Renewables: the energy of the future and its efficient implementation together with Energy Storage Systems

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Introduction

Few of us take the time to think about how the electrical energy we use in our homes, places of work, or transportation actually gets from where it is generated to our light bulbs, power sockets and trains. However, ongoing discussions about climate change have highlighted that there is room for broadening the range of energy sources we use to generate electricity, while also improving the reliability of the energy supply, beyond just adding more fossil fuel and nuclear power plants. Renewables, such as wind and solar, all provide fossil fuel-free alternatives to energy generation, and have had an impact on the electricity generation mix (Figure 1). However, these sources are dependent on weather conditions, and on the site where they can be installed.

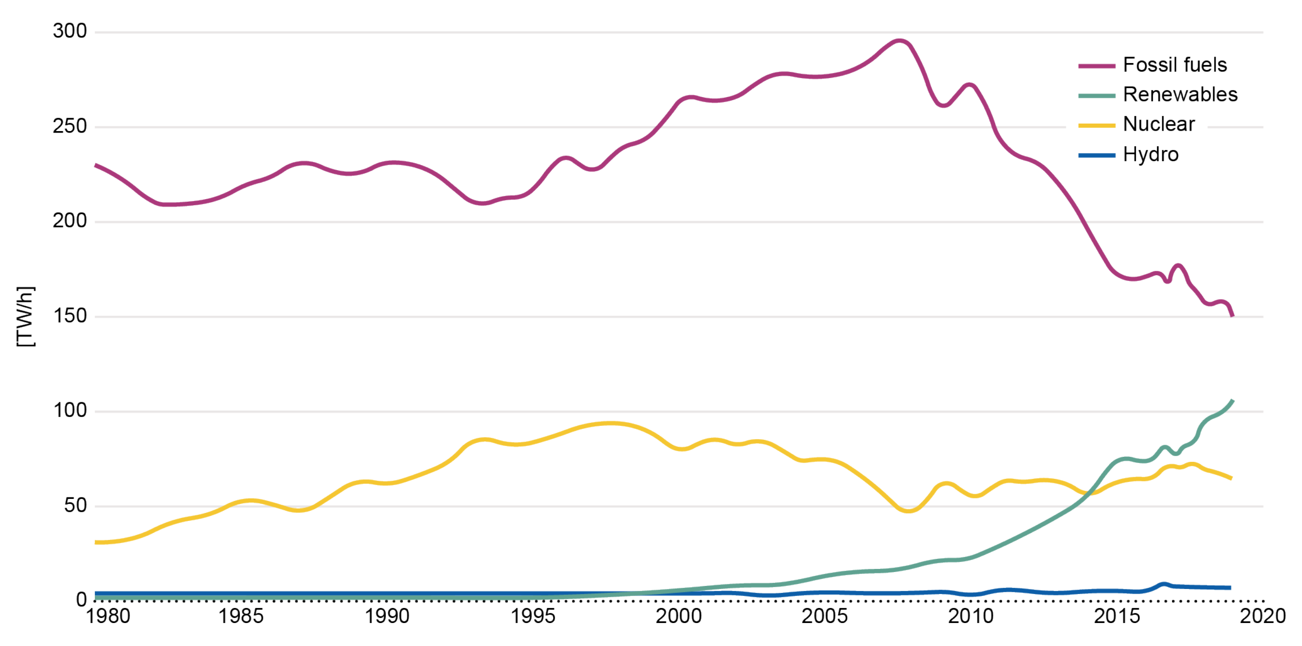

Figure 1 Electricity generation in the United Kingdom has seen a steady uptake in renewable energy sources coupled with a reduction in fossil fuel alternatives[1].

Electricity generation and the transmission of that energy is quite a complicated affair[2]. Because energy has typically always been generated on demand, procedures for Demand-Side Management (DSM) have been the core approach to balance supply and demand[3]. This ranges from reserve power generation on the one side, such as pumped-storage hydroelectricity, to physically reducing demand at the sites of specific large power users for short periods of time. In the United Kingdom (UK), the phenomenon of “TV pickup” also forms part of the DSM approach, using the country’s television viewing habits to predict peaks in electricity demand based upon when TV shows or sporting events conclude[4].

Overview of national power systems

Wind and solar energy, unlike their fossil-fuel alternatives, cannot be relied upon to provide the necessary fast response to plug load gaps in power generation. Instead, it makes more sense to collect and store this energy when it is generated, making it available for use at a later date. For this purpose, Energy Storage Solutions (ESS), large and small, are being developed, providing power for everything from charging electric vehicles to powering cities.

The most notable of the large ESS projects is the Hornsdale Power Reserve project in Australia[5]. This 100 MW/129 MWh battery facility has already kicked in twice to replace the power lost from a local coal-fuelled energy plant[6]. The site draws energy to recharge itself from the adjacent Neoen wind farm project, adding to its green credentials[7]. This allows it to store energy from a cheap and stable energy source while reacting faster than steam turbines or gas generators to support outages and summertime peak loads. The UK has also made significant investment in ESS, with 700 MW installed and a pipeline of some 11 GW planned[8].

