or exceed those currently observed in the energy storage industry. Tesla's ability to produce and track complete product genealogy will result in large degree of visibility on integrated product performance over time. Further, the lessons carried over from the automobile manufacturing are evident in both the quality management and personnel training systems.

7.2 Tesla battery manufacturing evaluation

This section contains the results of the first 21 March 2016 factory visit which was primarily focused on the battery manufacturing for Powerwall and Powerpack.

7.2.1 Facility overview at time of DNV GL visit

Two Pod manufacturing lines were present at the facility at the time of the DNV GL's visit: a manual line (Pod Line 1) and a partially-automated line (Pod Line 2). The product flow for the partially-automated Pod manufacturing line was easily understood in a conventional U-shaped path with a conveyer belt shuttling the in-process Pods between assembly, testing, and quality inspection stations. Tesla explained that all future high volume manufacturing is planned for the partially automated Pod Line 2, which is the focus of further discussion below. Robots were employed in Pod Line 2 for automating the heavy lifting tasks and for tasks with hazardous-voltage exposure risks.

In addition to the Pod lines, separate manual manufacturing lines were in place for the assembly, testing, and packaging of complete Powerwall and Powerpack products. DNV GL found the layout of the facility to be logical and orderly. The facility was high bay and more than adequate for the current volume of products. Adequate lighting was supplied, and the temperature was adequately controlled to provide a comfortable working environment.

7.2.2 Battery manufacturing lines

Tesla supplied DNV GL with a process flowchart for their various component and final product assembly lines related to Pod, Powerwall, and Powerpack assemblies. The Pod assembly process and manufacturing line is described below and illustrated with photos to present the Tesla manufacturing approach. The process flow chart for the Pod assembly is shown in Figure 7-9. Note that the various testing points are shown and indicated by the yellow diamond symbols. Failing a test at one of these points will results in corrective action before the assembly process can continue. Additionally, two quality inspections are included in the process which can trigger remedial actions.

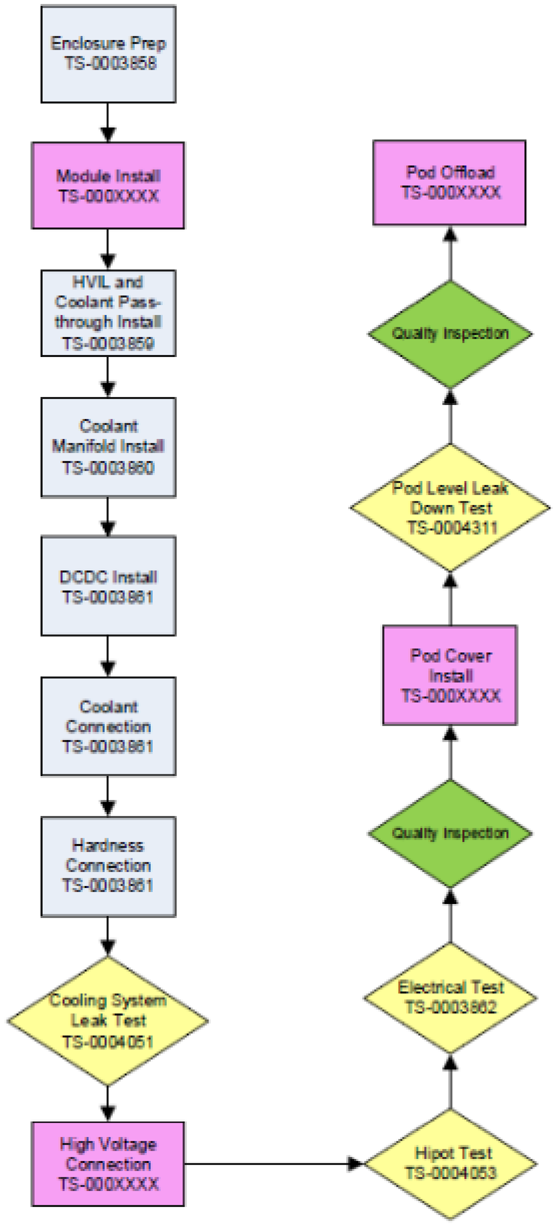


Figure 7-9 Pod Line 2 operation sequence diagram

The lower half of the Pod, denoted as the tub, as well as battery modules are loaded into bays. Robots automatically operate between these bays to perform module installation into each tub. Each tub is inscribed with a serial number for part tracking purposes. As seen in Figure 7-10.

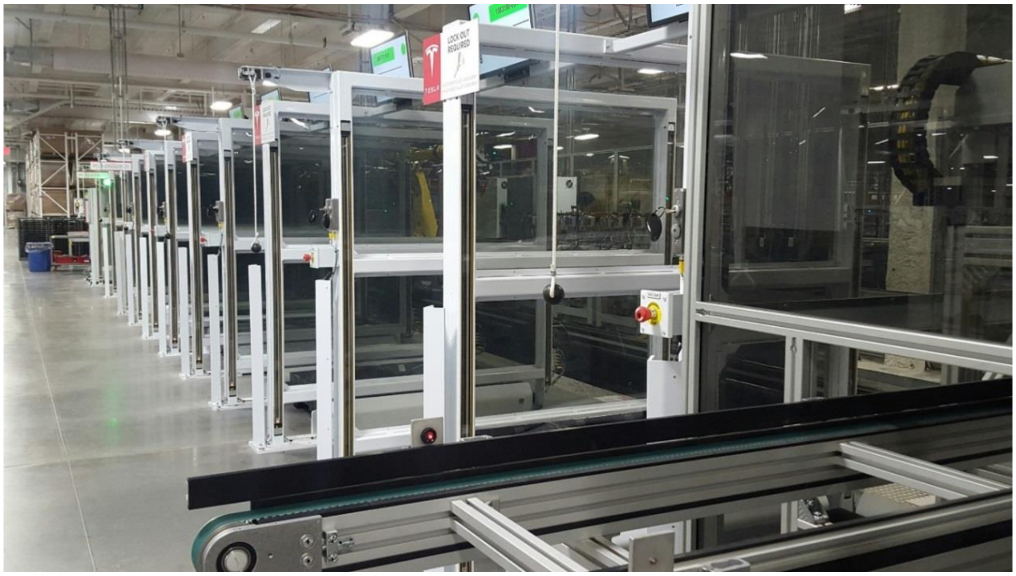


Figure 7-10 Emergency-off switches and bays with physical separation and sensors for safety are used while robots automatically operate between the bays

Following installation of the battery modules, several installation steps are performed including installation of the coolant manifold and DC/DC converter. Shown in Figure 7-11, robots are used for assembly automation and computerized testing with interlocks. Coolant system leak tests are performed to ensure all connection to the liquid coolant system are sound before coolant will be added to the system.

Figure 7-11 Pod line 2 Assembly and Testing - Robots are used for assembly automation and computerized testing with interlocks is done

In addition to the heavy lifting tasks, robots are used where electrical tests take place and there is a risk of electric shock. Figure 7-12 is a photo of the robots deployed to place the bus-bar connections which complete the Pod circuit, connecting the two battery modules within each Pod in series and connecting the modules to the DC/DC converter interface.

Figure 7-12 Robots used for automating the heavy lifting tasks and places with hazardous electrical interconnects

Following completion of the Pod circuit connections, end of line testing is performed including high-pot test and function electrical testing. These test bays are shown in Figure 7-13. Physical safety is maintained through physical separation, proximity sensors, and emergency-off switches. Proximity sensors are used to ensure robot movement will cease if a human enters the test bay while a Pod is being loaded or removed.

Figure 7-13 End of line testing showing emergency-off switches, bays with physical separation, and sensors for safety

Following the electrical tests, a quality inspection is performed prior to closing and sealing the Pod. Figure 7-14 shows one of Pod quality inspection stations. After the Pod is sealed, a Pod level leak test is performed to ensure the enclosure is properly sealed which will ensure safety venting thermal management per Tesla's design.

Figure 7-14 Quality control station: Quality controls are performed at several points on the production line

The Powerpack manufacturing operation sequence diagram is shown in Figure 7-15. The Powerpack operating sequence consists of manual processes which include assembly and installation of the thermal door, installation of the Pods into the enclosure, and installation of the coolant manifold which is followed by a leak test prior to coolant being filled into the system. Electrical connections are then installed and tested prior to the pack out of the system.

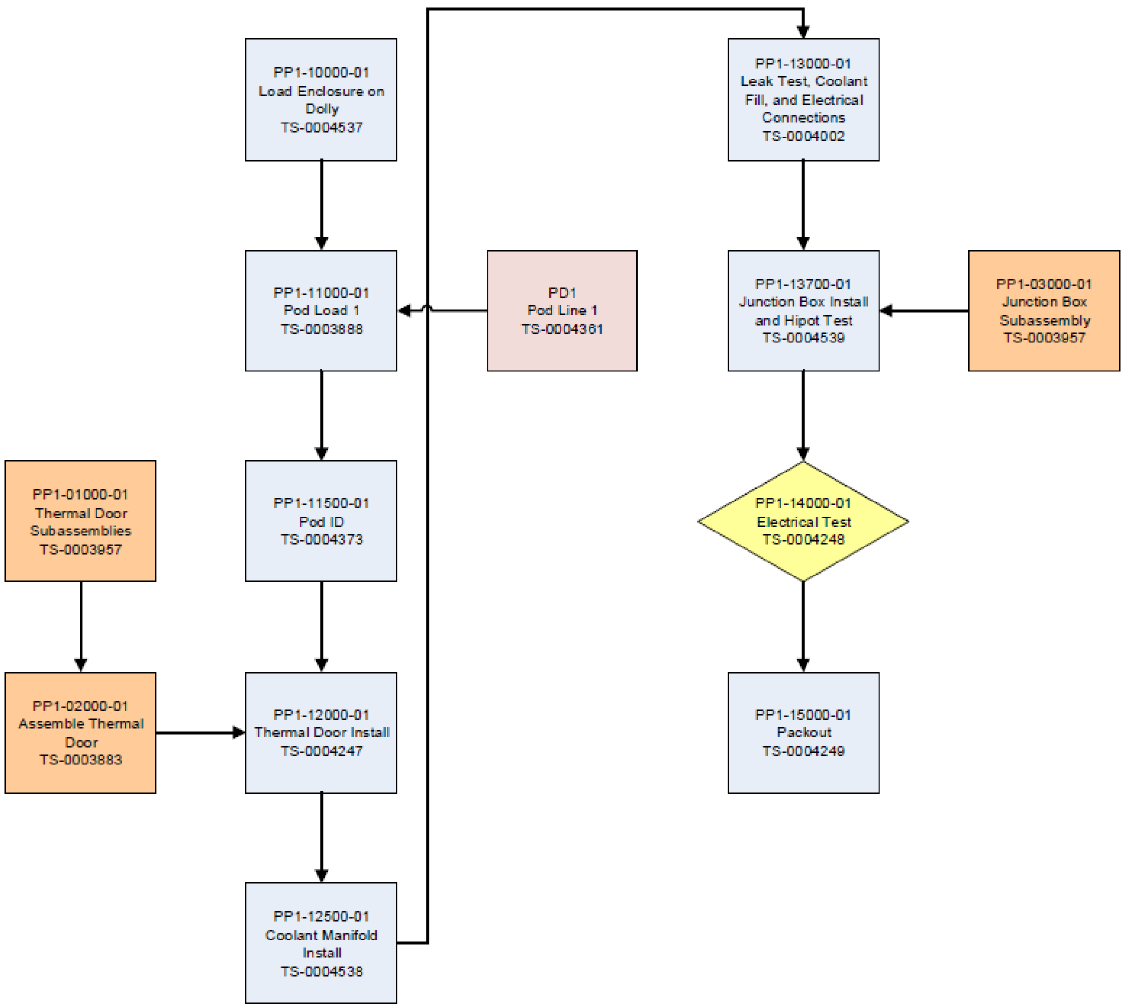


Figure 7-15 Powerpack operation sequence diagram

Below photos from Figure 7-16 and Figure 7-17 were taken during DNV GL's second site visit to the Gigafactory on 26 May 2017.

Figure 7-16 Another view of manufacturing line

Figure 7-17 Equipment testing area

7.3 Tesla inverter manufacturing evaluation

DNV GL toured the Gigafactory on a previous site visit, with the observations and opinions from that visit documented in the battery section, earlier in this report. In this section, updates and inverter specific information is provided based on the DNV GL Gigafactory visit on 26 May 2017, where the DNV GL team focused on the manufacturing processes and techniques for the Tesla-designed inverters.

7.3.1 Tesla inverter lines

In Figure 7-18, the inverter manufacturing line is shown, with inverter products moving from station-to-station, to the right. Instructions, tools, and parts can readily be seen at the first station.

Figure 7-18 Inverter manufacturing assembly line

In Figure 7-19, the Powerpack 2 Inverter without the cover is shown. The inverter is a complex assembly of power conversion, electrical filtering and control circuitry, cooled by a liquid cooling loop. Figure 7-20 shows the blind-mate power connections that allow the inverter to slide into the rack to complete the power circuit, without the need of making hand-bolted power connections at the front.

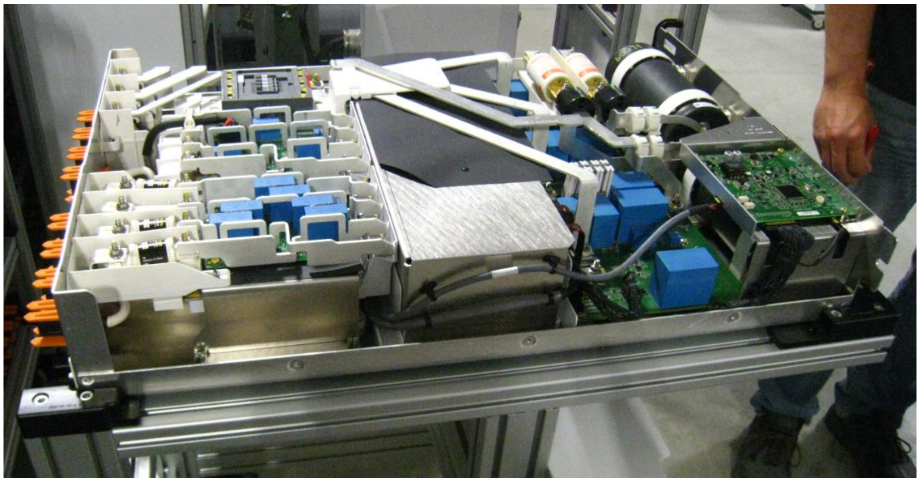


Figure 7-19 Powerpack 2 Inverter

Figure 7-20 Blind-mate power connection

7.3.2 Manufacturing quality management

The information contained in this section augments the review of the manufacturing quality management and systems described in the battery section of this report and focuses on systems related to the inverter manufacturing. As described earlier in this report, Tesla's quality management reports to the VP of Infrastructure Development, providing a direct link to upper management.

Tesla has a comprehensive Quality Assurance Program that complies with ISO 9001 standards. Per Tesla's program, the supply of parts and components are managed by the Purchasing, Design Engineering, and Quality departments which are then verified by the Supplier Industrialization team to ensure parts meet design specifications and capacity standards. Tesla uses component ratings, applied stresses, and resulting component life calculations to evaluate components. The component selection is managed in Tesla's data system. Documentation of the component selection ratings were not provided by Tesla.

Below Figure 7-21 through Figure 7-23 show the test equipment associated with the Powerpack 2 Inverter. Figure 7-21 and Figure 7-22 show a Powerpack 2 Inverter test station for automated inverter functional testing, including the IEEE 1547 grid-interactive requirements. The test is fully automated, removing the opportunity of operator error, while performing many tests of thresholds and response times within a 10-minute test period. During the tests, the 5-minute wait time for grid interconnection is temporarily reduced to seconds, to allow many tests to be performed in minutes instead of hours.

Figure 7-21 Inverter testing equipment bay area

Figure 7-22 Powerpack 2 inverter under test

The inverter burn-in test station shown in Figure 7-23 is supplied with 70°C coolant to simulate operation in a high ambient temperature. The Powerpack 2 inverter under tests operates for approximately 45 minutes while performing a series of functional tests designed to stress the inverter while verifying operation at the corners of the specification.

Each inverter is tested at full capacity of 62.5 kW and the following operational parameters and limits:

- Power factor limits
- 24 V logic current
- Conversion efficiency
- AC voltage and current in specification
- DC voltage and current in specification
- Powerstage temperature in range
- Coolant temperature in range

Additional tests are performed at the inverter cabinet level, including verification of the cooling system integrity and performance.

Figure 7-23 Burn-in testing area

7.3.3 Packaging, storage, and shipping

The Tesla Powerpack 2 Inverter is assembled and tested on a shipping pallet. This makes packing relatively easy, considering the size and weight of the unit. The plywood cover is added to the pallet to create a fully-enclosed shipping crate. At this point, the unit can be readily moved by forklift or pallet jack, and stored vertically, with no stacking allowed.

8 POWERPACK 2 SYSTEM INTEGRATION

8.1 Integration overview

This section reviews and evaluates the integration of the entire Powerpack 2 System. Some information is repeated here from previous sections in order to facilitate easy identification of key system components and system functions.

The Tesla Powerpack 2 System is a turnkey, grid compatible energy storage system comprised of Li-ion based battery modules and modular enclosures or building blocks that can be paralleled to achieve desired system power and energy ratings. The AC power building block is a single, multiple-module inverter which can be supplied by up to 20 energy storage Powerpack 2s, containing 174 kWh or 210 kWh of energy storage with a maximum charge or discharge, both peak and continuous, of approximately 87 kW or 53 kW for the 2-hour or 4-hour Pod configurations, respectively.

The photograph in Figure 8-1 shows a 625 kW @ 480 V AC /1 MWh system comprised of one inverter and five Powerpack 2s visible.

Figure 8-2 shows a block diagram a 625 kW AC Powerpack 2 System block with multiple Powerpack 2s. The diagram shows the major components, which, for convenience, are again defined here:

1. Powerpack 2 – Free-standing enclosure containing 16 parallel-connected battery Pods. The enclosure also contains thermal management system, 900 V DC bus, output connections, and monitoring and communication connections.