All of these different generation and storage approaches are combined in various ways to implement future electricity generation solutions:

- Solar
  - Centralized plants feeding into the national grid; grid-tied
  - Decentralized installations, mounted on private homes and commercial properties; grid-tied or sometimes stand-alone
- Wind
  - Onshore, built on available land
  - Offshore, clustered in coastal areas
- ESS
  - Before the meter, supporting the needs of a national electrical grid and co-located with renewable energy sources
  - After the meter, as a storage solution for private and commercial properties, again coupled with renewable energy electricity generation

For example, a private solar installation coupled with an ESS could be used to store energy during the day and then charge an EV overnight. It is also possible that such a solution could be used to cover for localized power outages in the form of a Virtual Power Plant (VPP), an approach being taken in Queensland, Australia[9].

How solar energy inverters meet differing application demands

Solar energy conversion solutions span power delivery of tens of kW to tens of MW, depending on where in the system they are located, and their purpose. At the top end of solar energy conversion are utility-scale, ground-level plants that feed directly into transmission and distribution networks of national electrical grids. Such installations would be expected to deliver a minimum of 5 MW of energy. Large decentralized solutions, such as those installed upon rooftops of commercial premises, are located closer to where energy demand lies. These will typically deliver under 5 MW of energy. At the bottom end are residential installations, again fitted to the rooves or even walls of privately owned properties. Such installations will be dimensioned to deliver up to 10 kW of energy (Figure 2).

The principle of energy conversion remains broadly the same across all these systems. The radiation and temperature-dependent energy from one or more photovoltaic (PV) panels are converted from a DC to AC voltage to match the local voltage and phase requirements. They will also utilize Maximum Power Point Tracking (MPPT) techniques to ensure that all the available power, depending on the radiation received, is extracted from the PV panel.

General requirements that apply to all the different solutions described above include a low demand on power cycling (since they are typically always on), a high robustness with regard to humidity, and either natural or forced-air cooling. System cost, end-to-end efficiency, as well as time-to-market is also a key concern, along with providing high reliability for a solution that can often be located in a difficult-to-access place. Power density and high efficiency round off the list of requirements.

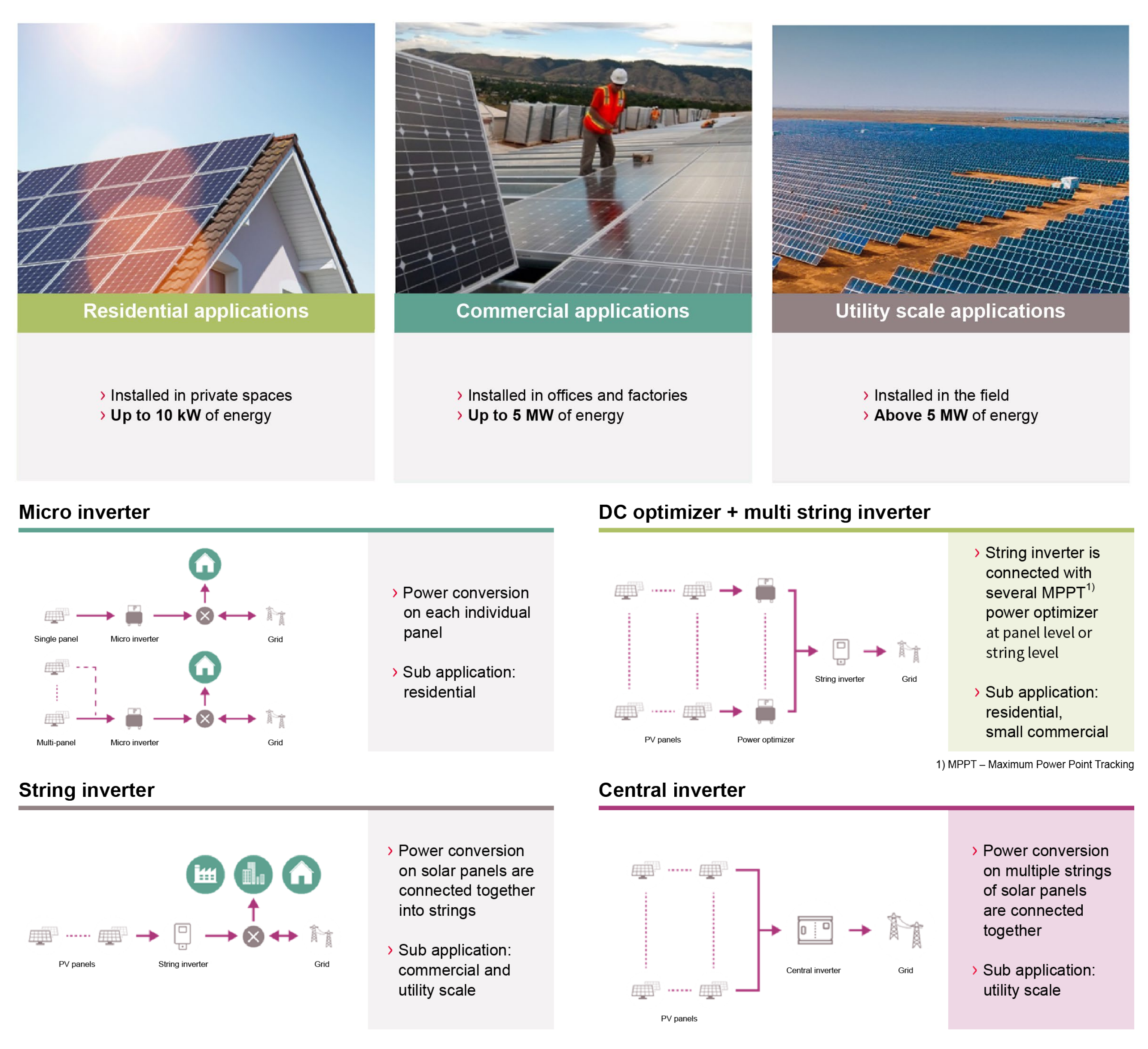

Figure 2 Application segments and their inverter types.

Residential installations often make use of micro inverters that convert the energy provided by single or multiple PV panels to AC to supply the grid. Larger commercial and some utility-scale installations, as well as some residential solutions, prefer to implement string inverters. Here several PV panels are linked in series to generate a DC voltage of between 600 V and 1000 V, even reaching 1500 V in utility-scale systems. The string inverter then converts this to single or three-phase AC. The largest utility-scale installations make use of several parallel strings of PV panels, with the solar inverter delivering several MW of AC power to the grid.

Implementation approaches for solar energy inverters

Micro inverters convert DC into grid compatible, single-phase AC, typically in three stages. The variable incoming DC PV panel voltage is boosted to a fixed DC voltage in the range of 40 V to 60 V, with switching frequencies lying around 100 kHz (Figure 3). The MPPT capability ensures that the maximum available power is always being drawn from the PV panel to deliver optimal efficiency.

There follows a DC-AC stage coupled to an AC-DC stage that are linked via a galvanically isolated transformer. These together can be considered to be the second DC-DC stage of the solution with switching frequencies lying around 80 to 120 kHz. Typical topologies at this stage range from Zero-Voltage Switching (ZVS) full-bridge to fly-back, phase-shift or even hard switched full-bridge converters, while resonant LLC topologies with a single bridge rectifier are also in wide use.

The final stage performs DC-AC conversion to create a grid-compatible single-phase output, switching in the 40 to 80 kHz range. The dimensions and cost of the isolation transformer, as well as the DC and AC filters between the stages, will largely be dependent on the ripple frequency, leading to designers typically opting for higher switching operation.

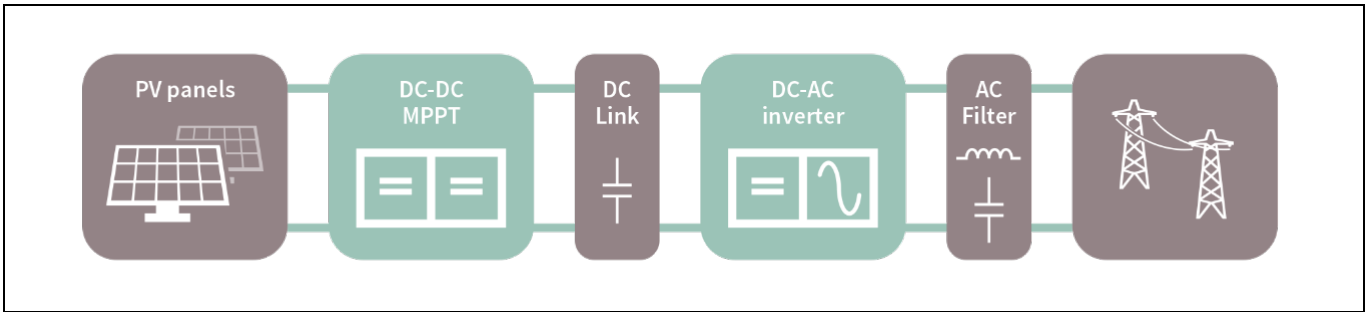

Figure 3 The conversion approach of a typical micro inverter.

At this power level, discrete power devices provide the optimal solution. The buck/boost DC-DC stages can make use of OptiMOS™ MOSFET and CoolSiC™ diode families. On the secondary DC-AC side, Infineon’s 600 V CoolMOS™ are the recommended devices for highest efficiency and most compact design.

String inverters are transformerless, grid-tied solutions achieving high efficiency at low cost. Initially, they convert the DC input from a collection of series-linked PV panels to a fixed DC voltage, including an MPPT to ensure maximum power draw from the PV panels. The incoming voltage from a residential solar array will be dimensioned at around 600 V, whereas the actual incoming voltage will lie in the 100 V to 300 V range. The DC-DC and MPPT stage will boost this to a fixed voltage of around 350 V. This will usually be implemented with a simple two-level boost topology (Figure 4).

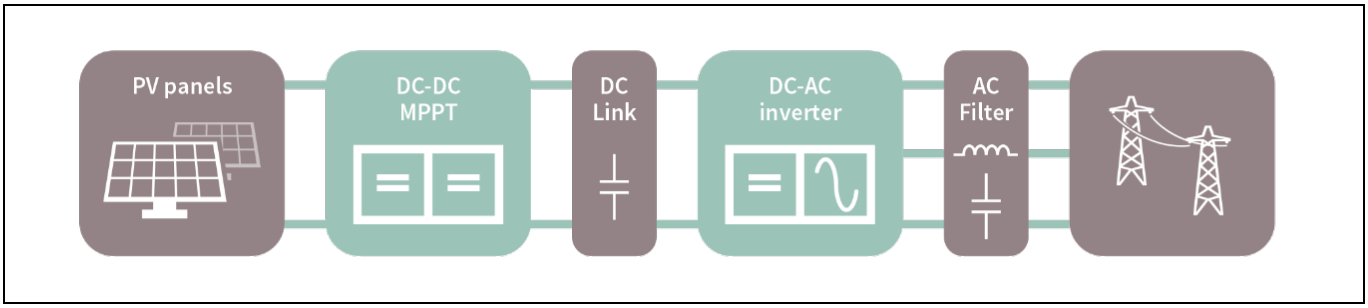

Figure 4 **String inverters typically consist of two stages, not requiring galvanic isolation.**