Figure 8-1 Industrial Powerpack 2 system

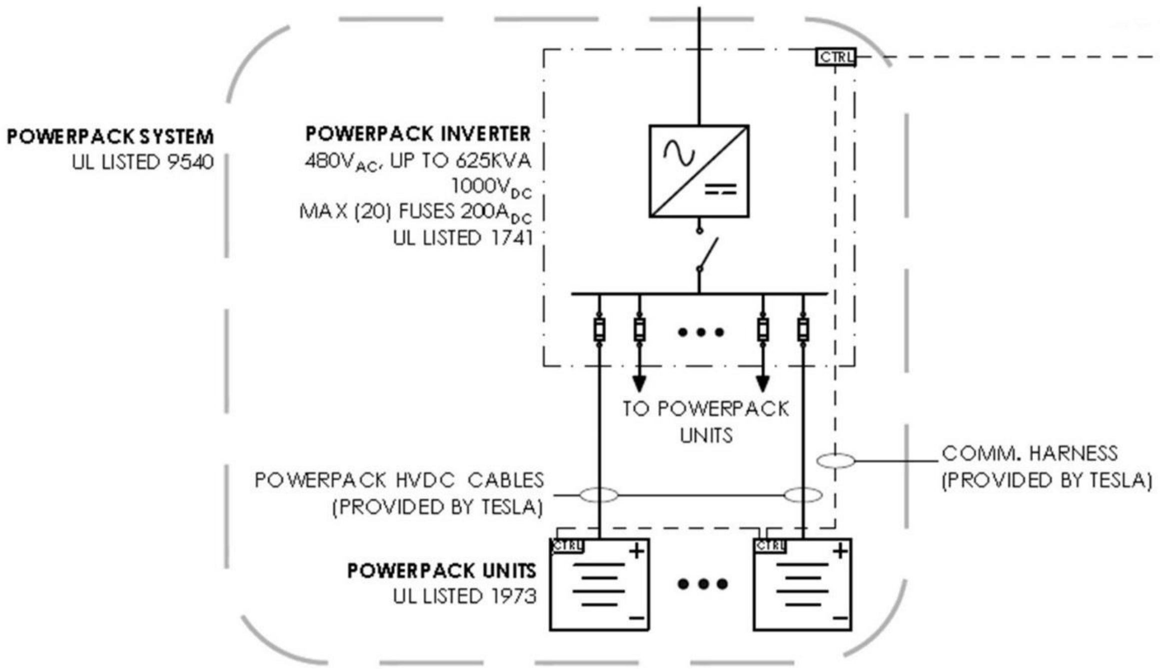


Figure 8-2 Powerpack 2 System block diagram

2. Pod (inside Powerpack 2) – A replaceable sealed enclosure containing Li-ion battery cells, overcurrent protection, DC/DC converter, battery management system, communication circuits, and DC output terminals for connection to the Powerpack 2 DC bus.
3. Powerpack HVDC Cables – A custom wireway that contains the cables connecting each Powerpack 2 to the inverter. The wireway runs along adjacent Powerpack 2s and is integrated at their base.
4. Inverter – The power conversion system that enables bi-directional power flow between the Powerpack 2 System DC bus and the end user 480 or 400 V AC bus or switchboard. The inverter is manufactured by Tesla.

8.1.1 On-site system integration

The major components listed above are integrated into a system at the customer location site. Manufactured individually, the components are tested and shipped to the site. Arriving usually on a flatbed truck, the large components are lifted from above with a crane or boom truck and lowered into place. The entire system becomes operational for the first time at the field location.

The on-site civil work in preparations for the installation of the major electrical components varies from site to site based largely on the system size, but primarily involves the fabrication of a concrete pad with buried electrical conduit with cables for system wiring. The "Powerpack 2 System Installation Manual" provides detailed instruction for site preparation and requirements.

The "Tesla Powerpack 2 System Site Design Manual" is a concise guideline of inspection points to assure that the site is complete and ready, and that the installation of the major electrical and foundation components complies with Tesla requirements for mechanical assembly and verification. Major inspection points include:

- Concrete pad for the Powerpack System shall have a minimum strength of 4,000 psi and minimum slab thickness of 8 inches.
- The reinforcement for a concrete pad shall be a minimum #5 rebar at 12 inches on center.
- The top of the pad shall be a minimum of 6 inches above expected flood elevations.
- The top of the pad shall be above adjacent grade, 4 inches minimum and 6 inches maximum, with the edge of the concrete a maximum of 12 inches from the front of the Powerpack System. If the site does not allow this pad height, then the pad must extend a full 4 feet in front of all Powerpack Units and include a ramp to allow service cart access.
- Six feet must be left clear in front of all Powerpack Units for unobstructed airflow.
- For sites with a CMA, the pad shall include the space allocated for spare Powerpack Units.
- The pad does not need to extend beyond the front face of the equipment to include NEC clearances. Pad dimensions should be determined by the structural edge distance requirements for the anchors and to meet geotechnical design criteria.

Although covered in more detail in Section 10, DNV GL notes that the installation documentation reviewed adequately describe two critical aspects of field installations: proper foundation slope and area grading to facilitate drainage, and equipment orientation to facilitate proper ventilation airflow. Allowing the exit air from air-cooled equipment to inadvertently route back to the air inlet, resulting in equipment over-heating, is a recurring issue in the power conversion industry. Tesla has clearly taken this issue into consideration in the layout design.

8.2 System codes and standards compliance – North America

This section addresses the entire Powerpack 2 system compliance to codes and standards for U.S. and Canadian installations.

Tesla previously retained DNV GL to provide an engineering review of the technology, applicable standards, certifications, and compliance to evolving battery related requirements in the National Electrical Code (NEC). Portions of this Section review draw upon information obtained during that project. DNV GL's overall assessment is that the Powerpack 2 System, certified as a field assembled system, has been evaluated to the appropriate UL standards. When installed according to the requirements of the listing and manufacturer instructions, it is fully code compliant with relevant articles of the 2014 and 2017 NEC.

One of the basic and primary considerations of the NEC is the use of equipment that is listed (certified) by NRTLs for the application and installation. Authorities Having Jurisdiction (AHJs – or permitting reviewers and inspectors) are authorized to approve equipment for installation without certifications, but most invariably their approval is based on equipment certification, per NEC article 110.3: "Examination, Identification, Installation, and Use of Equipment."

The following subsections summarize the certification considerations that will be most visible and important for NEC compliance.

8.2.1 Certification summary

Two notable UL standards have been developed to address need for systems level evaluation of products incorporating batteries and other energy storage technologies:

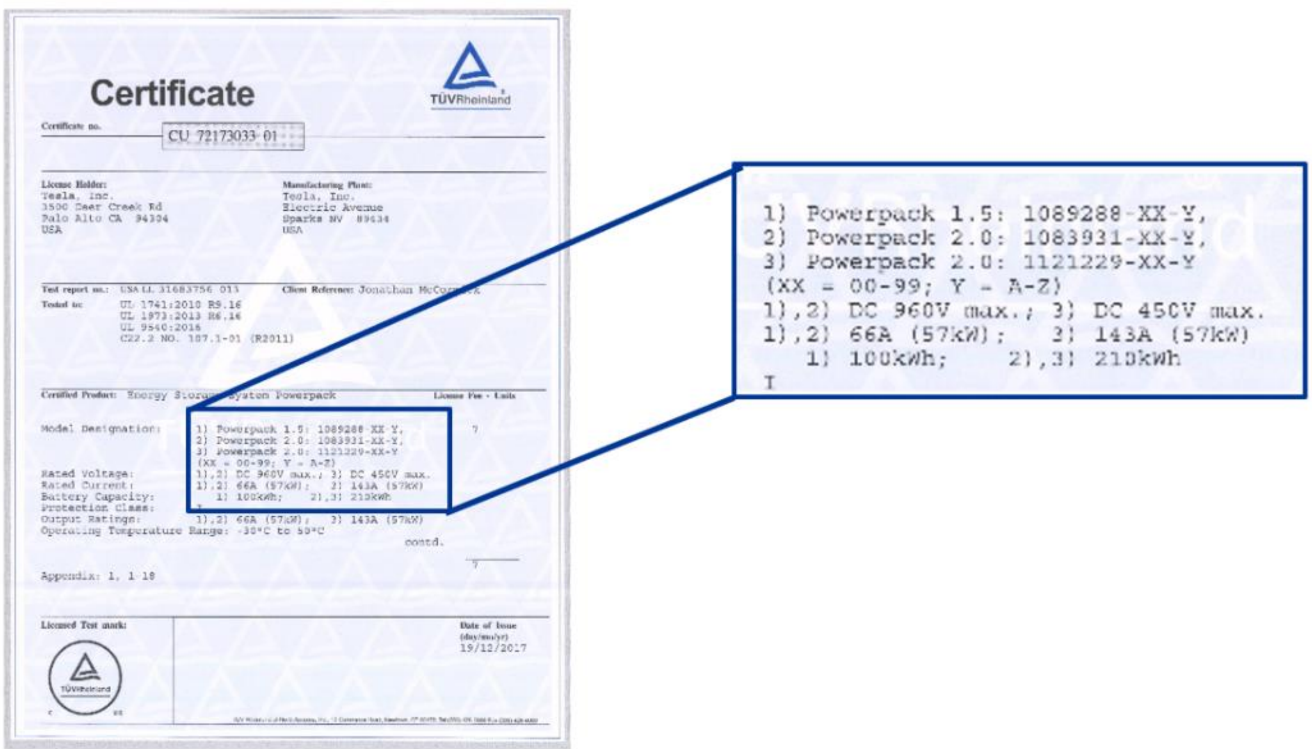
UL 1973 - *Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications*

UL 9540 – *Outline of Investigation for Energy Storage Systems and Equipment*

Although there is much in the detail, a broad view of the two standards is that UL 1973 covers a more detailed evaluation of the batteries and the immediate controls and protections that may be built into a battery based product, whereas UL 9540 is a broader system level standard. It provides a higher level umbrella evaluation extending to systems that interact with power sources and loads, potentially up to a complete grid-connected system. This almost invariably involves power conversion equipment for controlling the DC power flow to and from the battery and loads. By necessity therefore, a certification to UL 9540 typically involves subcomponent listings to UL 1973 and UL 1741, *Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources*.

Tesla's Powerpack 2 System certification follows this model, as illustrated above in Figure 8-2. The callouts and outlines indicate the standards covering the different components and assembled systems.

The umbrella UL 9540 certification addresses the field assembly of all Powerpack 2 System components up to the inverter's output terminals. The TÜV listing certificate refers to this complete assembly as the "Energy Storage System Powerpack." Since the last revision of this report, both the 2-hour and 4-hour versions of the Powerpack 2 have completed these certifications, as shown in Figure 8-3.


Certificate

TÜVRheinland

Certificate no. CU 72173033 01

License Holder:
Tesla, Inc.
3500 Deer Creek Rd
Palo Alto CA 94304
USA

Manufacturing Plant:
Tesla, Inc.
Electric Avenue
Sparks NV 89434
USA

Test report no.: USA LL 31683756 013

Client Reference: Jonathan McCormick

Tested to: UL 1741:2010 R9.16
UL 1973:2013 R6.16
UL 9540:2016
C22.2 NO. 107.1-01 (R2011)

Certified Product: Energy Storage System Powerpack

License Fee - Units

Model Designation: 1) Powerpack 1.5: 1089288-XX-Y,
2) Powerpack 2.0: 1083931-XX-Y,
3) Powerpack 2.0: 1121229-XX-Y
(XX = 00-99; Y = A-Z)

Rated Voltage: 1),2) DC 960V max.; 3) DC 450V max.
Rated Current: 1),2) 66A (57kW); 3) 143A (57kW)
Battery Capacity: 1) 100kWh; 2),3) 210kWh
Protection Class: I
Output Ratings: 1),2) 66A (57kW); 3) 143A (57kW)
Operating Temperature Range: -30°C to 50°C

contd.

7

Appendix: 1, 1-18

Licensed Test mark:

Date of Issue (day/mo/yr) 19/12/2017

Figure 8-3 TÜV certificate for UL 1741, UL 1973, and UL 9540 for Powerpack 2

Installation instructions referenced by the TÜV certification indicate that the industrial Powerpack 2 System is designed to allow up to twenty Powerpack 2s per inverter and provides details for the allowed physical configuration. The allowed layout configurations ensure, among other things, that the integrated wireways are utilized in a compliant manner. The diagram indicates the important component certifications within the overall Powerpack 2 System UL 9540 listing, and each is discussed in the following sub-sections.

8.2.1.1 Pods

TÜV's certification of the Pods included subcomponent evaluations to standards UL 1973:2013 and UL 1741:2010.

The UL 1973 evaluation covers the packaged battery (with protection subcomponents), and the UL 1741 evaluation covers the integrated DC/DC converter. Additionally, the battery cells are certified to UL 1642, *Standard for Lithium Batteries*. A basic requirement of UL 1973 is that the cell utilized in the product is certified as a subcomponent to the appropriate battery technology standard. The Li-ion cells that Tesla purchases from its suppliers carry a UL 1642 certification from 31 March 2016. Tesla provided the cell model number, which DNV GL independently confirmed in January 2019 to be included within the certification provided. The UL 1642 standard covers the cell level safety aspects, i.e., nail penetration, shock, crush, short, etc.

8.2.1.2 Powerpack 2s

As a relatively simple enclosure for paralleling multiple Pods, the Powerpack 2s do not have a stand-alone certification as do the Pods. Its evaluation is covered in the overall DC Powerpack 2 System certification to UL 9540, which references a myriad of standards by which the individual internal components were evaluated.

For example, these include standards covering the fuses, junction boxes, connectors, power supplies, cooling system parts, and the enclosure itself. The evaluation also required compliance to select aspects of UL 1973 and UL 1741 to address overall system electrical safety and durability.

Additionally, the Powerpack 2s were tested and certified to be in conformity with the following seismic requirements, with certificates shown in Figure 8-4:

IEEE 693-2005: IEEE Recommended Practice for Seismic Design of Substations	
	Qualification level; High PL: ZPA=1.0 g 2% damping
ICC-ES AC156-2012:	Seismic Certification by Shake-table Testing of Nonstructural Components
	Certification levels; S_{DS}=1.56 g z/h=1, I_P=1.5 and S_{DS}=2.50 g z/h=0, I_p=1.5

Tesla Motors, Inc.
3500 Deer Creek Road
Palo Alto, California, U.S.A.

Product:
Combiner box model #: 1060586 and Powerpack model #: 1060119

Manufacturers Declaration of Conformity

Tesla Motors, Inc. certify and declare under their sole responsibility that the above-referenced product, is in conformity with the seismic requirements:

IEEE 693-2005
IEEE Recommended Practice for Seismic Design of Substations.
Qualification level; High PL: ZPA=1.0 g 2% damping

ICC-ES AC156-2012
Seismic Certification by Shake-table Testing of Nonstructural Components.
Certification levels; S_{DS} =1.56 g z/h = 1, I_P = 1.5 and S_{DS} =2.50 g z/h = 0, I_P = 1.5

Products must be installed and operated with reference to the instructions in the Product Manual.

The following company Miyamoto International has issued a positive Statement of Opinion based on report number MI 1599025 'Seismic test qualification/certification report'. The technical report file is maintained at the corporate headquarters of Tesla Motors, Inc.

Valid until 06/30/2017

______01/31/2016________(mm/dd/yyyy)
Date

Jonathan McCormick
Test and Compliance Manager, Tesla Energy

TESLA

Report Number: MI 1599025
Seismic Test Qualification/Certification Report

Qualification level: IEEE 693-2005 High PL: ZPA=1.0 g 2% damping
Certification level: ICC-ES AC 156-2012: S_{DS} =1.56 g z/h=1 I_p=1.5
S_{DS} =2.50 g z/h=0 I_p=1.5

Powerwall, Powerpack, and DC Combiner
Models: 1067000-000-A, 1060119-00-D, and 1060586-20-B

Tesla Motors
3500 Deer Creek Road
Palo Alto, CA 94304

This is to certify that the above-named equipment and support meets all requirements in accordance to IEEE Standard 693-2005 and ICC-ES AC156-2012.

Prepared by:
Amir Gilani PhD SE
Manager Earthquake Engineering
Miyamoto International
2016-01-31

Reviewed by:
Shakhzod Takhirov PhD PE
Laboratory Manager
University of California, Berkeley
2016-01-31

REGISTERED PROFESSIONAL ENGINEER AMIR S.J. GILANI S 4733 EXP. 6.30.2017 STRUCTURAL STATE OF CALIFORNIA

REGISTERED PROFESSIONAL ENGINEER SHAKHZOD TAKHIROV No. C 70720 Exp. 06/30/17 CIVIL STATE OF CALIFORNIA

2016 March 12 (REV. 00)

1/28 (Tesla Powerwall IEEE High PL & AC156 QR .docx)

Figure 8-4 Certificates of Conformity and Testing - seismic requirements

8.2.1.3 Wireway, DC conductors, and connectors

The wireways interconnecting the Powerpack 2s with the inverter are integrated flush at the base of the Powerpack 2 enclosures to minimize footprint and to avoid extraneous conduit or external wireways on the pad. See Figure 8-5. The wireway, cables and connectors are custom components all evaluated as part of the field assembly.

Figure 8-5 Installed wireway flush in bottom of Powerpack 2 enclosures

The key sub-certifications include:

- UL 758 – Standard for Appliance Wiring Material
- UL 1977 – Standard for Component Connectors for Use in Data, Signal, Control and Power Applications

A UL 758 listing for the wiring was pursued to accommodate the use of flexible, high-temperature cable used in the automotive industry. The cable was selected to enable a smaller wiring system footprint. The approach is noted here because it is unusual for typical field wiring, which generally uses building wire or other installation cables covered by the NEC (in the U.S.) or international installation standards. UL 758's scope addresses internal appliance cable, but the exceptions indicate applicability in field assembled systems:

- Wiring that is "solely for use as factory-installed wiring either within the overall enclosure of appliances and other equipment (internal wiring) ***or as external interconnecting cable for appliances (external wiring),*** or for further processing as components in multi-conductor cables," and;
- "[does] not cover any wire, cable, or cord types that are presently covered in the National Electrical Code (NEC), NFPA 70, and are not intended for installation in buildings or structures in accordance with the NEC ***except within the scope of the installation instructions of the end-product*** for which their use is intended."

TÜV evaluated the cables for conditions of maximum wireway fill and ambient temperatures with consideration of as many as 20 Powerpack 2s connected to a single inverter. Some enhancements were implemented during the evaluation process, such as the application of protective tape to provide greater protection from abrasion in the wireway. The wireway is comprised of aluminum cable tray with powder coated Galvanneal covers and fastener plates.

The certification report notes that the integrated wireway system was evaluated for dry/damp locations and should be installed according to the installation instructions. It further notes that suitability is to be determined in the end application. The installation instructions include a number of provisions to ensure that water ingress to the wireway system is minimized:

- The pad or base shall slope a minimum of 1% and a maximum of 2% to allow positive drainage from the pad/base or towards a drain. There must be sufficient clearance between the equipment and any walls or obstructions to allow for proper drainage.
- The top of the pad shall be higher than the adjacent grade or ground surface, 3 inches minimum and 6 inches maximum.
- The top of the pad shall be a minimum of 6 inches above expected flood elevations.

DNV GL notes that strict adherence to these provisions is critical for maintaining a damp location classification for the wireway system, which is defined by the NEC (2014) as:

> *"Locations protected from weather and not subject to saturation with water or other liquids but subject to moderate degrees of moisture."*

Traditional measures for protected locations such as canopies or barriers should not be necessary if the protective provisions are met and enforced.