Dependent on the target output, the AC-DC stage that follows will generate a grid-compatible single-phase or three-phase output. Single-phase inverter typically, two-level (residential applications) or three-level Neutral-Point Clamped 2 (NPC2) topologies are chosen here, both of which can be implemented using four switches and four diodes. More advanced DC-AC stages make use of more switches and diodes in topologies such as H6, HERIC and MULTI LEVEL (Figure 5). In addition to the extra switches, extra gate drivers and auxiliary power are also required.

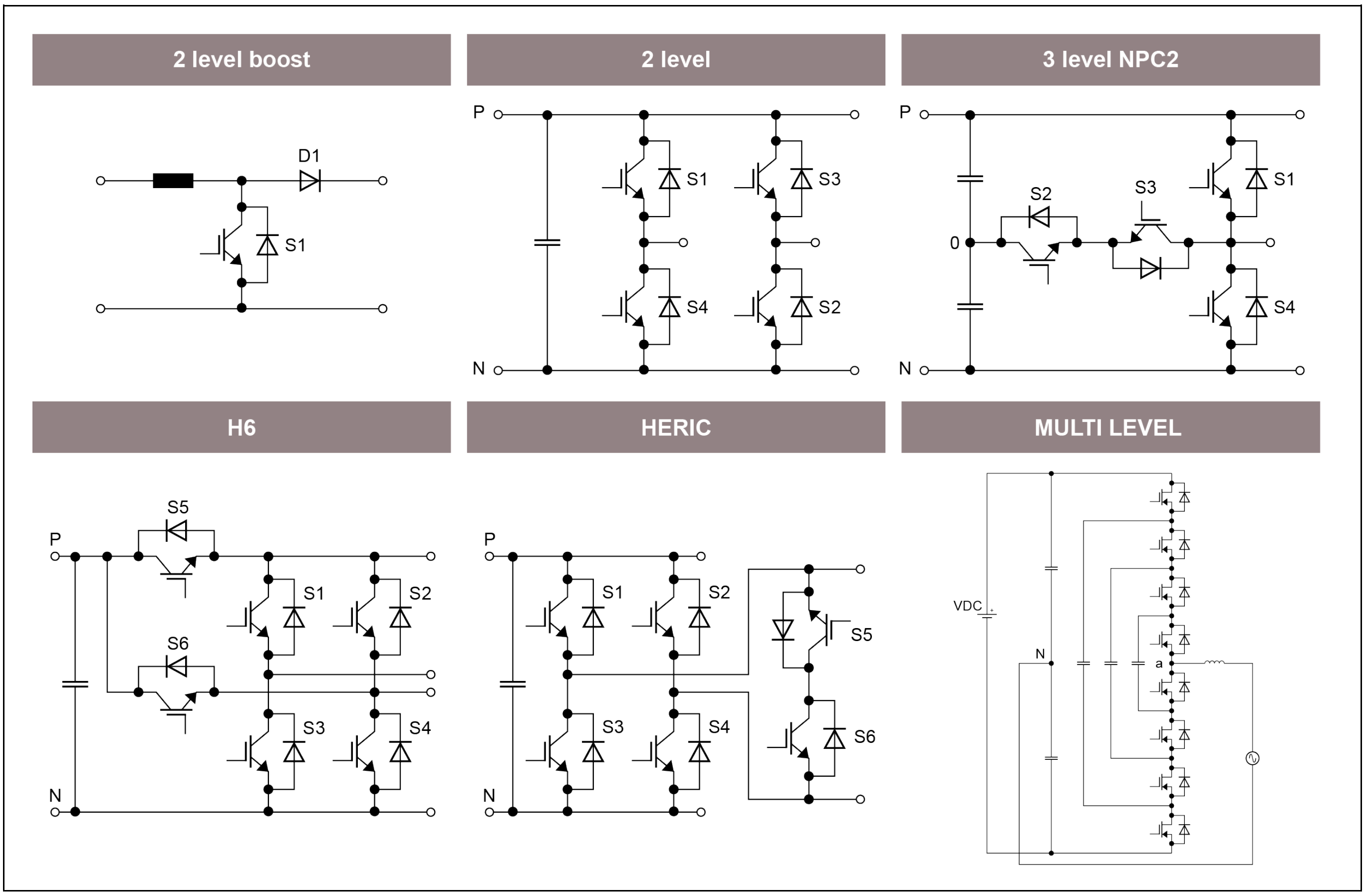

Figure 5 **2-level and 3-level topologies are more common, with the more complex H6, HERIC and MULTI LEVEL topologies used in more advanced solutions.**

Although more complex, there are significant advantages to be had. All topologies are noted for their higher efficiency, lower cost, smaller size and weight. The H6 topology features low leakage currents and higher efficiency requirements. It is also simple to control and is considered a mature topology, although its conduction losses are higher than the alternatives. Finally, the HERIC topology allows for a higher power density.