Furthermore, as of the date of this report, Tesla reports that they have achieved a wet rating for the automotive cable certification, which helps to mitigate installation concerns for the DC cables.

8.2.1.4 Tesla Site Controller

The Tesla Site Controller (referred to in some documentation as the Site Master Controller) has project and location specific attributes and may link any number of Powerpack 2 blocks (i.e. multiple inverter-DC block configurations). As such it was not included in the TÜV Rheinland certification of the DC block. According to Tesla, the controller is certified to standard IEC/UL 61010 by a contract manufacturing supplier. DNV GL does not have any significant concerns with respect to the Controller compliance.

8.2.1.5 Inverter

As described in the Certification Summary above, the inverter is not part of the Powerpack 2 System field assembly as evaluated and certified by TÜV. It is supplied separately and has been certified by Intertek to UL 1741, "Standard for Safety - Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources." The DC Bus Controller, which previously was installed in a separate DC Combiner Panel, is now integrated directly into the inverter, thus allowing the Powerpack 2 power and communication harnesses to connect within the inverter. The UL 9540 listing certificate from TÜV states that the DC Powerpack 2 System is "intended to be used in conjunction with the Tesla Industrial Inverter, where suitability is to be determined in the end application." The Tesla Industrial (Powerpack) Inverter is the inverter specified by Tesla for use as part of the Tesla Powerpack 2 System.

8.2.1.6 Inverter certification

UL 1741 is based on the IEEE 1547 "Standard for Interconnecting Distributed Resources with Electric Power Systems." A UL 1741 listing is generally required for all utility interactive inverters and employed in residential or commercial sized generating systems. Certification to this standard involves a series of design inspections and tests. Especially challenging are the anti-islanding, grid protection, surge, and EMI testing requirements.

Below in Table 8-1 are the major testing standards for North America relating primarily to the inverter. The Tesla inverter is the only inverter compatible and certified for use with the Powerpack 2.

Table 8-1 Testing standards for North America

Standard	Title
UL 1741	Standard for Safety Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources
IEEE 1547	Standard for Interconnecting Distributed Resources with Electric Power Systems
CSA 22.2N. 107.1-01	Safety Requirements for General Use Power Supplies (Canada)

Tesla reported that Intertek is their NRTL of choice and that they operate as a Satellite Test Site to perform the required testing. The Letter of Authorization to apply the ETL mark covers U.S. and Canadian standards requirements and is shown in Figure 8-6.

Intertek **AUTHORIZATION TO MARK**

This authorizes the application of the Certification Mark(s) shown below to the models described in the Product(s) Covered section when made in accordance with the conditions set forth in the Certification Agreement and Listing Report. This authorization also applies to multiple listee model(s) identified on the correlation page of the Listing Report.

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Applicant:	Tesla Motors, Inc	**Manufacturer:**	Tesla Motors, Inc.
Address:	3500 Deer Creek Road Palo Alto, California 94304	**Address:**	Electric Avenue Sparks, Nevada 89434
Country:	USA	**Country:**	USA
Contact:	Mr. Jonathan McCormick	**Contact:**	John Paul Jose
Phone:	650-391-7144	**Phone:**	775-276-7604
FAX:	na	**FAX:**	na
Email:	jmccormick@tesla.com	**Email:**	jojose@teslamotors.com

Party Authorized To Apply Mark: Same as Manufacturer
Report Issuing Office: Cortland
Control Number: 5005998 **Authorized by:** Elizabeth Komarnicki
for Dean Davidson, Certification Manager

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This document supersedes all previous Authorizations to Mark for the noted Report Number.

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Intertek Testing Services NA Inc.
545 East Algonquin Road, Arlington Heights, IL 60005
Telephone 800-345-3851 or 847-439-5667 Fax 312-283-1672

Standard(s):	Inverters, Converters, Controllers And Interconnection System Equipment For Use With Distributed Energy Resources [UL 1741:2010 Ed.2 +R:07Sep2016] Power Conversion Equipment [CSA C22.2#107.1:2016 Ed.4]
Product:	Industrial Inverter
Brand Name:	NA
Models:	1095371-xx-A where x = numbers from 0 through 9

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ED 16.3.15 (1-Jul-16) Mandatory

Figure 8-6 Listed by Intertek to UL 1741

8.2.2 NEC battery related requirements

Battery installations are covered under Article 480 of the current (2014) and past editions of the NEC. Article 690.71 is also relevant if a battery system is operating in conjunction with photovoltaic systems, but that is not the case here. Because of the increase in productized battery systems and applications, the new NEC 2017 includes a new Article 706 that incorporates much of the existing language of Article 480 but gives more complete guidance for systems that don't involve field connections to the batteries themselves.

One of the more important additions included in the NEC 2017 Article 706 is a new term and definition for "Energy Storage System" and its sub-categorizations:

> **Energy Storage System (ESS)**
> A device or more than one device assembled together capable of storing energy for use at a future time. ESS includes but is not limited to electrochemical storage devices (e.g., batteries), flow batteries, capacitors, and kinetic energy devices (e.g., flywheels and compressed air). These systems can have AC or DC output for utilization and can include inverters and converters to change stored energy into electrical energy.

Energy Storage System, Self-contained.
Energy storage systems where the energy storage devices such as cells, batteries, or modules and any necessary controls, ventilation, illumination, fire suppression, or alarm systems are assembled, installed, and packaged into a singular energy storage container or unit.

> Informational Note: Self-contained systems will generally be manufactured by a single entity, tested and listed to safety standards relevant to the system, and readily connected on site to the electrical system and in the case of multiple systems to each other.

Energy Storage System, Pre-engineered of Matched Components.
Energy storage systems that are not self-contained systems but instead are provided as separate components of a system by a singular entity that are matched and intended to be assembled as an energy storage system at the system installation site.

> Informational Note: Pre-engineered systems of matched components for field assembly as a system will generally be *designed by a single entity and comprised of components that are tested and listed separately or as an assembly to safety standards relevant to the component* and readily assembled on site as a system and connected on site to the electrical system. [Emphasis added].

Energy Storage System, Other.
Energy storage systems that are not self-contained or pre-engineered systems of matched components but instead are composed of individual components assembled as a system.

> Informational Note: Other systems will generally be comprised of different components combined on site to create an ESS. Those components would generally be tested and listed to safety standards relevant to the application.

The Tesla Powerpack 2 System clearly falls under the sub-category of "Pre-engineered of Matched Components" as indicated in the emphasized text. The most important implication of this definition is that the integrated system, as a listed field assembly, has been evaluated and certified as a complete unit, and any additional NEC requirements should only apply to connections and installation aspects outside the boundary of the assembly.

When considering the relevant requirements of the 2014 NEC Article 480 and the NEC 2017 Article 706, DNV GL's overall assessment is that the certified listed field assembly, when installed according to the requirements of the listing and manufacturer instructions, is fully code compliant with both the NEC 2014 and NEC 2017 articles.

DNV GL acknowledges that the absence of manual disconnect switches on any of the Powerpack 2s could give pause to some U.S. inspectors upon first review. However, the inherent protection and disabling functions of the Powerpack 2 System (validated by the certification) effectively ensure that there is no situation in which such switches would be required or would provide any real benefit. These protections and disabling functions monitor for system-level faults or user-initiated actions that cause the power electronics to shut down at the Pod level. Only authorized service personnel would need to physically isolate individual Powerpack 2s, using the connectors internal to the enclosures.

8.2.3 Grounding and bonding

DNV GL reviewed the Powerpack 2 System's compliance to U.S. NEC requirements for grounding and bonding. The review covers equipment grounding and electrode ground requirements for the DC block and inverter. The review does not cover AC side grounding requirements, which are site-specific but also well understood by contractors and inspectors.

The NEC requires metal enclosures, raceways, and other exposed non–current-carrying metal parts of electrical systems to be connected to an equipment ground conductor. The TÜV certification addresses the bonding of applicable metal parts within each enclosure, such as the bonding of enclosure doors to the main chassis. The primary equipment grounds for the installation involve an equipment ground conductor connecting to each Powerpack 2 and the inverter, as well as the mechanical connections in the wireway trays and covers.

The Powerpack 2 installation manual states that a copper ground conductor should be connected from each Powerpack 2 to the inverter. A single ground conductor can be used to ground multiple Powerpack 2s in the same path or string, to a maximum of five containers. The wireway trays and covers are bonded together with plates and mechanical connections and were evaluated as a continuous ground system as part of TÜV's certification. A single connection is made from the inverter to the first section of the wireway, using the same equipment ground conductor that connects to the string of Powerpack 2s.

Electrodes and grounding electrode conductors (GECs) are used to establish earth reference for services and separately derived systems. Separately derived systems are typically associated with AC or DC systems that have a neutral referenced to ground. However, ungrounded systems may still be considered separately derived for the purposes of creating an earth reference for metal enclosures and other exposed non–current-carrying metal components. Article 250.169 covers Ungrounded DC Separately Derived systems for this purpose and requires that a GEC be connected to an electrode from any point on the separately derived system from the source (i.e., Powerpack 2) to the first system disconnecting means (inverter) or overcurrent device (inverter). In other words, an electrode ground connection is required to be established at the inverter.

8.2.4 Protection system considerations for compliance

There are multiple inherent and developed protection features within the Powerpack 2 System that reduce the failure impacts normally associated with stand-alone batteries. The power electronic interface (DC-DC converter) in each sealed Pod isolates the low-voltage DC battery circuit from the primary 900 V DC bus. This isolation provides a level of basic fault protection and allows advanced controls to protect against events such as over-charge, over-discharge, response to exceeded temperature limits, imbalanced charging, failure of the cooling system, DC miswiring, system ground faults, internal battery short circuits or ground faults, and individual component failures.

The UL 1973 certification required the development of a FMEA to identify anticipated single contingency faults which could lead to a hazardous condition, and to ensure that appropriate mitigation is in place. Mitigation methods can rely on active means (e.g. as provided by a BMS or other devices relying on electrical supply), only if there are redundant passive or fail-safe means to provide backup protection. Tesla completed the FMEA as part of the TÜV evaluation, demonstrating that the Powerpack 2 System provides very fast response to fault situations through power electronic control, backed up with passive fusing and/or fail-safe de-energization of specific sub-systems.

8.2.4.1 Overcurrent and short-circuit protection

Overcurrent protection is provided at the various circuit integration levels:

- Wire-bond fusing of low-voltage battery module
- Inline 25 A fuses on the 900 V plus/minus pod output circuits

- Each Powerpack 2 circuit is fused at 200 A on both poles at the inverter.

In most fault conditions, the fuses cannot operate because of the response of the power electronic interface. For example, TÜV's testing revealed that a short at the Powerpack 2 output with 16 fully charged Pods results in near instantaneous voltage collapse and a spike of current lasting less than 1 ms. The typical fault spike from a single Pod was below 180A for less than 1 ms, whereas the Pod fuse curves show a capability of 300 A for up to 10 seconds.

Short-circuit testing internal to the Pod on the battery cell side of the DC-DC converter resulted in cleared wire-bond fusing as expected.

8.2.4.2 Ground fault detection

The Tesla Powerpack 2 System incorporates sensitive ground fault detection analogous to the type used in ungrounded PV systems. The 900 V DC bus fed by the paralleled Pods and Powerpack 2s is ungrounded, therefore there is no inherent fault current if one pole makes contact with a grounded surface. Instead of a traditional ground fault current detector, faults are detected with an isolation monitor that measures the resistance to ground from both poles. If the resistance drops below an isolation degradation threshold of 1,000 Ω/V, a warning alarm triggers a service request for investigation or repair. If the resistance drops below a fault threshold of 100 Ω/V, the ground fault alarm is triggered by the system and all Pods cease to operate. Isolation detection is also employed for the battery cell circuits internal to the Pod. A ground fault in the 50 V circuit causes the Pod to limit its maximum allowed state of charge to minimize potential fault energy but allows the Powerpack 2 to continue operating normally otherwise.

8.2.4.3 Redundant disable functions

The Powerpack 2 System incorporates multiple system disable functions to provide an additional level of safety. All Pods shut down and the system 900 V DC bus is fully de-energized in the event of any of the following:

- Powerpack 2 cabinet door is opened
- Any Powerpack 2 output connector is disconnected
- The inverter DC disconnect is opened
- The inverter door is opened

The disable function is a based a on a discrete enable signal, which is hardwired, and not software controlled.

8.2.5 Arc-flash

The NEC (Art. 110.16) requires that equipment be labeled with quantifiable arc-flash hazard information so that service personnel can plan and use appropriate personal protective equipment (PPE). Arc-flash hazards are typically determined using information from NFPA 70E, *Standard for Electrical Safety in the Workplace*, and IEEE Standard 1584-2002, "Guide for Performing Arc-Flash Hazard Calculations." The evaluation for AC systems is well understood, and for DC systems a commonly accepted approach is to use the maximum power method, defined in NFPA 70E Informative Annex D.

The key result from an arc-flash evaluation is the determination of PPE required to perform work in or around the equipment being analyzed. This is determined using either a hazard/risk category (HRC) table of various tasks – defined by voltage class and conventional AC switchgear activities – or calculations of the specific incident energy (IE) potential of the arc flash at the equipment given the available power connected to it. Incident energy calculations are preferred for DC systems if the arc duration (due to controls or overcurrent protection) is much shorter than the 2 second durations assumed by the HRC tables.

For the Tesla Powerpack 2 System, arc flash should not be a factor during normal operation or with any normal maintenance procedure. Maintenance provisions include locking open and tagging the DC disconnect switch at the inverter. As described in the previous section, the 900 V DC bus is de-energized if the inverter DC switch is opened or if a Powerpack 2 enclosure is opened. Live parts in the inverter's combiner section are shielded as well with an internal barrier when the enclosure door is open. In typical operations, maintenance personnel therefore need only verify that the bus is de-energized once inside the inverter or Powerpack 2 enclosure.

The arc-flash calculation is beyond the scope of this review and should be performed by qualified engineering on an installation-by-installation basis, to allow for the proper selection of PPE for service personnel.

8.2.6 Battery safety

Safety precautions addressing the potential for fire, explosion, or released chemicals and gases are an important aspect for any electrochemical battery. DNV GL's evaluation concludes that Tesla has addressed these issues appropriately, via compliance with several mitigation measures covered in UL 1973, and published documentation in the installation manual, Safety Overview, and Emergency Response Guide. DNV GL notes that it has not received UL 1973 documentation for the 2-hour Powerpack Pods.

The following excerpt summarizes the battery safety measures covered by UL 1973 and certified for the Tesla Powerpack 2 System by TÜV:

- Products must be robust to internal fire exposure: they must demonstrate that a single cell failure will not cascade to cause a fire external to the product, or an explosion.
- Products must be robust to mechanical stresses: they must withstand drop and impact tests as well as other mechanical stresses.
- Products must be robust to environmental stresses: they must withstand high heat and humidity tests, as well as salt fog exposure and other environmental stresses.
- Products must be robust to electrical abuse: they must withstand overcharge and short circuit tests, as well as other abuse conditions.

Moreover, DNV GL finds that the Tesla Powerpack 2 System design achieves levels of redundant protection that go beyond the requirements of UL 1973. This is by virtue of the combined protection provided by layers of power electronic isolation, overcurrent protection at the cell and Pod level, and multi-stage enable loops that de-energize all batteries under numerous shutdown and personnel access situations.

In conversations on a site visit on 2 December 2015, Tesla also added additional information on their approach to UL 1973 testing. The core safety test in UL 1973 involves initiating thermal runaway in a single cell central to a full pack or module. Tesla takes this to additional levels of severity by inducing thermal runaway in multiple cells simultaneously; in addition, these circumstances are evaluated with and without the liquid cooling system activated, as well as under flood conditions. The fact that Tesla tests their systems beyond the key relevant standards (UL 1973, in this case) shows an appreciation and understanding of what is necessary for these systems to be deployed safely, and the willingness to go beyond what is commonly mandated.

Beyond required regulatory standards, Tesla has demonstrated industry leadership in partnering with NFPA (FPRF) to perform one of the first large scale burn tests in the industry. This testing showed that multiple internal failures (thermal runaway) do not necessarily compromise the entire system and further supports compliance with UL 1973 beyond the standard. However, exposure to external fire for extended periods of time may lead to internal fire, though this testing represented an extreme case and would be indicative of extreme fire conditions around the battery. DNV GL recommends further full scale testing to verify these findings.

Additionally, units should be installed such that they are compliant with NFPA 1 and NFPA 70 (NEC), and IFC 2018 at a minimum, and to additional local standards as applicable.

8.2.7 North America compliance summary

DNV GL's overall assessment is that the Powerpack 2 System, certified as a field assembled system, has been evaluated to the appropriate UL standards and is compliant with NEC requirements for U.S. and Canadian installations. A review of detailed certification reports from TÜV indicate a robust level of protective features covering overcurrent and short-circuit conditions, ground fault detection, and shutdown functions. Grounding and bonding measures for the assembled components are addressed appropriately with respect to code and the listing. The system installation is unusual in two aspects particularly, when compared to more typical electrical installations of related technologies (e.g. solar PV systems). The differences may cause confusion with respect to compliance upon first review but have been adequately addressed by the complete system certification.

- Disconnecting means: There is a general expectation that individual power supply cabinets (in this case the Powerpack 2 units) would each have accessible manual disconnecting means, either at each cabinet or at the inverter. In the Powerpack 2 System, however, the inherent protection and disabling functions effectively ensure that there is no situation in which such switches would be necessary or would enhance safety. All battery sub-systems are de-energized by shutting down the inverter (or with the inverter DC disconnect switch). The assembly of enclosures is appropriately certified as a single integrated energy storage system. Only authorized service personnel would need to physically isolate individual Powerpack 2s for replacements and internal maintenance, using the connectors internal to the enclosure/wireways.
- Cable systems: The automotive cables connecting the Powerpack 2s to the inverter, and their custom wireways, are supplied with the Powerpack 2 System equipment for field assembly. These are not typical field installed cable but have been evaluated according to UL 758 and for the application with considerations for temperature, fill, and cable protection. DNV GL notes that strict adherence to installation instructions providing for positive drainage away from the wireways is prudent, however the recent listing of the wire for wet locations allows for periods of wetness.

It is anticipated that battery related requirements in the UL standards and NEC code will continue to evolve as energy storage system installations become more commonplace. DNV GL views the modular design approach and converter-based interfaces utilized by Tesla to be well-suited to adapt to these changes as they occur.

Tesla has considered battery safety in terms of thermal propagation, electrical system design, and hardware and software safety features, and leverages ten years of battery safety engineering in Tesla's vehicles. Pre-engineered battery safety on a modular level removes the necessity for site by site battery safety design, such as the arrangement of cells and thermal propagation considerations.

8.3 System standards compliance – International

Requirements for system component standards and installations vary on a country by country basis. The IEC has battery and converter related standards which are applicable in most countries; however, these do not cover system integration aspects as thoroughly as UL 1973 and UL 9540 in the U.S. Energy storage related standards and requirements are also evolving rapidly, and manufacturers will therefore have to continue adapting to the specific requirements imposed in the future. DNV GL has not performed an exhaustive analysis of country requirements outside of the U.S. but is of the opinion that Tesla has obtained the appropriate international certifications necessary to appropriately enable system installations in these evolving markets. This section summarizes these international certifications.

8.3.1 Pod

TÜV Rheinland has certified the Pod to IEC 62619 (DRAFT 2014), “Secondary cells and batteries containing alkaline or other non-acid electrolytes: Safety requirements for large format secondary lithium cells and batteries for use in industrial applications.” As a safety standard, the requirements are analogous to those of UL 1642 and include tests addressing phenomena such as short-circuits, impact, thermal abuse, thermal event propagation, and overcharge. Tesla has also self-certified the Pods for transportation according to UN/DOT 38.3, “Transportation Testing for Lithium Batteries” (5th edition 2009, with Amendment 1 in 2011).

DNV GL has confirmed that TÜV Rheinland has also certified the Pod to IEC 62109-1, “Safety of Power Converter for use in Photovoltaic Power Systems – Part 1: General requirements.” This covers the DC/DC converter and protective circuits. While written mostly for PV systems, the scope also includes inverter connection to “other DC source or load circuits such as batteries.” It is therefore analogous to UL 1741 for U.S. requirements. DNV GL agrees with TÜV that IEC 62109-1 is the most applicable standard for the electronics at this time.

8.3.2 Powerpack 2 and DC block

Tesla and TÜV leveraged the UL DC Power Block certification efforts to provide a parallel certification to IEC 62109-1. This certification encompasses the electrical safety of the same field-assembled components covered in the UL 9540 listing: the Pods, Powerpack 2s, and wiring systems, and provides an umbrella type certification for the assembly. While IEC 62109 is not as encompassing for battery storage systems as the UL standards, DNV GL is satisfied with the intent and purpose of the certification given the rigor of the evaluation that preceded it for the U.S. market.

8.3.3 Inverter

For the Inverter, the international regulatory requirements are largely detailed in a group of IEC standards. Tesla contracted with TÜV Rheinland Australia Pty Ltd (TÜV), to certify the 50Hz version of the Tesla Powerpack Inverter to the following standards:

- IEC/EN 62109-1:2010
- IEC/EN 62109-2:2011
- IEC/EN 62040-1:2008+A1
- IEC 62116:2014
- G59/3/09.13
- IEC 61727:2004

- AS 4777.2-2005
- AS 4777.3-2005
- AS 62040.1.1-2003
- RCM Tick Mark

9 POWERPACK 2 INTEGRATED SYSTEM LEVEL PERFORMANCE

This section will focus on core functionality and performance of the Tesla Powerpack 2 System as well as some key operating requirements of the system. This review is based on the system level specifications for both the 2-hour and 4-hour systems and test and performance data made available to DNV GL for review. This section review will include a discussion of system sizing, power and energy ratings, round-trip efficiency, and cycle life. Environmental and microgrid interoperability requirements will also be reviewed. Finally, the field history and fleet level management systems for the first generation of commercial batteries will be reviewed. A review of application performance and controls design is the focus of Section 9.

9.1 System space requirements

Depending on the size and capacity desired, up to 20 Powerpacks can be combined together with an inverter to form a Block. A Tesla Powerpack 2 system may then be comprised of multiple connected blocks to form a larger system, controlled by a single Tesla Site Controller. As previously described, Powerpack 2s can be installed in scalable increments. As each Powerpack has a fixed energy capacity, greater pad footprint space is needed as more energy is required, shown with the 4-hour system as an example in Figure 9-1.

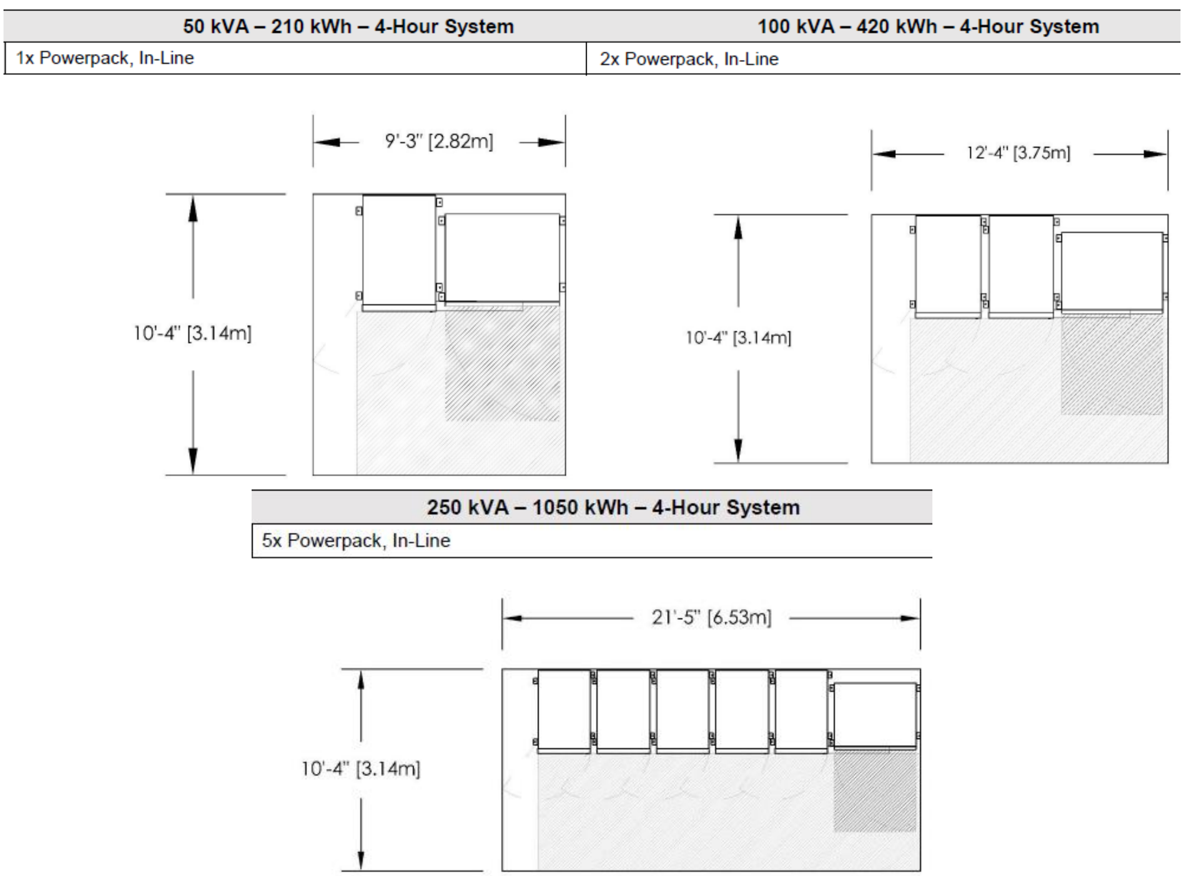


Figure 9-1 Various sample Powerpack 4-Hour systems footprint space requirements

A Capacity Maintenance Agreement (CMA) is available for all Powerpack 2 systems over 4 MWh, guaranteeing power and energy capacity over 10, 15 or 20 year terms, depending on the system. A capacity maintained system requires the addition or replacement of battery packs over time in order to maintain original system ratings. For systems with a CMA, site infrastructure is designed to accommodate these additions or replacements over time. Additional inverter units are not required over time as the initial site design includes sufficient inverter power capacity to account for battery degradation and incremental additions, optimizing the performance of each modular block. The Tesla Powerpack 2 System specification describes up to 20-year capacity-maintained systems operated up to one full cycle per day. Technical details and characteristics differ between systems with and without a CMA. The differences are highlighted in the specification and noted, where applicable, within this section.

DNV GL notes that Tesla's detailed specification considering systems with and without a CMA is more mature than other similar products on the market. The market is demanding systems with both of these options, but a large amount of project-by-project design is still the norm in the industry with respect to capacity maintenance. DNV GL looks favorably on this detailed treatment in the specification.

9.2 Power capability and duration

Available power output of the Tesla Powerpack 2 System is highly dependent on state of energy (SOE) and temperature. After an ambient temperature soak in the off state, a 2-hour system is designed to have the charge and discharge capabilities as shown in Figure 9-2. The soak temperature-SOE graphs represent the modeled battery system performance under varying conditions, for non-CMA systems at beginning of life (BOL). The green ranges indicate the system's optimal operational ranges, allowing charge and discharge at rated power and energy. The yellow and red zones still allow charge and discharge of the system, but at reduced power. Exact de-rated power values (in kW) are shown in the black boxes along the graph lines. Similarly, charge and discharge capabilities for the 4-hour Powerpack 2 systems are shown in Figure 9-3.

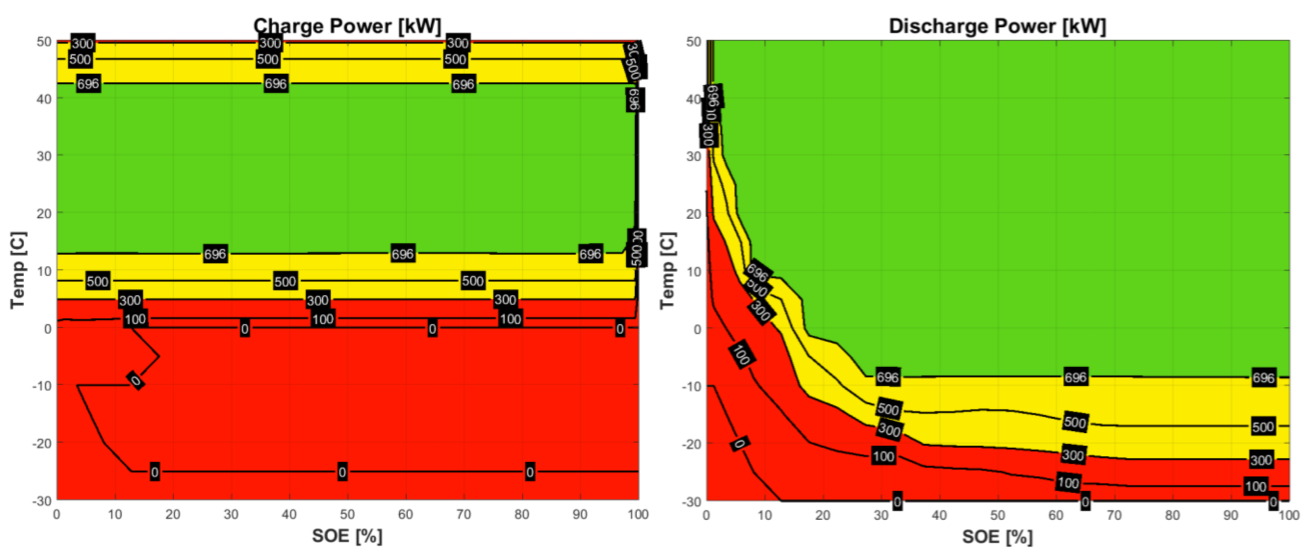


Figure 9-2 Charge and discharge power capability graphs for the 2-hour Powerpack 2

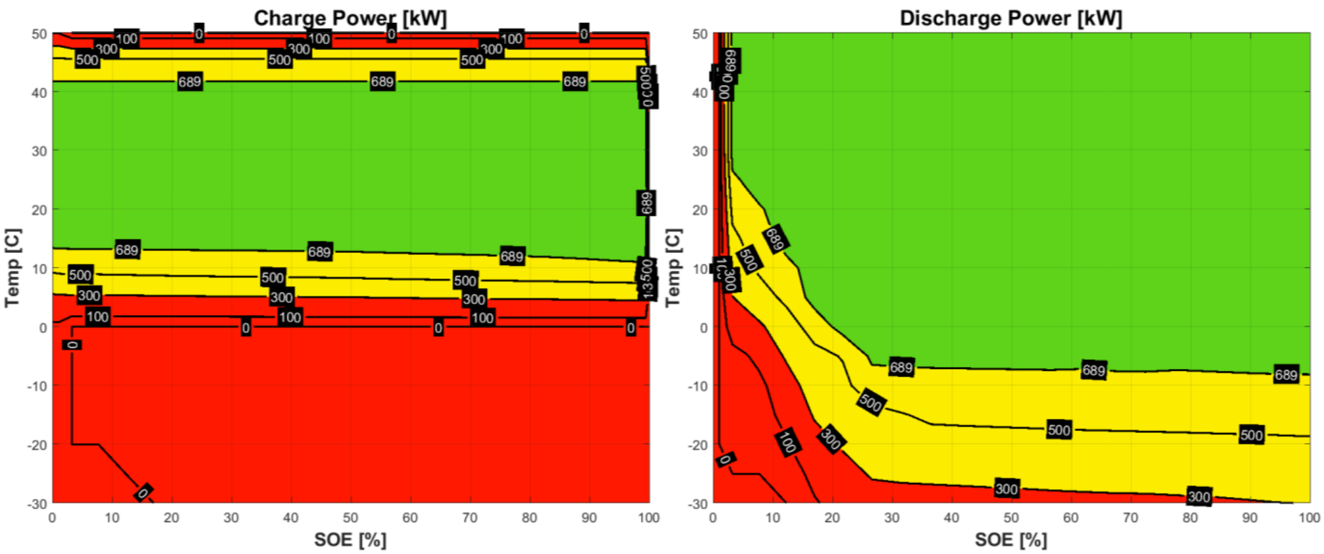


Figure 9-3 Charge and discharge power capability graphs for the 4-hour Powerpack 2

De-rating of power as a function of SOE and temperature is typical and in line with industry norms, though given the low C-rates utilized by the system, it is not uncommon for de-rating to be minimized as far less stress is placed on the batteries. This de-rating can also be managed by maintaining proper temperature ranges. De-rating on the discharge side is utilized to both preserve battery life and maintain proper voltage for the power electronics, since voltage will drop at lower SOE. The thermal management system in the Powerpacks can also be used to maintain the system in the optimal state in ambient conditions, although operating in this state will result in lower overall efficiency due to increased parasitic loads.

In normal operating conditions, the system becomes operational immediately. In worst case conditions, the batteries can be pre-conditioned from any starting temperature to be fully operational within 15 hours. Although the battery cells can discharge in sub-zero temperatures, in order to charge, the battery cells must first be heated to at least 0°C.

9.3 Efficiency and self-consumption

This section details Tesla's expected efficiency ratings for each system as a function of power, discharge duration, and temperature conditions for both CMA and non-CMA systems. The temperature conditions include Standard Test Conditions (STC), Hot, and Cold conditions. STC is defined as a temperature of 25°C and pressure of 1atm, Hot is defined as 45°C and 1atm, and Cold is defined as 20°C and 1atm. The efficiency described in this section is AC-AC roundtrip efficiency and is a function of the AC energy put into the system and the inverter versus the AC energy obtained from the inverter on discharge. The ratings are separated by system duration, with opinions and conclusions following.

9.3.1 Two-hour system

Roundtrip efficiency (RTE) ratings across various normalized power levels at Year 0 or BOL and Year 10 at STC for the 2-hour system are shown in Figure 9-4. Following, Figure 9-5 lists RTE for various temperature ranges, durations, and parameters.

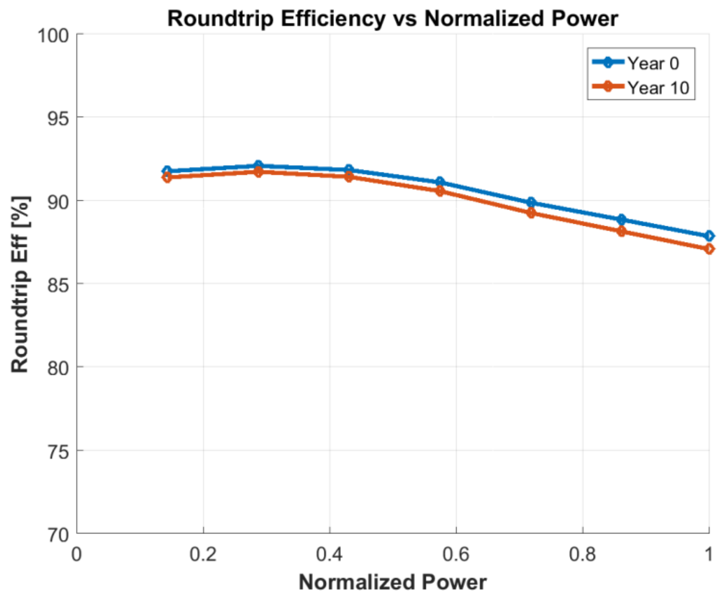


Figure 9-4 AC-AC RTE vs. power for 2-hour Powerpack 2

Parameter	Frequency Regulation Option at 650 kWp***	1.2 Hour Peak Power Option at 650 kWp**	1.6 Hour System at 634 kWp	2.0 Hour System at 609 kWp
Roundtrip Efficiency (BOL) inclusive of thermal management loads	**STC:** 88% T_{AMBHOT}: 82.0% $T_{AMBCOLD}$: 88.0%	**STC:** 84.0% T_{AMBHOT}: 77.0% $T_{AMBCOLD}$: 85.5%	**STC:** 86.0% T_{AMBHOT}: 78.0% $T_{AMBCOLD}$: 86.5%	**STC:** 88.0% T_{AMBHOT}: 80.5% $T_{AMBCOLD}$: 88.0%
Minimum Roundtrip Efficiency (non-CMA) over 10 years	**STC:** 87.5% T_{AMBHOT}: 81.5% $T_{AMBCOLD}$: 87.0%	**STC:** 82.5% T_{AMBHOT}: 75.5% $T_{AMBCOLD}$: 84.0%	**STC:** 84.5% T_{AMBHOT}: 76.5% $T_{AMBCOLD}$: 85.0%	**STC:** 87.0% T_{AMBHOT}: 79.0% $T_{AMBCOLD}$: 87.0%
Auxiliary load for Tesla Site Controller (kWh)*	0.3 kWh	0.3 kWh	0.3 kWh	0.3 kWh

**Over a 24-hour period.*
***Based on a 1.6 hour charge and a 1.2 hour discharge.*
**** Based on the power profile provided by Sandia National Laboratories as part of the draft NEMA Standards Publication ESS-1-2017. A summary of the power profile can be found in Appendix 6.2 of that document, and the full power profile can be made available upon request.*

Figure 9-5 RTE for 2-hour systems under various conditions

DNV GL finds that the efficiencies shown above are in line with industry, especially given the more advanced implementation of a liquid thermal management system and the addition of the DC/DC converters to the battery system architecture.