On the other hand, multi-level inverters are able to utilize low-voltage OptiMOS™ MOSFET switches based upon trench topologies that offer very low $R_{DS(on)}$ and body diode recovery charge Q_{rr}. The greatly reduced conduction losses combined with reduced switching losses make it possible to reach higher efficiency levels than are possible in traditional inverters. The drawback is the greater level of complexity necessary to realize a multi-level design compared to traditional topologies and the higher number of switches and isolated gate drivers needed. However, at power levels in the 3 to 5 kW range, the benefits of the multi-level design, such as reduction in size and weight and higher efficiency and power density, justify the added complexity.

Three-phase string inverters typically, 2-level or 3-level topologies are preferred here (Figure 6). In particular, 3-level topology is widely used for its higher efficiency. Mainly for 1000 V PV array system, 3-level NPC1 & NPC2 is preferred. NPC1 enables to use of 600 V devices and allows more than 20 kHz switching frequency operation even for oversized PV panels. 3-level NPC2 uses both 600 V and 1200 V device, the best fit topology for less than 20 kHz switching frequency operation. For the 1500 V PV system, 3-level ANPC is widely used for its low cosmic ray induced failure rate and its higher efficiency over the full range of power factor operation.

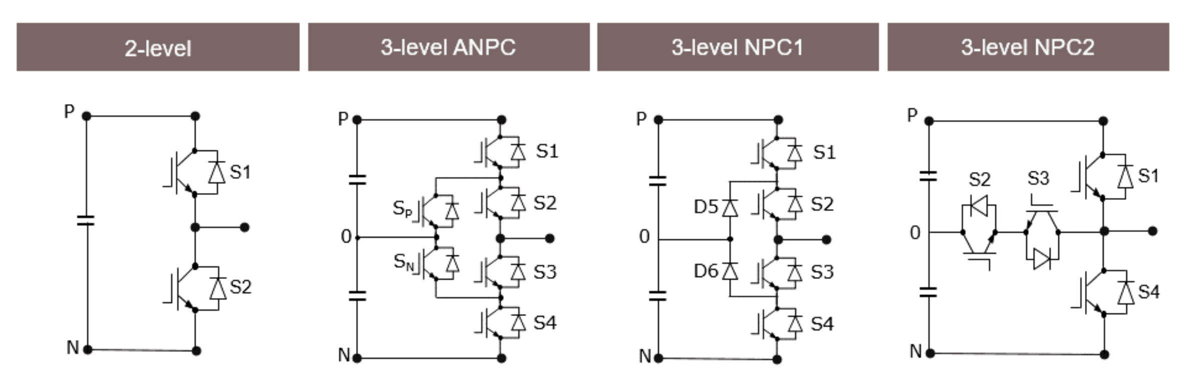

Figure 6 **2-level and 3-level topologies are more common, 3-level topology is widely used for its higher efficiency.**

The dimension and weight of the complete solution depends on the implementation of the AC filter stage along with any cooling solution that may be required.

Choosing to go with discrete or module approach in the design depends largely on the quantity of power the solution is being dimensioned for. Broadly speaking, below 10 kW inverters should utilize a discrete approach whereas systems targeting ≥ 30 kW will benefit from the use of power modules. The zone in between will depend largely on a variety of factors, from system requirements through to mechanical mounting and the production costs associated with the use of discrete devices versus modules.

Discrete CoolSiC™ MOSFET switches, CoolSiC™ Schottky Diodes, IGBT TRENCHSTOP™ 5, TRENCHSTOP™ IGBT6, and IGBT HighSpeed 3 can cover applications as far as 30 kW, whereas power modules from the CoolSiC™ MOSFET Easy 1B/2B, 3-Level EasyPACK™ 1B/2B and Booster EasyPACK™ 1B/2B should start being considered for systems beyond 30 kW.

Central inverters target utility-scale solutions, making use of a single stage of power inverter with a transformer or isolated design (Figure 7). Incoming PV panel DC is usually 1000 V, although 1500 V systems are increasingly being seen thanks to the cost benefits this approach offers. DC is converted into grid-compatible AC using 2-level or 3-level NPC1, NPC2 or even active NPC (ANPC) topologies, with 3-level delivering efficiency advantages. Particularly notable is the 3-level ANPC thanks to its higher efficiency over the full range of power factor operation. Again, the AC filter size, volume and cost depend greatly on the balance between switching frequency chosen and cooling requirements, with low losses and high current density for the power modules being key requirements.

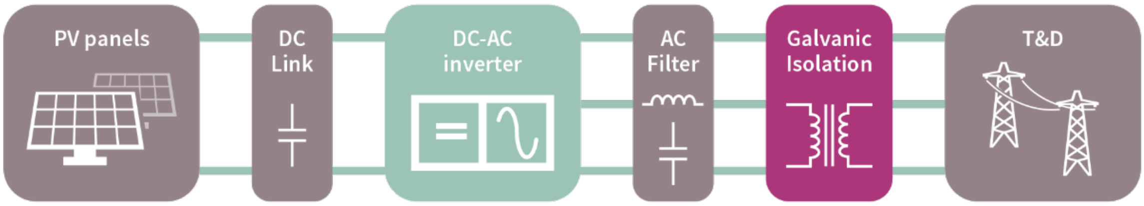

Figure 7 Block diagram of a central inverter as used in utility-scale applications.