The system’s self-consumption is also related to the system’s efficiency. Per 24-hour period when the system is off, for a 2-hour Powerpack 2 comprised of 7 Powerpacks, regardless of temperature (STC, Hot, or Cold), the system self-consumes 1-2 kWh (<0.2% total capacity) on the DC (drawn from the Powerpack) side and 3 kWh (<0.3% total capacity) on the AC (drawn from the grid) side. When the system is in stand-by mode, per 24-hour period, losses range from 3-8 kWh on the AC side at STC, 10-16 kWh under hot conditions and 175-181 kWh under cold conditions where upper limits are for grid disconnected systems. DC losses in standby mode, when grid connected, for all temperatures range from 6-7 kWh (<0.6%) and vary when connected to the grid with 8 kWh under STC, 16 kWh losses (<2%) under hot conditions and 181 kWh losses (~15%) when operating in cold conditions. The higher self-consumption during operation, as compared to the consumption of the system in an “off” state, is logical, with the extreme temperatures requiring greater expending of system energy. As such, DNV GL recommends that sites are appropriately chosen, availability of auxiliary power is verified, and systems appropriately sized to consider these factors.

9.3.2 Four-hour system

Similarly, to the 2-hour system, RTE ratings across various power levels at BOL and EOL at STC for the 4-hour system are shown in Figure 9-6. Following, Figure 9-7 lists RTE for various temperature ranges and parameters.

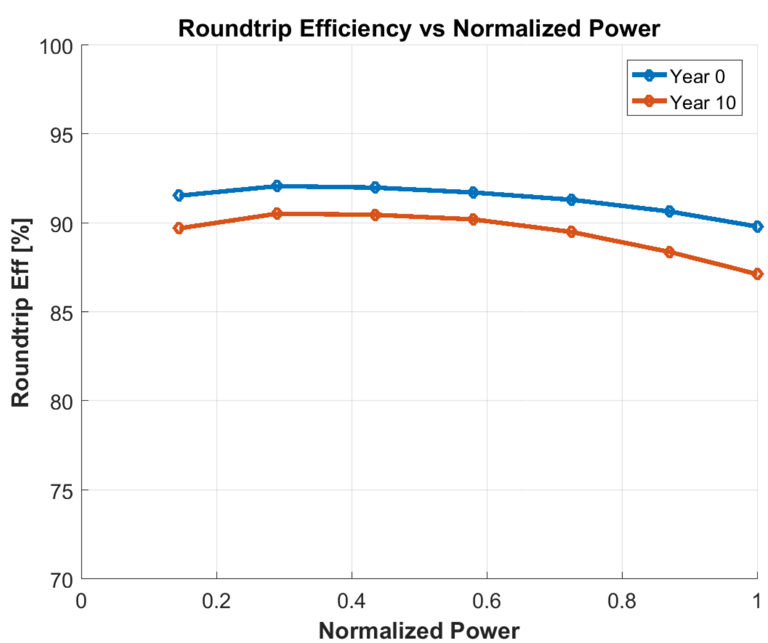


Figure 9-6 AC-AC roundtrip efficiency v power for 4-hour Powerpack 2

Parameter	Value for 4 Hour System or Longer at 636 kWp
Roundtrip Efficiency (BOL) inclusive of thermal management loads	**STC:** 89.5% **T_{AMBHOT}:** 84.5% **$T_{AMBCOLD}$:** 89.0%
Minimum Roundtrip Efficiency (non-CMA) over 10 years	**STC:** 86.0% **T_{AMBHOT}:** 79.5% **$T_{AMBCOLD}$:** 86.0%
Auxiliary load for Site Master Controller (kWh)*	0.3 kWh

*Over a 24-hour period

Figure 9-7 Efficiencies for 4-hour system under various conditions

As with the 2-hour system, DNV GL finds that the 4-hour system efficiencies shown above are in line with industry, especially given the more advanced implementation of a liquid thermal management system and the addition of the DC/DC converters to the battery system architecture.

The system's self-consumption is also related to the system's efficiency. Per 24-hour period when the system is off, for a 4-hour Powerpack 2 comprised of 13 Powerpacks, regardless of temperature (STC, Hot, or Cold), the system self-consumes 2-3 kWh (<0.1% total capacity) on the DC side, with losses on the AC side (drawn from the grid) of 3 kWh (<0.1%) in the off mode. When the system is on in stand-by mode, per 24-hour period, AC losses are 3 kWh under STC, 14 kWh under hot conditions and 284 kWh under cold conditions. Under the same period and operating mode, the DC losses range from 10-13 kWh (<0.5%) under STC, 11-25 kWh losses (<1%) under hot conditions and 10-295 kWh losses (~11%) when operating in cold conditions. As mentioned in the 2-hour section, the upper limits for DC losses correspond to grid disconnected systems. The higher self-consumption during operation, as compared to the consumption of the system in an "off" state, is logical, with the extreme temperatures requiring greater expending of system energy. As such, DNV GL recommends that sites for the 4-hour system are appropriately chosen and systems appropriately sized to consider these factors.

9.4 Cycle life and capacity maintenance

Tesla provided DNV GL with accelerated life test data on degradation. This data was based on the product type and cell type, the climate zone, the hours at which the product was maintained at an SOC less than 80%, and the number of cycles. It notes the degradation of the product over 15 years, depending on the combination of these variables, with a total of 840 unique combinations. DNV GL notes that under all test conditions specified for just the Powerpack 2, capacity retention over 10 years was in all cases in excess of 70% of the original capacity. This is in line with Tesla's claims, and industry averages.

Tesla provided DNV GL with details on its testing process, to give additional confidence in the conclusions drawn from the modeled degradation profiles. Tesla utilized a three-step process to procure the results provided. First, the selected cells or modules are put through long term cycling and shelf-life tests. Second, data from field operation of similar products is used as a baseline for how the product will be used. Finally, the test data, field data, and other inputs are combined into a simulated life cycle, producing degradation forecasts. This simulated life cycle is tuned for targeted markets, under cycling rates, rest at high SOC, climates, and battery configurations. DNV GL finds this level of diligence to be beneficial to customer confidence in the retention guarantee.

DNV GL reviewed the document titled *Powerpack System 2 Operation and Maintenance Manual*. The document states that Tesla or a Tesla-approved entity shall be responsible for arranging all corrective maintenance over the lifetime of the system. DNV GL considers all maintenance activities to be essential in maintaining the batteries state of health.

9.4.1 Powerpack 2 operation and maintenance

All Powerpack 2 battery modules are designed for a 15-year lifespan, and the inverter for a 20-year life. Preventative maintenance on the units shall be performed annually, including radiator and cabinet cleaning. Every five years, the battery packs will be serviced, including refrigerant refill and pump replacement. All other internal components will be replaced, repaired, or supplemented as needed or as contracted.

9.5 Microgrid interoperability requirements

The Tesla Powerpack 2 System specification outlines a number of microgrid interoperability requirements. When the storage system is required to act as the primary voltage and frequency source of the microgrid, all distributed energy resources on the microgrid shall have the ability to perform frequency droop and spinning resources shall not be coupled with the Tesla Powerpack 2 System. During islanding, the energy storage system shall accomplish load following at the rated load with voltage fluctuation of not more than 1%. The microgrid operating frequency shall stay within ±3% of nominal (50Hz or 60Hz). Spinning resources, diesel generators for example, shall only be coupled with the Tesla Powerpack 2 System when the spinning resource is operating as the primary voltage and frequency source, and the Tesla Powerpack 2 System is operating in PQ mode.

This list represents minimum integration requirements; sites outside of these requirements will require evaluation and integration on a per site basis. At the current stage of the market, interoperability is commonly a point of uncertainty for project developers and system integrators designing microgrid systems with integrated storage. DNV GL looks favorably on the inclusion of these terms in the system specification and encourages further development and refinement moving forward.

9.6 Reliability and field history evaluation

Tesla provided DNV GL with reliability statistics and fleet level management systems of all Powerpack 1 deployments as of Q1 2017, as well as Powerpack 1 and Powerpack 2 deployments between Q3 2017 and Q3 2018. As previously noted and with the same caveats as described in Section 6.4, Tesla has deployed Powerpack projects in 30 countries with a total of 390 MW with 800 MWh of energy storage at 450 customer sites as of Q3 2018. DNV GL has included assessments of availability from the original report, focusing just on Powerpack 1 units, as well as new data for Powerpack 2 sites. While this data demonstrates performance of similar systems and the robustness of Tesla’s process, past performance may not be indicative of future performance, as the cells, inverters, and controls have all been updated between the multiple generations of systems.

9.6.1 Fleet availability

The systems in the field are polled once an hour to verify online or faulted status. Any faults indicated automatically flag a service team or a diagnostician's review. Tesla's service infrastructure is discussed in more detail in Section 11. Tesla defines a system as unavailable if either the DC block or the inverter is faulted. At the time of initial report, the average age of a Powerpack project was 4.6 months, and the oldest installations were nearing a year in service which led to the classification of all field failures as manufacturing variations. Tesla observed that the older systems have seen an increase in system availability as manufacturing or installation variations were resolved. Availability of all Powerpack 1 systems, commissioned as of Q1 2017, is shown in Figure 9-8. Idle sites are defined as sites which, at the time, had been taken offline or had not yet come online.

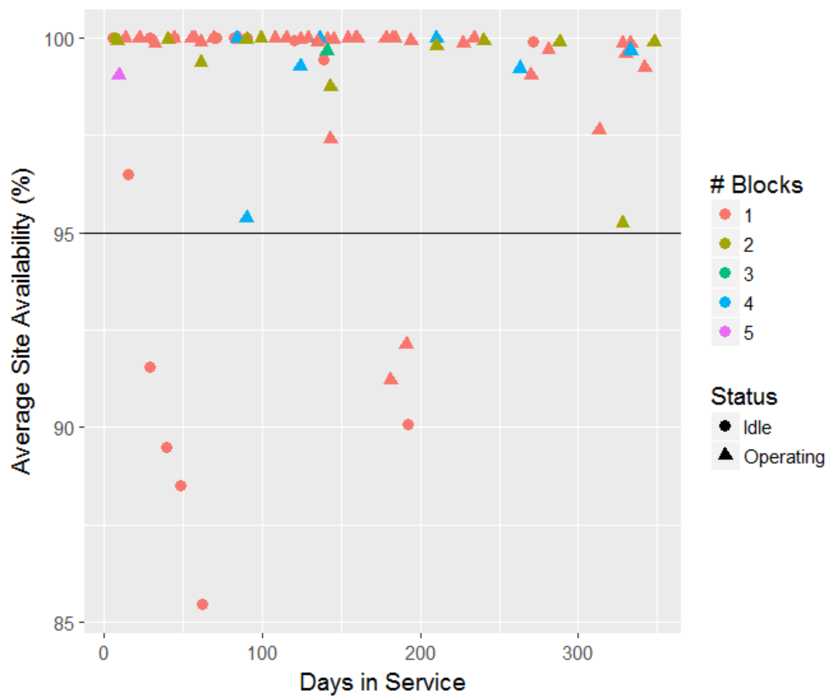


Figure 9-8 Powerpack 1 availability trends by days in service, as of Q1 2017

To additionally support the claim of high availability, Tesla provided DNV GL with a graph depicting the count of sites at various levels of availability, and the statistical distribution of these values, shown in Figure 9-9. At the time, 90.8% of Powerpack 1 sites had availability higher than 95%, and as provided by Tesla in a separate table, 82.9% of sites had availability greater than or equal to 99%. Though most systems are 1 block systems, the trend does not appear to significantly change based on increasing system size. Tesla further informed DNV GL that sites with multiple blocks may be repaired without taking the entire system offline. DNV GL notes that, while this level of availability is impressive, customers who require 24/7 uptime would still be affected negatively by limited outages.

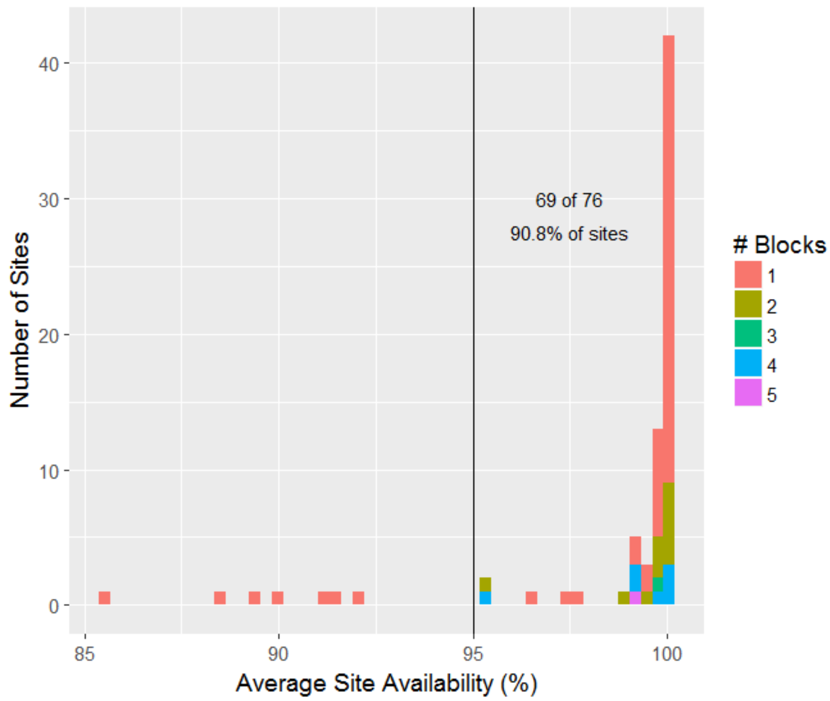


Figure 9-9 Availability distribution for Powerpack sites, as of Q1 2017

In addition, Tesla provided DNV GL power availability statistics for Powerpack 1 and Powerpack 2 sites spanning a period of one year, from 17 September 2017 to 12 September 2018. Fleet availability metrics only included operational sites with at least 2,000 hours of data logged and did not include outliers, such as sites used for testing. As such, a total of 148 Powerpack 1 (PP1) and 78 Powerpack 2 (PP2) sites were analyzed with an average availability of 96.6% over the year. When categorizing the Powerpack generations separately, it is apparent that Powerpack 1 sites have higher average availability of 96.8% compared to 96.1% for Powerpack 2 sites. A closer look at the availability data provided by Tesla for this subset of its fleet shows that 90.5% of Powerpack 1 and 89.7% of Powerpack 2 sites had an average availability of 90% and greater. The median values in Table 9-1 show that 50% of the Powerpack 1 and Powerpack 2 sites had availability of over 99% and Powerpack 2-only sites had over 97.8%. Tesla informed DNV GL that the reduction in availability for Powerpack 2 is due to the length of time in the field which is affected by early-life faults.

Table 9-1 Availability statistics for Powerpack 1 and Powerpack 2 (Sep 2017 to Sep 2018)

	PP1 and PP2	PP1	PP2
Number of sites	226	148	78
Average	96.6%	96.8%	96.1%
Median	99.0%	99.4%	97.8%

9.6.2 Field failures

As part of the initial report, Tesla provided DNV GL with a list of all field failures across the original 76 Powerpack 1 sites shown in Table 9-2. As with the previous data sets, all of these installations are Powerpack 1 systems, not the Powerpack 2 system which is the subject of this report. The volume of failures listed here are in line with those seen for fleets of similar systems on the market. The service infrastructure to assess and repair such failures is addressed in Section 11.

Tesla has demonstrated its ability to track the operating status and performance of a fleet with a significant number of systems. As Tesla gains more experience with operating commercial and utility Tesla Powerpack 2 System, tracking metrics like average uptime can build additional confidence for projects which require high expected availabilities (>95%).

Table 9-2 Field failure list for all Powerpack 1 sites, as of Q1 2017

Component	Sites	Total units
Pod	5	~20
Combiner box fuse	1	1
combiner box transformer	1	1
DCBC	1	1
DC Combiner PS	1	1
Inverter	1	1
High Voltage Junction Box	10	11
PP pump	1	1
Sitemaster computer	1	1
Battery Meter Transformer	1	1
Voltage sense fuse	1	1

For each of these failures, Tesla conducted a root cause analysis. In some cases, a root cause was unable to be determined. For the purposes of this report, only the two items which have emerged as trends, the Pods and High Voltage Junction Boxes, are described. For Pod failures, Tesla has identified a dual root cause: a voltage sensing issue combined with a non-standard factory state, where the Pod leaving the factory at a lower than expected SOE, causes over discharging. Due to the system design, as previously discussed in Section 4, a failure in a single Pod does not impact system availability. Tesla has addressed the over-discharge issue by correcting this state during commissioning. For the High Voltage Junction Box failure, the root cause was determined to be wires pinched during manufacturing. Tesla has addressed this through updates to the manufacturing process, and, since failures in the High Voltage Junction Box do impact availability, Tesla additionally has implemented a secondary check during commissioning. This type of root cause analysis is in line with best industry practices. DNV GL was not provided copies of the root cause analysis to review the process but has assumed it matches the process described for Tesla's manufacturing.

Tesla also provided DNV GL an updated list of failures for Powerpack 1 and 2 sites for a one-year period between October 2017 to October 2018. The list shown in Table 9-3 below includes annual failure rates and total replacements for both Powerpack 1 and Powerpack 2 equipment including the Pod, Powerstage and other components. It should be noted that the total of 213 replacements under the others category also includes counts from failure modes that have undergone a complete root cause investigation. As such, the resolved failure modes and their associated totals are not shown under this category though pending root cause analysis totals are shown in the table below.

Table 9-3 Summary of Failures (Oct 2017 to Oct 2018)

Component	Annual Failure Rate	Total Replacements (last one year)
Pod	0.19%	105
Powerstage	4.69%	175
Others		213
Site Master computer--Unknown	2.61%	9
Site master antenna --Unknown	2.61%	9
Site master antenna --poor connection	1.45%	5
DC Bus Controller--Unknown	1.43%	12
THC--Unknown	1.11%	10
DC Combiner Box Fuse--Unknown	1.06%	5
Rectifier Board Fuse--Unknown	0.85%	4
Tesla Inverter AUX--Unknown	0.85%	4
High Voltage Junction Box--Unknown	0.78%	7
Thermal Door Power Supply--Unknown	0.67%	6
Dynapower Inverter--Unknown	0.66%	1
Inverter Busbar--Unknown	0.64%	3
DC Current Shunt--Unknown	0.64%	3
PP Aux ASM--Unknown	0.52%	13
Thermal Door--Unknown	0.33%	3
Fuse - Sitemaster AC Mains--Fuse blown	0.29%	1
Sitemaster Fuse--Unknown	0.29%	1
LV Shelf (Aux, DCBC, Fans, etc.)--Voltage Sensing	0.21%	1
Busbar Isolator--Unknown	0.21%	1
Inverter Pump--Unknown	0.21%	1
Tesla Inverter Rectifier Board--Unknown	0.21%	1
LV Shelf Fan--Unknown	0.21%	1
Thermal Fan Harness --Unknown	0.11%	1
Powerpack fan--Manufacturing defect	0.08%	2
Pack Com Harness--No Comms	0.04%	1
Powerpack Compressor--Unknown	0.04%	1
PP TD2 Pump Harness PN: 1128105-00-B--Unknown	0.04%	1

As described earlier, common failures during the initial review were related to the Pod and High voltage junction box. Failure statistics provided by Tesla, as of October 2018, indicate ~20% of total replacements for the one-year period were for the pod. The replacement trend of the pod is on the same order of magnitude compared to the initial review and has decreased slightly according to the most recent data provided. Approximately 35% of total replacements were related to the Powerstage, which is a modular component within the Tesla inverter, and its failures are also described in Section 5.11. Tesla has been performing detailed analysis to address these failures and Tesla’s Powerpack configuration, which ensures redundancy through multiple Powerstages arranged in parallel, still allows for high system availability. The majority of other replacements with annual failure rates over 1% were related to site master computer/antenna, DC bus controller, total harmonic current (THC) and DC combiner box fuse. Based on the data presented, it was not clear whether the failure trend for components other than the Pod and Powerstage are increasing or decreasing.

In general, DNV GL finds that the demonstrated reduction in Pod failures is a positive trend, and the modular architecture appears to be appropriately protecting availability rates. DNV GL finds the provision of this data to be relatively comprehensive; however, the fleet is still very young, and more conclusive understanding of performance will be possible over time.

9.7 Performance review summary

The level of detail in several areas in Tesla Powerpack 2 System specification is seen by DNV GL as industry leading. For example, the provided roundtrip efficiency for different temperature levels at both BOL and over 10 years is unique to the Tesla specification. The detailed data for power, roundtrip efficiency, availability, and cycle life is useful now during a time of increased scrutiny of these values as they relate to lifetime cost. The specificity for required considerations for islanded operation is also stated very clearly in the specification and has not been observed in competing commercial products specifications.

The availability data is based on both the original Powerpack 1 installations and a sub-set of the Powerpack 2, and are thus discussed to demonstrate Tesla’s general ability to design systems with high availability and low failure rates, rather than exclusively that of the Powerpack 2. Although DNV GL believes Tesla’s infrastructure, processes, and experience are supportive of continuing the noted trends, these data cannot be taken as proof of such, due to changes in cell chemistry and interconnection, inverter ratings, and controls.

10 POWERPACK 2 SYSTEM INSTALLATION REQUIREMENTS

This section provides an overview of the basic and notable installation requirements for the Powerpack 2 System. More detailed information is available in the product manual, "Powerpack System 2 Installation Manual" (Installation Manual) and "Powerpack 2 System Site Design Manual" (Design Manual). As described in the code compliance section, a key feature of the Powerpack 2 System is its pre-engineered set of components for field assembly. The installation process requires strict adherence to the instructions, which were carefully planned to minimize time and materials to appropriately install and test the system. The summary presented here follows the basic structure and order of the more detailed instructions in the Installation Manual.

10.1 Important safety considerations

The Powerpack 2 system is designed to operate in temperatures between -30 °C to +50 °C. The system should not operate in ambient temperatures exceeding +50 °C or be installed near heat sources that can add thermal load to the system and potentially create hazardous situations for the battery.

Installations in enclosed spaces should account for the ventilation of gasses in the unlikely event of thermal runaway. However, it is important to note that there are not gases generated during normal operation, as is common with traditional energy storage systems.

Sites such as parking garages and buildings must be evaluated by Tesla on an individual project basis.

10.2 Installer information

The installer information covers the necessary information for a contractor to install a Tesla Powerpack System, including the following steps:

- Install all equipment, including physical aspects such as proper anchoring, door swing, access, etc.
- Ensure proper pad grading, drainage, and access.
- Check electrical terminations for polarity and torque for all equipment.
- Check harness termination(s).
- Check ethernet cable(s) with VDV Scout Pro or Pro LT (VDV501-053 or 068) or equal.
- Conduct insulation resistance "megger" testing for all wires.
- Check inverter phase with a Greenlee 5702 Phase Sequence Indicator or equivalent.
- Check meter wiring and CT polarity.
- Record site information (serial numbers, unit and meter locations, inspection date, etc.) and email a scanned copy to Tesla.
- Perform inverter and Tesla Site Controller start-up.

Personal protective equipment (PPE) is to be provided by the contractor and includes safety glasses, hard hats, appropriate boots, and appropriate gloves (cut and electrical). Tesla also requires customized tools for the installation process, including a custom torque tool, Powerpack unit anchor template, and inverter anchor template, shown in Figure 10-1 and Figure 10-2.

Figure 10-1 Anchor torque tool kit required for installation

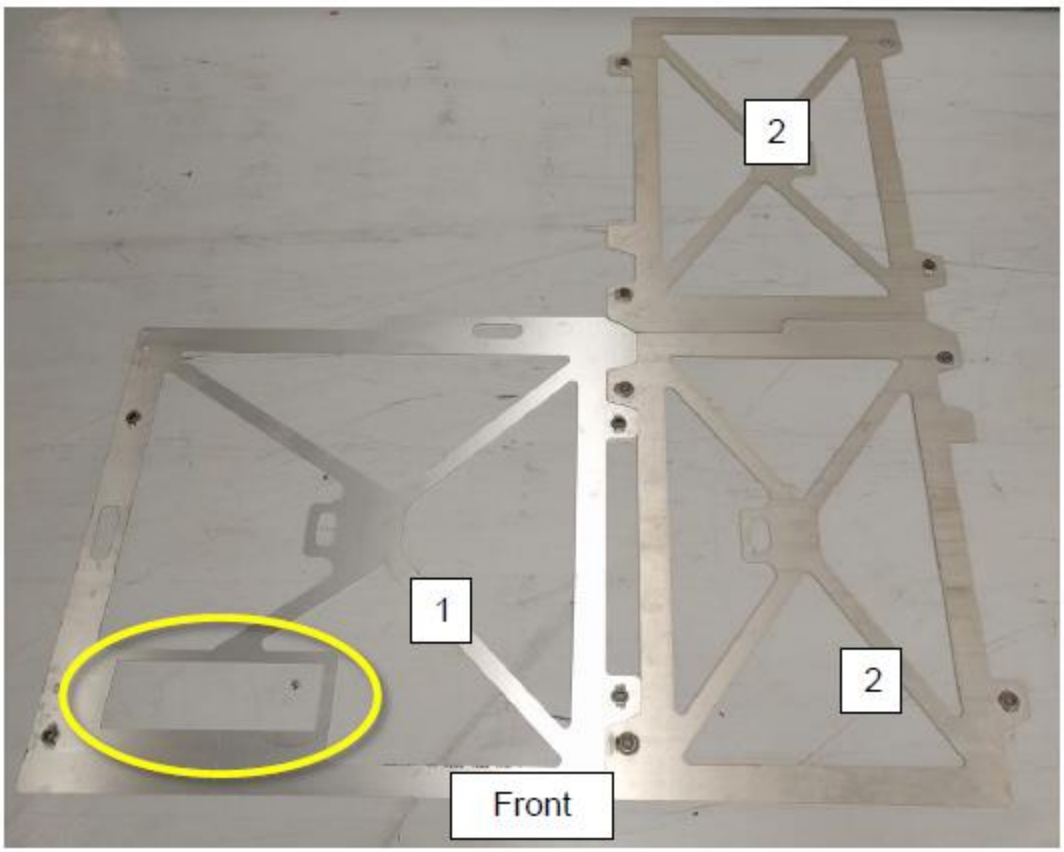


Figure 10-2 Inverter Template (1) and Powerpack Unit Template (2)

DNV GL considers the installer information, PPE, and customized tools to be in line with expectations.

10.3 System description

The Installation Manual covers a general introduction of the subcomponents and integrated system, as discussed in detail above. Further, the Installation Manual details the part numbers, system specifications, and configurations. Table 10-1 details the system specifications for the Powerpack 2 units, inverter, and site controller.

Table 10-1 Powerpack 2 system specifications

Equipment	Length	Width	Height	Max. Shipped Weight	Mount
Powerpack Unit, 4-hr	1308 mm (51.5")	822 mm (32.4")[1]	2235 mm (88")[1]	2175 kg (4795 lbs)	Pad
Powerpack Unit, 2-hr	1308 mm (51.5")	822 mm (32.4")[1]	2235 mm (88")[1]	2075 kg (4575 lbs)	Pad
Powerpack Inverter	1014 mm (39.9")	1254 mm (49.4")[1]	2242 mm (88.3")[1]	1120 kg (2470 lbs)[2]	Pad
Tesla Site Controller	255 mm (10")	560 mm (22")	742 mm (29.2")	21.4 kg (47.2 lbs)	Rack, Wall

DNV GL considers the description and specifications to be in line with expectations.

10.4 Transportation

The Installation Manual provides shipping guidance, an emergency response guide, and loading and unloading instructions. Tesla recommends that no more than nine Powerpack units be shipped on a 45' flatbed truck. The Powerpack units ship with a 25% SOC and should not sit longer than 12 months between date of manufacture and installation or the units require a recharge.

Tesla provides an emergency response guide, titled "Tesla Lithium-Ion Battery Emergency Response Guide", with Powerpack 2s for shipping and transportation. The emergency response guide provides an overview of precautions, hazards, and emergency response procedures.

Powerpack units and Powerpack inverters must be loaded and unloaded by strapping them to a forklift and always positioned upright. If batteries are stored onsite for longer than one month, the Powerpack units must be stored between -20 °C and 30 °C and no greater than 95% humidity, non-condensing.

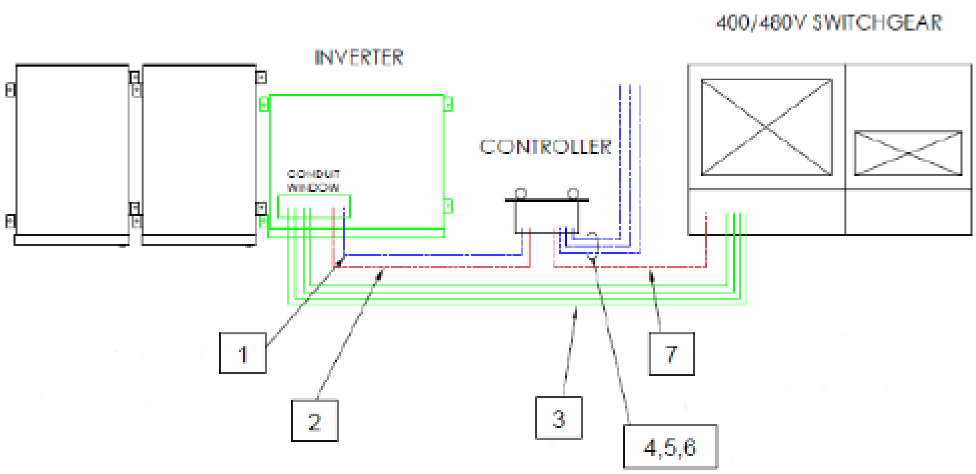
DNV GL considers the recommended transportation requirements to be appropriate.

10.5 Site infrastructure

Prior to Powerpack 2 system installation onsite, the conduit and concrete pad must be completed.

10.5.1 Conduit

The underground conduit is provided and installed by the contractor and runs between enclosures, carrying power conductors and communication lines that are not run through the wireways. An example underground conduit plan is shown in Figure 10-3.



1	One communication conduit between inverter and Tesla Site Controller (CAT5e/CAT6)
2	One DC power conduit from inverter to Tesla Site Controller (only needed for microgrid)
3	Up to four AC power conduits from inverter to site AC switchgear
4	One conduit from Tesla Site Controller to battery meter (CAT5e/CAT6)
5	One conduit from Tesla Site Controller to site meter if applicable (CAT5e/CAT6)
6	One conduit from Tesla Site Controller to customer communication interface (CAT5e/CAT6)
7	One Tesla Site Controller AC power conduit from switchgear 400/480 VAC, 2-pole, 10 A circuit

Figure 10-3 Example underground conduit plan

10.5.2 Foundation inspection

The equipment pad or foundation (concrete, structural steel deck, or skid) must be strong enough to support the weight of the enclosures. Per Tesla, each Powerpack 2 enclosure weighs 4,795 lbs. (4-hour unit), 4,575 lbs. (2-hour unit), and 2,470 lbs. (inverter). The following pad or skid properties are to be checked before beginning to anchor enclosures:

- The top of the pad is above adjacent grade, 152mm (6 in) maximum, with the edge of the concrete a maximum of 305 mm (12 in) from the front of the Powerpack System. If the site does not allow this pad height, then the pad must extend a full 4 feet in front of all Powerpack Units and include a ramp to allow service cart access.
- Six feet must be left clear in front of all Powerpack Units for unobstructed airflow.
- The pad slopes a minimum of 1% and a maximum of 2% (0.6-1.15 degrees) to allow positive drainage from the pad/base or towards a drain.
- The pad must be sloped in one plane.
- Concrete finish has a smooth, even surface of uniform texture and appearance, free from bulges, depressions, and other imperfections that would impact equipment anchorage or foundation/base drainage.
- Any walls installed around the pad are designed to prevent standing water (drain, weep holes, etc.) with sufficient clearance between the equipment and any walls or obstructions to allow for proper drainage.

10.6 Site installation

Site installation requirements include the following key areas.

10.6.1 Site access

Tesla requires access to all Powerpack 2 equipment, including the ability to remove locks, so that they can perform necessary service and maintenance. DNV GL considers this level of site access to be in line with expectations.

10.6.2 Fencing

A perimeter wall, screen, or fence may be used and is recommended to be at least seven feet, with equipment clearances consistent with the next section.

10.6.3 Clearances

Clearance requirements for the major components are shown in the table below (excerpted from the Site Design Manual). Some exceptions are allowed, and notably, Powerpack 2 side and back clearances are increased to 6 inches if installed in a snow environment, to improve drainage.

Table 10-2 Clearances

Equipment	Front	Sides	Back	Top
Powerpack Unit	1830 mm (72")	105 mm (4.1")	30 mm (1.25")[2]	1524 mm (60") for combustible materials, 915 mm (36") for service clearance
Powerpack Inverter	1830 mm (72")[1]	105 mm" (4.1")	100 mm (4")	915 mm (36")

10.6.4 System layout configurations and limitations

The arrangement of Powerpack 2 enclosures and inverter units are restricted to a set of pre-engineered layouts. Wire management systems and harness lengths are pre-manufactured based on the selected layout. Therefore, the components must be installed according to the dimensions defined in the layouts. Some of the basic configuration requirements are as follows:

- The maximum number of Powerpack 2s feeding a single inverter is 20.
- Layouts limit the number of contiguously mounted Powerpack 2s sharing the same wireway and equipment ground connection to five. So, for example, an inverter block with 20 Powerpack 2s will have four separate wireway systems, each collecting the outputs from five Powerpack 2s. The installation manual appendix includes detailed diagrams for the allowed layouts.

Large system configurations require interior access roads to provide access to the interior containers, as shown in this layout excerpted from the installation manual shown below in Figure 10-4.

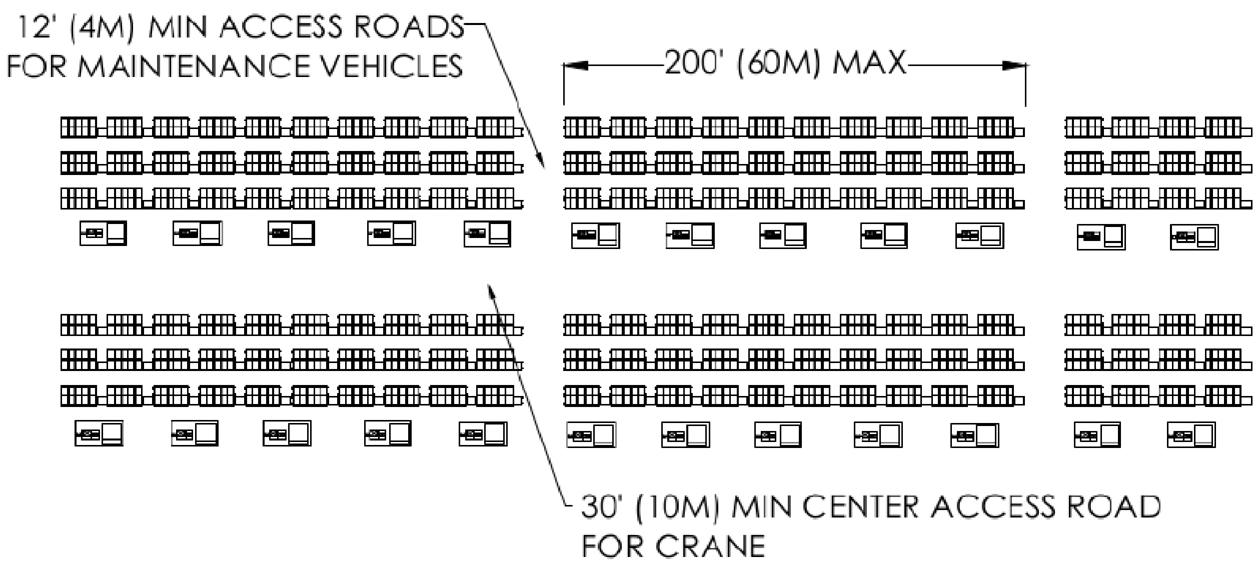


Figure 10-4 Layout drawing

DNV GL considers the system layout recommendations to be well defined in line with industry standards.

10.7 Wiring

Tesla provides most all the wiring harnesses and assemblies for the installation, including connectors for the Powerpack 2 DC and communication cables. Exceptions include:

- Equipment ground conductor for connections between the Powerpack 2s and inverter
- Underground conduits within the pad (inverter and Tesla Site Controller, and AC side connections)
- AC cables and basic communication cabling (e.g., Cat5e)

A copper ground conductor is connected from each Powerpack 2 to the inverter. A single ground conductor can be used to ground multiple Powerpack 2s in the same path or string, to a maximum of five enclosures as described earlier. The wireway trays and covers are part of the equipment ground path, shown in Figure 10-5, and a single ground wire connection is made from the inverter to the first section of the wireway, using the same equipment ground conductor that connects to the string of Powerpack 2s.

Figure 10-5 Cable management wireway location

An electrode ground connection is required to be established at the inverter, using either attachments to the pad rebar or driven ground rods.