Central inverters make use of power modules, with 3-level NPC topologies turning to the 62 mm, EconoDUAL™ 3 and PrimePACK™ 3/3+ families. A single-phase, 3-level NPC2 design can be implemented using two 62 mm modules, a common emitter and a standard DUAL configuration, featuring 1200 V, 600 A, IGBT4 switches. Further, 3-level NPC1 / ANPC single-phase design can be implemented using three standard DUAL modules, are more likely to benefit from EconoDUAL™ 3 (IGBT 7) in addition to PrimePACK™ 3/3+.

Common to all solar inverter solutions are drivers, and here design engineers have a range of high-side (1ED) and half-bridge (2ED) products in the EiceDRIVER™ family. With SiC MOSFETs switching at up to 50 V/ns or above, it is essential that gate driver strength matches the switch’s needs, as well as providing accurate timing and tight tolerances. Negative gate voltages or a Miller clamp may also be required, along with fast short-circuit protection, as SiC devices are less short-circuit capable than IGBT alternatives. EiceDRIVER™s to match the CoolSiC™ range are available, with devices such as the 1EDC20I12MH being UL 1577 certified for 2.5 kV(rms) for one minute.

Current sensing within the inverter solution can be implemented optimally using XENSIV™ devices, such as the TLI4971. Everything from simple monitoring and system feedback to central control systems, to control of the switching inverters can be covered by programmable devices such as the XMC™ 4000 range of ARM® Cortex®-M4 microcontrollers. Finally, the auxiliary supply is optimally implemented using AC-DC integrated power stage devices such as those in the CoolSET™ family.

How wind turbine technology is implemented

Wind turbines can be broadly classified into two categories based upon generator type; Doubly-Fed Induction Generators (DFIG) in the 1.5 MW to 6 MW power range, and Permanent Magnet Synchronous Generators (PMSG) with full convertor-based turbines rated between 1 MW and 10 MW. Both types use back-to-back power converters. DFIG systems provide maximum energy capture under variable wind conditions, with one set of windings (stator) feeding the grid directly, and the other (rotor) connected through an AC-DC to DC-AC converter to the grid. Typically, around one third of the energy generated is handled by the installed power electronics that are also responsible for handling power-speed control to compensate for changes in wind speed, providing lower costs and power losses compared to comparable alternatives. One of the main advantages of DFIG turbines are their highly optimized system cost resulting in their use primarily in onshore wind turbines.

Full convertors decouple the generator from the grid utilizing a full-scale power AC-DC to DC-AC converter. This approach reduces mechanical shock on the turbine in the event of grid faults, as well as providing operation over a wide range of wind speeds (Figure 8). Full converters for low-, medium- and high-speed Permanent Magnet Synchronous Generators (PMSG) provide maximum flexibility to meet Low Voltage Ride Through (LVRT) and other grid code requirements.

In both cases, key criteria for the electrical conversion are high power density, excellent system efficiency, long lifetime, and a high level of robustness and reliability. This is especially the case with offshore installations that, due to weather conditions, may only be accessible by sea up to 65 percent of the time in a year, and 90 percent by helicopter[10].