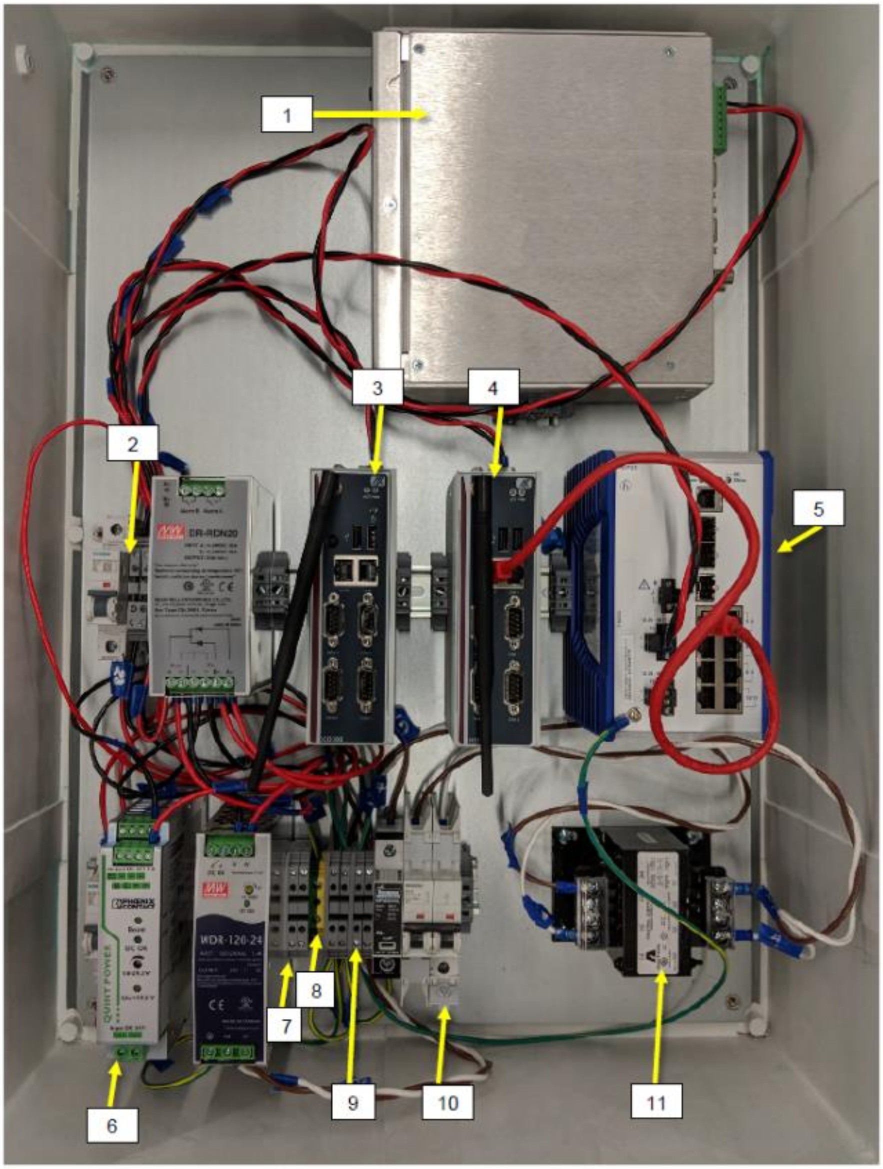
AC wiring, based on the system full load rating, between the inverter (480V, 3-phase, in North America, and 400V, 3-phase international) and an AC switchboard, and between the AC switchboard and a transformer (as applicable), are the responsibility of the installing contractor. All cable sizing, grounding, overcurrent protection and installation must adhere to NEC requirements for U.S. installation and local requirements for installations outside of the U.S.

DNV GL considers the wiring instructions to be comprehensive and in line with expectations.

10.8 Tesla Site Controller

The Tesla Site Controller can be powered from the AC switchboard, using a 480 V AC, 10 A, 2P circuit breaker, or other AC or DC voltages based on the configuration designed for the specific site. The Installation Manual details the steps to install the Tesla Site Controller, configure the transformer, connect the demand response controller (if needed), and connect the protection relay. Figure 10-6 shows the internal components of the Tesla Site Controller.

DNV GL considers the Installation Manual’s instructions on installing the Tesla Site Controller to be adequate.



1	Real-Time Automation Controller (RTAC): optional (PN 1129636)
2	Terminals for computer power
3	Tesla Site Controller Computer 2 (optional, PN 1052303)
4	Tesla Site Controller Computer (primary): includes four RS-232/422/485 ports, Ethernet ports
5	RSP Network Switch: Connects both Tesla Site Controller computers to the inverter using Ethernet
6	DCDC converter and surge protector: Connector for 24 V backup power
7	Jumpstart terminals (optional): used to connect a 12 V power supply that can jumpstart a microgrid inverter if needed
8	Grounding terminals
9	Terminals for transformer wiring
10	Fuse block between AC mains and transformer: Default configuration is shipped with 0.5A KLDR Fuse (PN: 1053860-00-A) for 480 VAC, other fuses are in the accessory kit
11	Transformer, 120/240/480 V

Figure 10-6 Interior picture of Tesla Site Controller

10.9 Energy meters

All sites require a Battery Meter that measures the power and energy flowing to and from the battery system, as shown in Figure 10-7. The Site Meter and Generator Meter are optional but may be required for some control functions or at sites that integrate with PV generation.

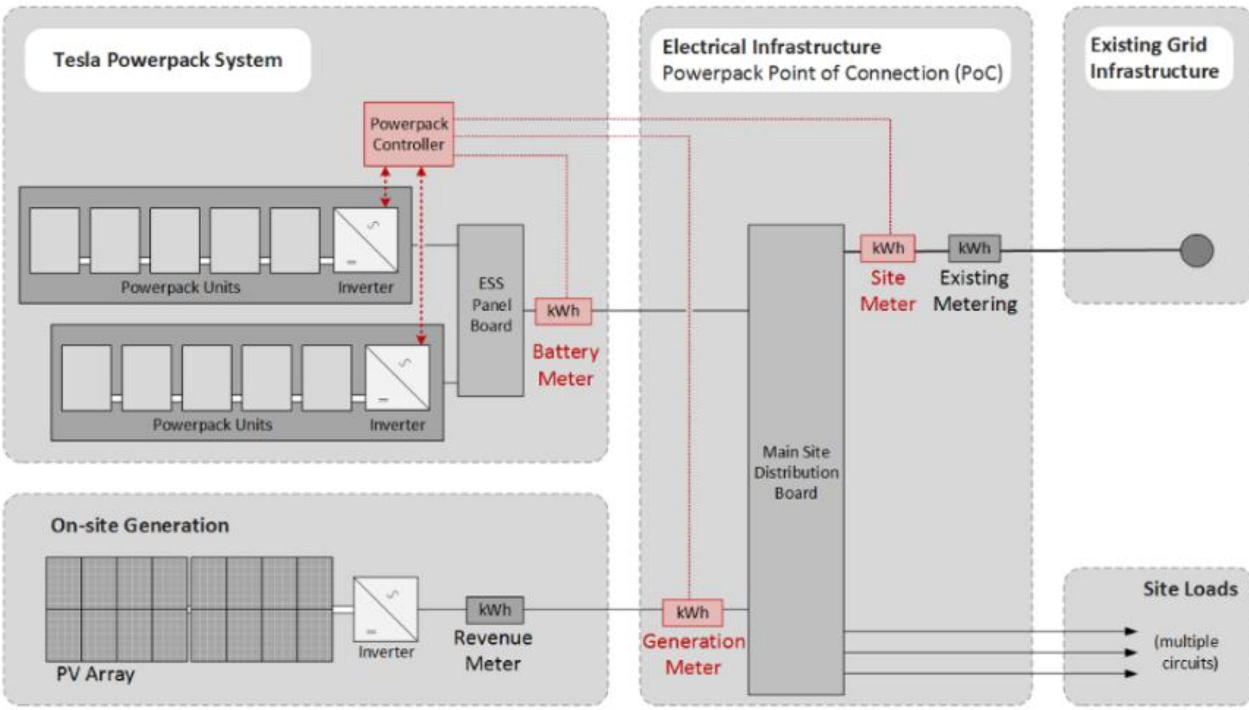


Figure 10-7 Tesla metering overview

Tesla details the connection requirements, CT installation, and meter configuration in the Installation Manual. DNV GL considers the recommended procedures to be appropriate.

10.10 Commissioning

The Tesla Energy Services Commissioning Protocol, dated 16 February 2016, is a two-page description of the scope of work to be provided by Tesla Energy Services during the commissioning of a Powerpack 2 System. The level of effort described in this document requires approximately 16 hours per inverter block to complete. Tesla reports that it is working on automating the commissioning process and expects to reduce this time significantly.

After the contractor responsible for installation completes the entire installation and construction checklist, Tesla is responsible for the remainder of the commissioning process, including:

- Confirm Tesla Site Controller communication with the Tesla Server.
- Confirm Tesla Site Controller communication with the Powerpack Inverter.

- Confirm Powerpack Inverter communication with Powerpack Units and basic functionality.
- Test inverter block and system level performance.
- Complete system start-up sequence checklist.

DNV GL considers the commissioning overview to be in line with expectations. DNV GL did not review a detailed, completed commissioning report.

11 POWERPACK 2 PRODUCT SUPPORT EVALUATION

This section of the report reviews the available product support for the Tesla Powerpack 2 System including a discussion of the system warranty, capacity maintenance agreement, and Tesla service infrastructure.

11.1 System warranty

For systems sold in the U.S., Tesla offers a 15-year warranty that the Powerpack 2 will perform to specifications and be free from defect, starting from the commissioning date or 90 days after purchase, whichever is earlier, to the terms of the warranty. In the case of capacity maintained offers, the term of the warranty matches the term of the capacity maintenance period. As such, the capacity maintained pricing presented includes a warranty on all Tesla Energy equipment for the term of the capacity maintenance period.

The warranty for U.S. sales covers all costs associated with the replacement or repair of any failed components, including materials, removal, transportation, and reinstallation. The warranty will not be extended regardless of any changes, repairs, or additions to the system. The warranty does not cover normal wear and tear, any minor aesthetic issues that do not impact Tesla Powerpack 2 System performance, damage that occurs after expiration or void of the warranty, or theft or vandalism. Further, the warranty is void in the cases of force majeure events, any work, changes, or removal done by anyone other than a Tesla-certified installer, and use or storage of the Powerpack 2 in any manner other than specified in the specifications, guidelines, installation manual, and User/Operation Manual. The warranties will be suspended if Tesla is prevented or hindered from communicating with the System, due to the actions of the site owner. The warranties terminate if the system owner fails to establish the communication link within 30 days of the commissioning date or fails to restore the communication link within 30 days following the conclusion of any force majeure event or scheduled or unscheduled maintenance that causes or requires its interruption. Further, the Powerpack 2 is not intended for use as a primary back-up power source for any life-support systems, medical equipment, or other uses where product failure could lead to injury, loss of life, or catastrophic property damage. Due to this, Tesla disclaims any liability if a customer utilizes the product in such a manner.

The law that governs USA products is that of the State of California. Within the limited warranty for the USA, Tesla delineates in detail the allowable methods of recourse, trial, and arbitration, and how damages may be calculated.

The detailed terms defining the performance warranty are outlined below in Table 11-1 and Table 11-2. The energy retention terms are specified with respect to both warranty years and aggregate discharge throughput (shown in kWh per kWh of nameplate per year), with the warrantied minimum energy retention percentage (tested under standard test conditions) decreasing over time and throughput. Tesla specifies specific aggregate discharge throughput limitations for the first 10 years in order to guarantee a stepwise decline in energy retention percentage. This throughput is equivalent to slightly less than one daily cycle. Similarly, the terms for years 11 – 15 are not only restricted based on throughput, but the customer is only eligible for those terms if the aggregate throughput during the first 10 years did not exceed 2,040 kWh per kWh of nameplate energy capacity.

Table 11-1 Performance guarantee details, years 1 - 10

Period (Warranty Years[8] following Commissioning Date)	Aggregate Discharge Throughput Limitation	Minimum Energy Retention Percentage
1	348	95%
2	679	91%
3	996	88%
4	1302	83%
5	1599	79%
6	1889	77%
7	2173	75%
8	2451	73%
9	2725	71%
10	2994	70%

Table 11-2 Performance guarantee details, years 11 - 15

Period (Warranty Years following Commissioning Date)	Aggregate Discharge Throughput Limitation	Minimum Energy Retention Percentage
11	2,200	66%
12	2,350	62%
13	2,500	58%
14	2,600	54%
15	2,750	50%

DNV GL observes that Tesla's warranty provides a well-defined battery energy retention guarantee – citing a guaranteed capacity level at multiple steps as a function of either energy throughput or calendar time passed. This approach to degradation assessment is desirable as it is both logical and comprehensive and demonstrates manufacturer confidence into projections for lifetime performance of their system. However, DNV GL has not reviewed test data validating these values, and as such cannot comment upon their technical appropriateness or the level of risk associated with meeting them.

In addition, the caveat that the customer is not eligible for the guarantee in years 11 – 15 unless the Powerpack 2 was operated in such a way that throughput is below a set value of 2,040 kWh per kWh of nameplate capacity tacitly places that as a limit on the throughput in the first 10 years. Based on other similar products, this 15-year warranty goes beyond what is currently industry standard, and DNV GL thus does not find this restriction to be excessive.

In the event of a justified claim, Tesla will have sole discretion to repair or replace the defective system or component with an equivalent, or refund the current market price of an equivalent energy storage system at the time of the Warranty claim. In such circumstances, Tesla shall also be responsible for the costs of teardown, disassembly, transportation, re-assembly and re-installation of the System or component subject to Tesla's Return Material Authorization (RMA) policy. Refurbished parts may be used to repair the system, and any component may be replaced by a refurbished component of the same type. The warranty does not cover: normal wear and tear or deterioration, superficial defects, or dents or marks that do not impact the performance of the System; vibration that does not impact the performance of the System; damage that occurs during shipping or transportation; damage or deterioration that occurs after the expiration, theft, or vandalism of the system or any of its components.

DNV GL notes that these terms are in line with industry norms for energy storage system warranties.

11.2 Capacity maintenance agreement

Beyond the capacity guarantee defining degradation, as above, Tesla also provided details on their approach to the optional Capacity Maintenance Agreement (CMA). The Tesla CMA guarantees system energy capacity for a set term of years within a defined set of usage parameters, such as energy throughput. In short, a capacity maintained system will receive additional battery packs installed within existing infrastructure to increase capacity levels available should they fall below the agreed upon threshold. Thus, under such agreement, the site is designed to provide for these accommodations at the time of commissioning, primarily allocating additional physical bays for battery packs to be placed in at a later time. The system’s inverter is designed to accommodate these modifications upon initial construction, so it is not required to be replaced or serviced for these additions. Tesla's modular approach to system architecture is particularly supportive of these types of service capabilities.

If at any time during the CMA term, the available energy storage capacity is less than the guaranteed capacity, Tesla defines a daily liquidated damage payment to the customer based on an agreed upon calculation in the executed CMA. Payment of the daily liquidated damages begins on the date that Tesla receives the capacity shortfall notice and ends on the date when the available energy capacity equals or exceeds the guaranteed amount. Capacity shortfalls will be verified through performance of a standard capacity test, which is also defined in the template CMA. Tesla further provides a calculation for required downtime to provide preventative or corrective maintenance to maintain the CMA.

DNV GL looks favorably on the well-defined capacity maintenance agreement template developed by Tesla, but, as with the assessment of the warranty, has not reviewed data demonstrating the appropriateness or effectiveness of the modification schedule.

11.3 Service infrastructure

Tesla offers end-to-end support for its products, based on the contracts applicable to the installation. To support this, Tesla maintains service locations for all product support functions in numerous locations around the world as shown in Figure 11-1.

Figure 11-1 Sales, Service and Support locations worldwide

Powerpack systems are designed to be connected devices. Connectivity allows for a significant level of remote diagnosis and corrective action. To proactively address issues before customers may even be aware, Tesla's system monitors the Powerpack 2 system status 24/7. Faults are automatically detected and generate troubleshooting tickets in the Tesla monitoring system. Those tickets are sent directly to Tesla Services team for remote investigation within 1 business day, and tickets promoted to field service are queued for the field service team for corrective and preventative actions if necessary. Typically, Tesla can update systems remotely to affect fleet-wide bug fixes and introduce new functionality. If a customer notices a failure or performance issue, they can notify the Tesla Services team directly via email or through an online service portal, which tracks all issues in the same ticketing system.

Tesla provides customers with two layers of support through in-depth technical support and Service Engineering teams. Both teams analyze issues leveraging a crowd-source common knowledge base, including a listing of corrective actions for the most common failure modes, and data visualization tools to assist in diagnosis, prioritizing issues based on total in field potential cost and customer impact. In-depth technical support teams typically screen issues before they are promoted to Service Engineering if they cannot be resolved immediately. The Service Engineering team focuses on providing feedback for new features or bugs in the system and determining the root case for any in-field failure. Additionally, field service is provided by the Global Field Service team.

In the case of repairs, Tesla assigns the appropriate team to perform the required services. For all battery-related issues, the in-house Global Field Services team will address the tickets. For other components of the Powerpack 2 system, Tesla may either utilize the in-house Global Field Services team or contact the appropriate vendor, to complete the service request. In either case, the technician will be dispatched to address the reported issue based on the severity within the time frame stated in the Tesla Warranty Agreement with the customer. Tesla maintains a database of all failures and replacements in the field.

In the case of a defective component, an RMA is initiated, and the item in question is replaced by Tesla Service Technician and returned to the Tesla factory. The defective component is received by Tesla's Materials Review Board (MRB) and processed into its Warp Service tracking system. The MRB team then performs an initial assessment of the defective component to determine next steps. If the defective component requires remanufacturing, it is escalated to the Tesla Remanufacture team. If the defective component must be removed from operation, it is escalated to the Tesla Environmental Sustainability team. If the defective component action is unknown, it is escalated to the Tesla Energy Service Engineering team for further review.

11.4 Product support summary

The Tesla step-function energy retention guarantee, specified as a function of energy throughput and years in operation, is very well defined. The optional capacity maintenance guarantee is similarly well structured and provides a standardized approach for meeting an emerging need of the industry. DNV GL has not reviewed testing data for these values, and cannot comment on any risk associated with not meeting them. DNV GL has a positive opinion of Tesla's maintenance and service infrastructure, finding it to be in line with best practices and suitable to support the growing Tesla fleet.

12 SITE VISIT TO AN OPERATING SYSTEMS IN THE FIELD

On 29 June 2017 DNV GL conducted a site visit for the Powerpack 2 installation located at their customer's SCE R&D site in Pomona, California. It was a clear, sunny day and the energy storage system was in standby mode, meaning it was actively waiting for command to start charging or discharging. The energy storage capacity at this customer's facility is 630 kWh and power output of 150 kW. Figure 12-1 shows the electrical one-line drawing of this installation site.