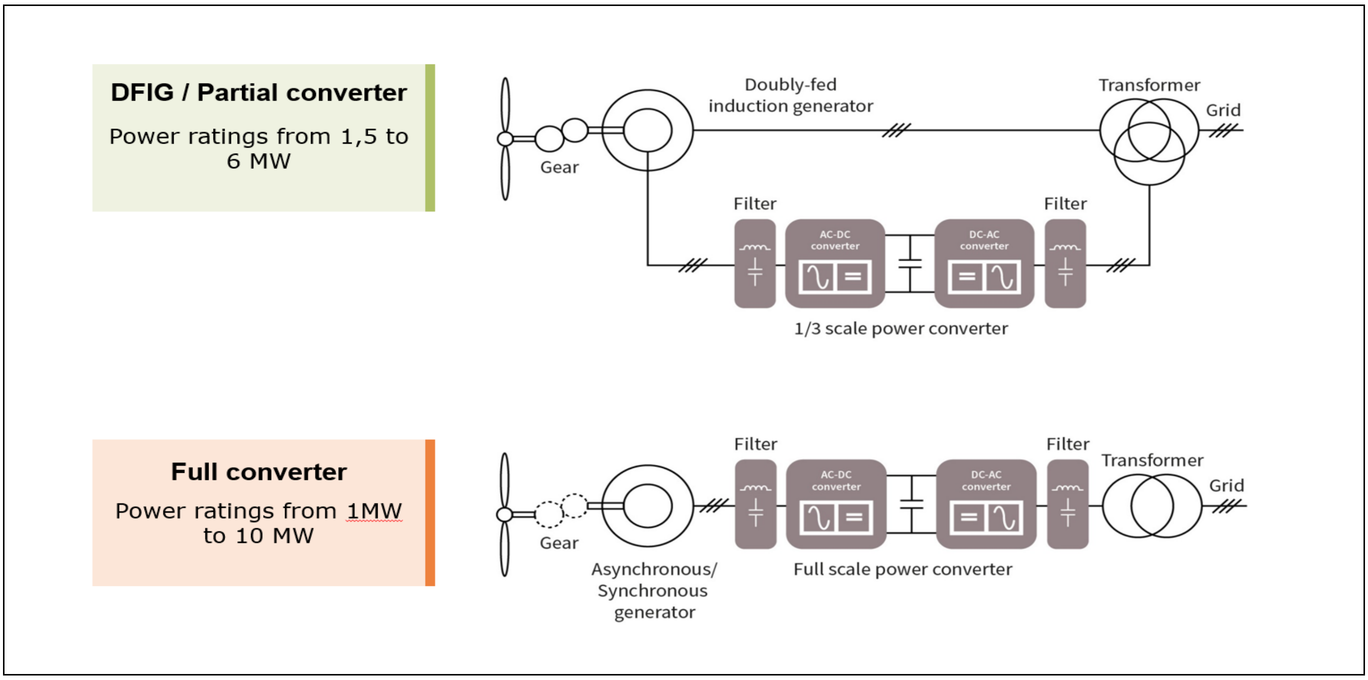

Figure 8 Wind turbines commonly use either a DFIG partial converter or full converter approach; both have high demands on efficiency and robustness.

Implementation approaches for wind turbine converters

In order to determine the cost effectiveness of the energy used, and the number of years to investment break-even point, a measure of Levelized Cost of Energy (LCOE) is used. To minimize LCOE and maximize the returns, wind turbines and their components need to operate for up to 25 years without any failures. This is a challenge for power semiconductors operating under variable wind speed and experiencing large power cycling stresses.

To handle such challenging conditions, Infineon IGBTs, specifically IGBT5 with .XT joining technology in PrimePACK™ 3+ modules, and IGBT4 devices in PrimePACK™ 3 modules, are the components of choice. The latest generation IGBT5, integrating an EC5 diode, have a reduced thickness, lessening both static and dynamic losses to support the ever-increasing power densities being demanded.
In addition to the above-mentioned modules, some converter designs are available with EconoDUAL™ and EconoPACK™+ modules.

In order to achieve 10 µs short-circuit withstand time in the IGBT5 with .XT PrimePACK™ 3+ modules, the device's thermal capacity is increased by means of a thick copper metallization on its front side. Here, the silicon chip is bonded via a copper bonding wire, replacing the aluminium wire used previously. The silicon chip is now sintered to the DCB rather than being soldered, while standard soldering of the DCB in the modules has been replaced by high-reliability (HiRel) system soldering.

As a result, a 6 MW wind turbine can be upgraded to deliver the same performance with 30 percent less power modules, delivering reductions in system and installation costs. In addition, system lifetime is now estimated to achieve more than 40 years (Figure 9).

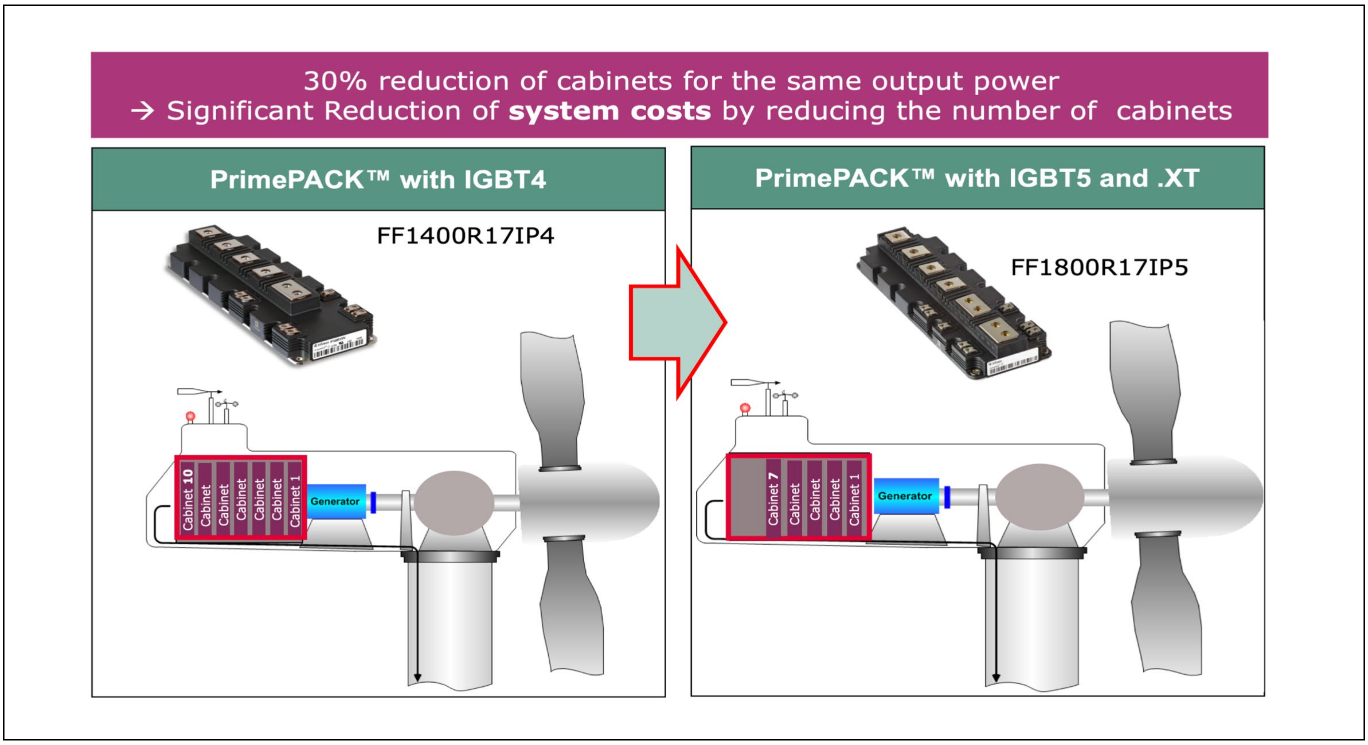

Figure 9 **A move to PrimePACK™ with IGBT5 and .XT technology requires fewer components and space, and delivers a > 40 year expected lifetime.**