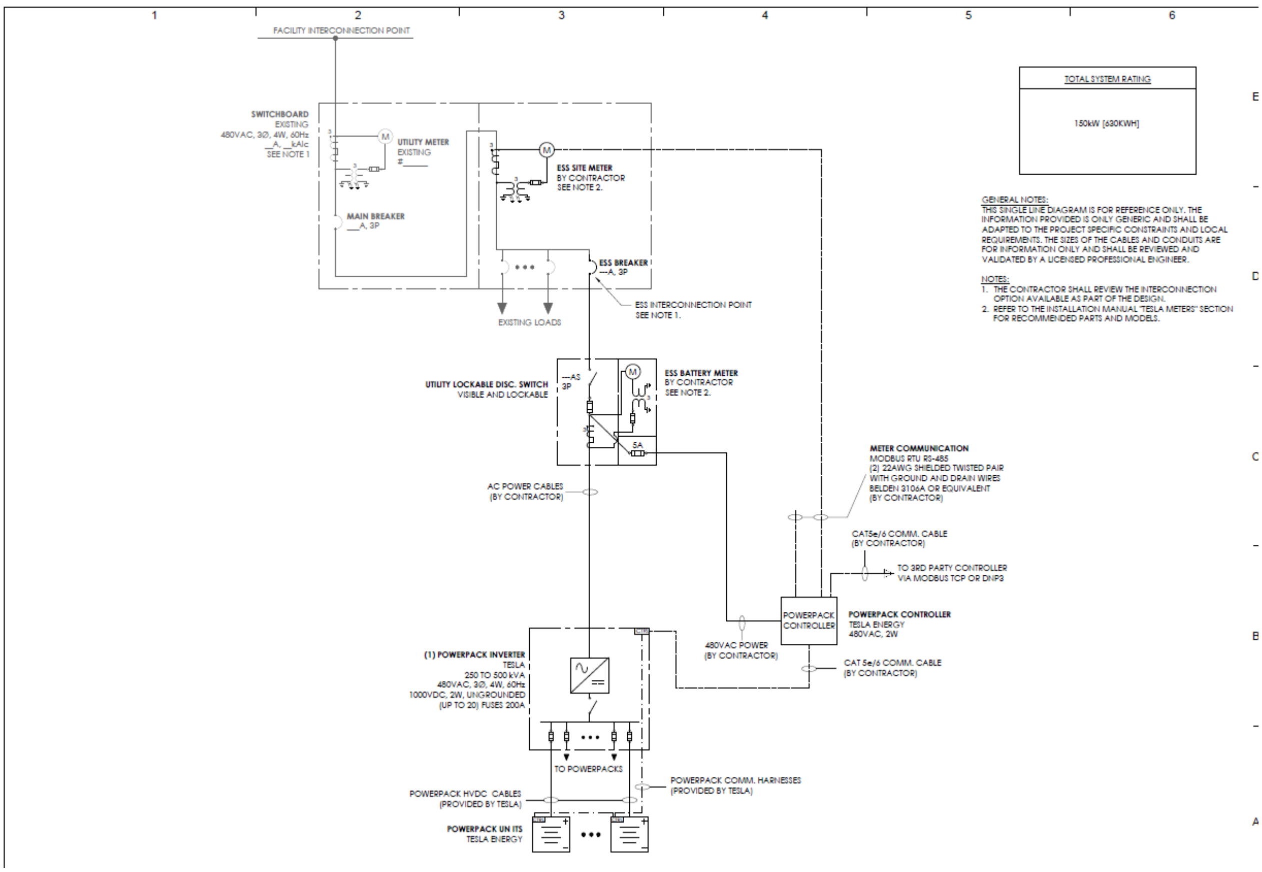


Figure 12-1 Electrical one-line drawing of the SCE installation visited by DNV GL

Figure 12-2 shows the inverter on right side and the three Powerpacks to the left of the inverter.

The customer uses Tesla's GUI setup to actively control the capacity of energy routed from the grid utility to the battery storage system. This type of active control is not typically used to control the system; however, due to nature of customer's site conditions, the Powerpack 2 performed as expected to customer's needs.

Figure 12-2 Powerpack 2 site visit installation

The inverter interface is minimal, with only a single lever to disconnect the inverter on the cabinet door. A padlock on the inverter cabinet's handle prevents access by unqualified personnel. The battery cabinets require a special tool to open the doors, meeting access safety requirements. All AC and DC wiring is held within the inverter cabinet and routed from under the testing bed (concrete pad) and to the switchgear on the right-hand side (not shown in picture).

All access to the cabinets is from the front, with large doors improving visibility once inside the cabinets. No additional structure for protection from the sun and elements was required, simplifying the installation. The resulting group of cabinets is uniform and tidy.

Figure 12-3 Inverter cabinet

The battery packs are held within the three separate cabinets to the left of the inverter. The cable wiring is fed through the wireways at the bottom front of the cabinets, readily seen in Figure 12-3, and routed into the inverter from the bottom.

At the time of site visit, it was 1:30 p.m. and the battery storage unit felt cool to the touch. However, the batteries were not being dispatched as the customer setting at the time was set to power the building loads. When DNV GL asked to observe a power transferred from loads to battery storage, the interface was performed easily over a computer GUI interface. DNV GL was able to witness power transferred from loads to energy storage and heard only a minimal amount of "high whining" noise only when ear was put next to storage. The fans were not "on" as the system had not been discharging for an extended period. The fans operate only when units require cooling.

Installation of energy storage system was done via boon trucks, attaching to lifting eyes, shown in Figure 12-4, to lower the inverter and battery cabinets in place.

Figure 12-4 Installation eyes

Mounting templates, shown in Figure 12-5 a), were provided to pre-drill mounting holes for the system over the concrete testing bed. Also, shown in Figure 12-5 b) are the feet used to secure the cabinets to the concrete, with small seismic plates to distribute the load.

Figure 12-5 a) Mounting templates, b) mounting feet with seismic plates

Overall, the system was installed in neat order. No rust or discoloration was observed at this relatively new site.

Customer brought to the attention that some alarms have occurred that were readily addressed and cleared, while there was one hardware failure where the system reported a temperature sensor failure, requiring a service call by Tesla to replace the sensor.

Drainage for this site was not an issue as customer and Tesla worked on installing Powerpack 2 on slightly raised testing bed so that rainfall would flow into the trenches at the sides of the storage system. Conduit was routed underneath the surface of the trenches. See Figure 12-6. Due to the proximity of DC cables to the concrete surface, DNV GL believes it prudent to install such forms of drainage.

Figure 12-6 Trenches for drainage

The Tesla Site Controller was housed in a separate location, within the switchgear communications enclosure, as shown in Figure 12-7.

Figure 12-7 Tesla Site Controller

Site visit monitoring data was not provided on the day of site visit. However, monitoring data was provided for 6 July 2017. The customer performed a 150 kW charge and discharge of battery (Figure 12-8). Below in Figure 12-9 is a snapshot of the site monitoring data.

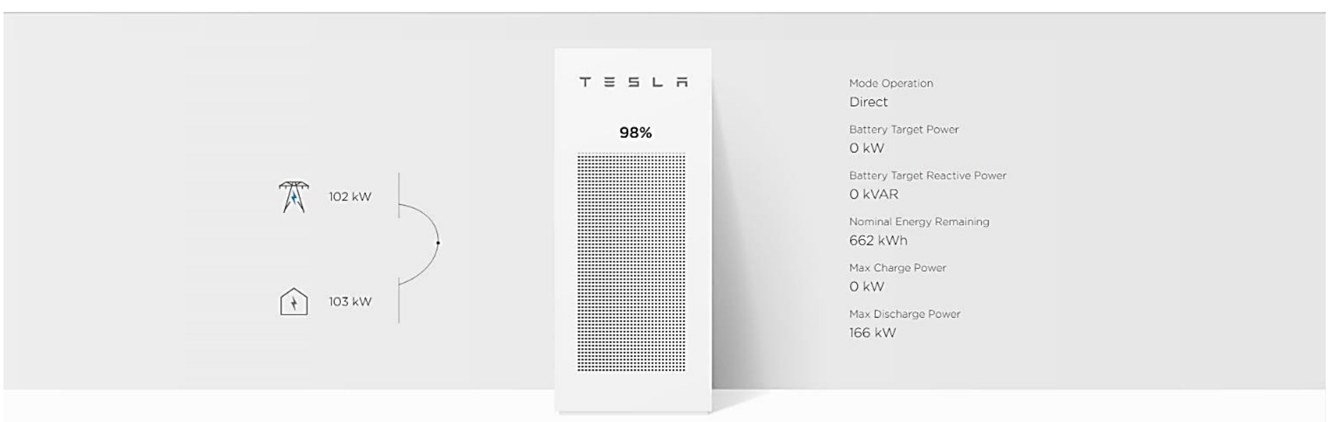


Figure 12-8 Figure Data monitoring GUI

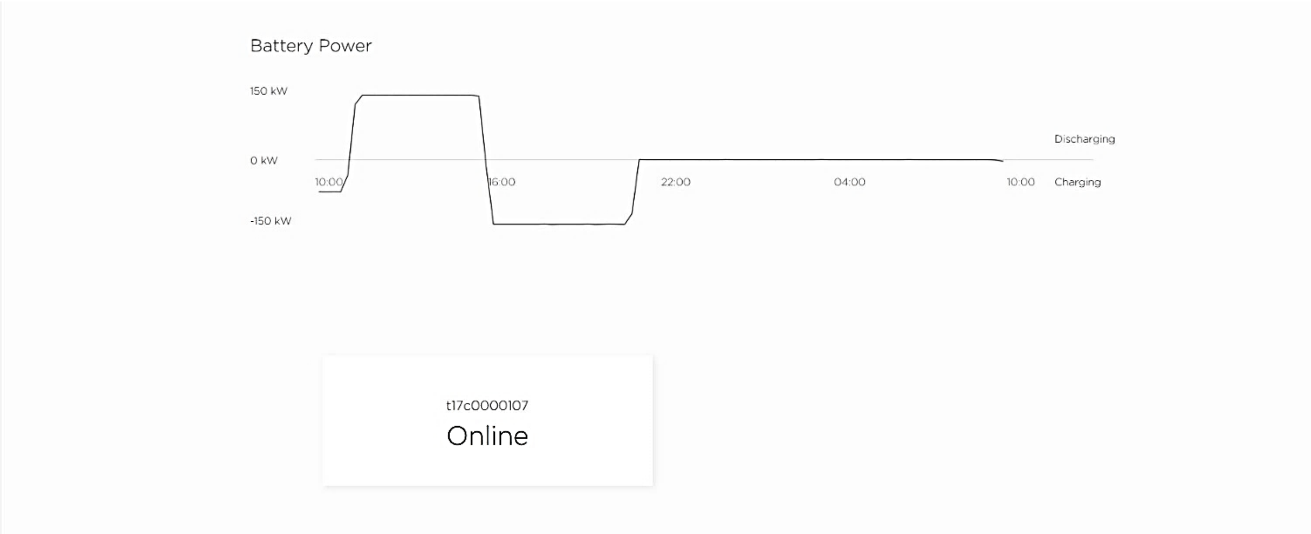


Figure 12-9 Data monitoring chart

Because the installation is a test site for evaluating the performance and impact of energy storage, the data shown represent responses to simple commands of battery discharge at 150 kW and battery charge at 150 kW. The data indicate a smooth, steady response without oscillation or overshoot.

12.1 Site visit summary

The Tesla Powerpack 2 System installed at their customer's SCE R&D site in Pomona, California, appears suitable for an industrial application, with the uniformity in color and the symmetrical layout pleasing in appearance. All cables are routed within conduit in the testing bed underneath the Powerpack 2, or in the wireways tightly coupled to the enclosures. The concealed cable routings help to achieve Tesla's goal of a tidy installation.

The actual installation activities involve the use of a crane or boom truck to hoist the enclosures from above and lower them into position. This is a common practice for industrial applications. The ventilation openings in the front of the Powerpack 2s allowed back-to-back positioning of the cabinets on site, resulting in an efficient use of space on the concrete pad, however the installation visited did not take advantage of this feature, due to the small number of cabinets installed. The pad was described as level, however trenches around the testing bed allow for water drainage. In general, DNV GL found the installation inspected to be suitable for the industrial environment in California, and pleasing in appearance.

13 SUMMARY AND CONCLUSIONS

Tesla, Inc. is a well-known manufacturer of electric vehicles with battery energy storage as a core competency. Tesla entered the stationary energy storage business in 2015 with the introduction of both residential and industrial systems. The Powerpack 2 System is a modular, fully integrated AC-coupled industrial energy storage system. The Powerpack 2 System consists of rechargeable Tesla Lithium-ion batteries, Bi-directional inverters, DC controllers, wireways, and Tesla Site Controller, which manages the system for a variety of energy storage applications. Tesla manufactures the Powerpack 2s and the scalable Powerpack 2 Inverter, and manages the integration of the full system.

Throughout this report, comments are made that should be reviewed in detail indicating the views of DNV GL on key areas of product design and performance. The comments herein resulted after reviewing extensive documentation presented by Tesla, interviewing key personnel, performing a manufacturing review at the Gigafactory facility located in Sparks, Nevada, and visiting a functioning site in Pomona, California.

This report was derived in part from a similar DNV GL Technology Review conducted on the earlier generations of the Powerpack product line (Technology Review of Tesla Powerpack System, dated May 2016). As such some of the information was derived directly from that report with appropriate updated information as required. Throughout the evolution of this product line the product names have also evolved resulting in the current model Powerpack 2. The previous production model is now referred to as the Powerpack 1. The Powerpack 2 incorporates updated battery and inverter technologies manufactured by Tesla.

DNV GL assessed the new cell and cell interconnection design with the battery Pods, and its effect on the overall system capabilities. For both the 2-hour and 4-hour system, the increase in energy density is noted. Further, from a design perspective, the modularity of both Tesla Powerpack 2 Systems' design is unique and allows for flexibility with respect to meeting project specific needs with a standardized set of modular components. DNV GL views the battery Pod as a key differentiating element in Tesla's approach to energy storage system design. DNV GL believes the advantages of the integrated DC/DC converter at the Pod level and thermal management system at each Powerpack 2 are highly beneficial for stationary energy storage for grid applications.

The Tesla Site Controller is an embedded computer that performs many activities of communications and controls. It resides in a separate outdoor rated enclosure, with related components for communications and a power supply. Many commissioning activities involve the interconnection and verification of functionality of this system element, as the highest-level point of control, residing with the Powerpack 2 System. DNV GL finds the Opticaster software, which provides the forecasts and control inputs for the Tesla Site Controller when operating in autonomous mode, to represent an emerging industry standard design. Based on the limited data provided, the cited inputs appear sufficient for achieving acceptable performance for optimized economic dispatch. As more data is collected by Tesla, DNV GL recommends that this report be updated to provide additional credence to this assessment.

The earlier model Powerpack line incorporated a third-party OEM inverter. The new Tesla manufactured Powerpack 2 Inverter consists of multiple Powerstages, creating a scalable inverter platform with power circuit redundancy. The Powerstages consist of a multi-level Silicon Carbide (SiC) switching topology, for high efficiency, packaged in an enclosure suitable for outdoor use.

The major components of the Tesla Powerpack 2 System have undergone extensive review by third-party, Nationally Recognized Testing Laboratories, for both the North American market and the international markets. Due to the complexity of the system, the compliance certifications are extensive and impressive. Much information is provided in this report as a result of a lengthy study of the compliance and safety features of the Tesla Powerpack 2 System.

At their Gigafactory manufacturing facility in Sparks, Nevada, Tesla is working to bring their experience, quality requirements, and part-tracking from the production of electric vehicles to the manufacturing of stationary energy storage systems. The Gigafactory manufacturing process is built upon 10 years of manufacturing experience in the electric vehicle industry. This legacy of electric vehicle manufacturing presents a unique perspective within the grid storage industry with respect to manufacturing, quality, and safety.

Like many large, stationary systems, the Tesla Powerpack 2 System is physically integrated at the customer location. The major components are first factory tested individually, and then interconnected and tested as a system, on site. The required civil work to prepare the site and the necessary interconnection electrical work are typical for outdoor equipment installed on a concrete pad located near the point of use. Proper water drainage is an important characteristic of a suitable installation for the Tesla Powerpack 2 System.

The system availability data reviewed by DNV GL was based on both the original Powerpack 1 installations and Powerpack 2, and are thus discussed to demonstrate Tesla’s general ability to design systems with high availability and low failure rates, rather than solely that of the Powerpack 2. Although DNV GL believes Tesla’s infrastructure, processes, and experience are supportive of continuing the noted trends, DNV GL recommends that this report be updated when a greater volume of data is available to validate these reliability statistics.

As of Q3 2018, approximately 146 Tesla Powerpack 2 Systems incorporating the Powerpack 2 Inverters have been installed, or are in the installation process. Some of the larger systems incorporate multiple Powerpack 2s and Inverters. DNV GL expects that like other large system applications, the Tesla Powerpack 2 System components including the inverter will be subject to software updates and design revisions as the product matures and field data become available. Tesla reports that, just as with their vehicles, Tesla does not have model years, but rather rolls in improvements on an ongoing basis. Additionally, Tesla states that backward compatibility and ease of integration with existing products is guaranteed, especially since Tesla sells Powerpack 2 systems.

DNV GL believes that Tesla’s warranty provides a well-defined battery energy retention guarantee – citing a guaranteed capacity level (percentage of initial AC energy capacity) at multiple steps as a function of either energy throughput or calendar time passed. This approach to degradation assessment is desirable as it is both logical and comprehensive and demonstrates manufacturer confidence into projections for lifetime performance of their system. The optional capacity maintenance guarantee is similarly well structured and provides a standardized approach for meeting an emerging need of the industry. DNV GL has not reviewed testing data to confirm the technical appropriateness and risk levels associated with these guarantees.

The design maturity of the various major components varies, with the Tesla battery elements exhibiting the most prior field experience in their electric vehicles and Powerpack 1 energy storage systems. As with any system consisting of many key components, the system complexity will affect reliability. Customers should expect that for the components with less field operation, issues may be discovered as systems see more operation time resulting in opportunities for product improvement. DNV GL believes that field operation for a longer period with more fielded units will be necessary to provide a clearer picture of the long-term reliability. More field operating history should be included in any future update to this report.

In Summary, DNV GL has reviewed all available documentation and test data, covering all the major components as well as the full Powerpack 2 System and appreciates many of the unique attributes of the Powerpack 2 System design, manufacturing processes, component selection, and integration techniques. In addition to visiting and evaluating the Tesla Gigafactory, DNV GL visited and evaluated an operating Powerpack 2 System. DNV GL believes that with continued diligence in monitoring further field operating history that the Tesla Powerpack 2 System will be well positioned to address emerging applications for energy storage in both the North American and International markets.

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas and energy industries. We also provide certification services to customers across a wide range of industries. Combining leading technical and operational expertise, risk methodology and in-depth industry knowledge, we empower our customers' decisions and actions with trust and confidence. We continuously invest in research and collaborative innovation to provide customers and society with operational and technological foresight. Operating in more than 100 countries, our professionals are dedicated to helping customers make the world safer, smarter and greener.