The role Energy Storage Systems play in the electrical grid

The intermittent nature of renewable energy generation means that ESS will increasingly play an essential role in our electricity networks. Battery-based ESS technology can, as has been shown in Hornsdale, respond to power drop-outs in under a second, making use of clean energy sourced from collocated solar or wind plants. In such cases, the ESS is considered to be “before-the-meter” and functions as bulk storage coupled with either renewables generation or transmission and distribution systems. ESS also plays a role “behind-the-meter” when it is found in residential and commercial situations (Figure 10).

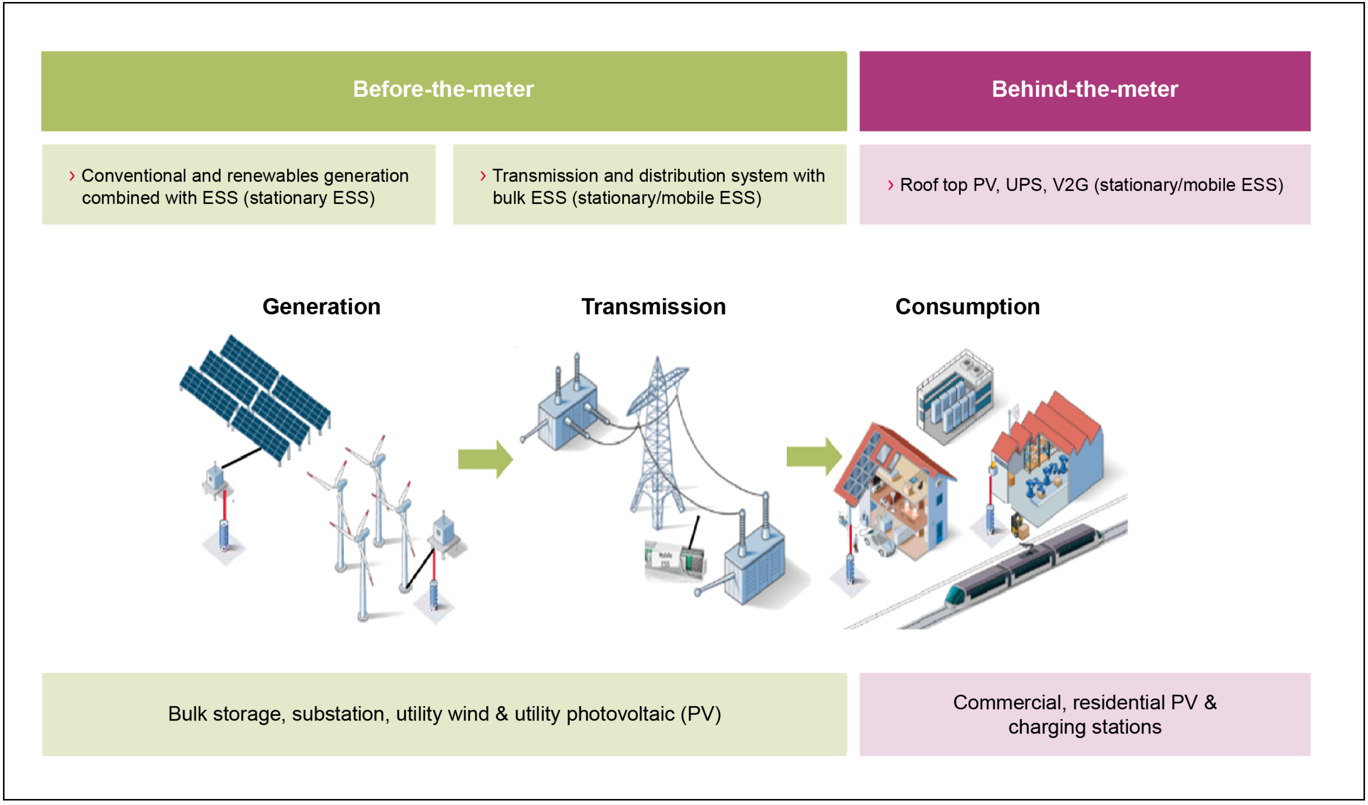

Figure 10 **ESS appears in combination with electricity generation and transmission “before-the-meter” as well as in commercial and residential environments “behind-the-meter”.**

Implementation approaches to ESS

ESS requires much of the same technology already discussed. The Power Conversion System (PCS) handles AC-DC and DC-AC conversion, with energy flowing into the batteries to charge them or being converted from the battery storage into AC power and fed into the grid. Suitable power device solutions depend on the voltages supported and the power flowing. In addition, the Battery Management System (BMS) handles cell charging, balancing and health. This is complemented by a microcontroller providing system control and communication, essential elements to ensure that the ESS can be integrated into a larger system (Figure 11).

In the PCS, solutions lying under 30 kW are typically best served with discrete solutions, whereas above 100 kW the module approach makes most economical sense. The area in between is best reviewed on a case-by-case basis to determine use of discrete or module solutions.

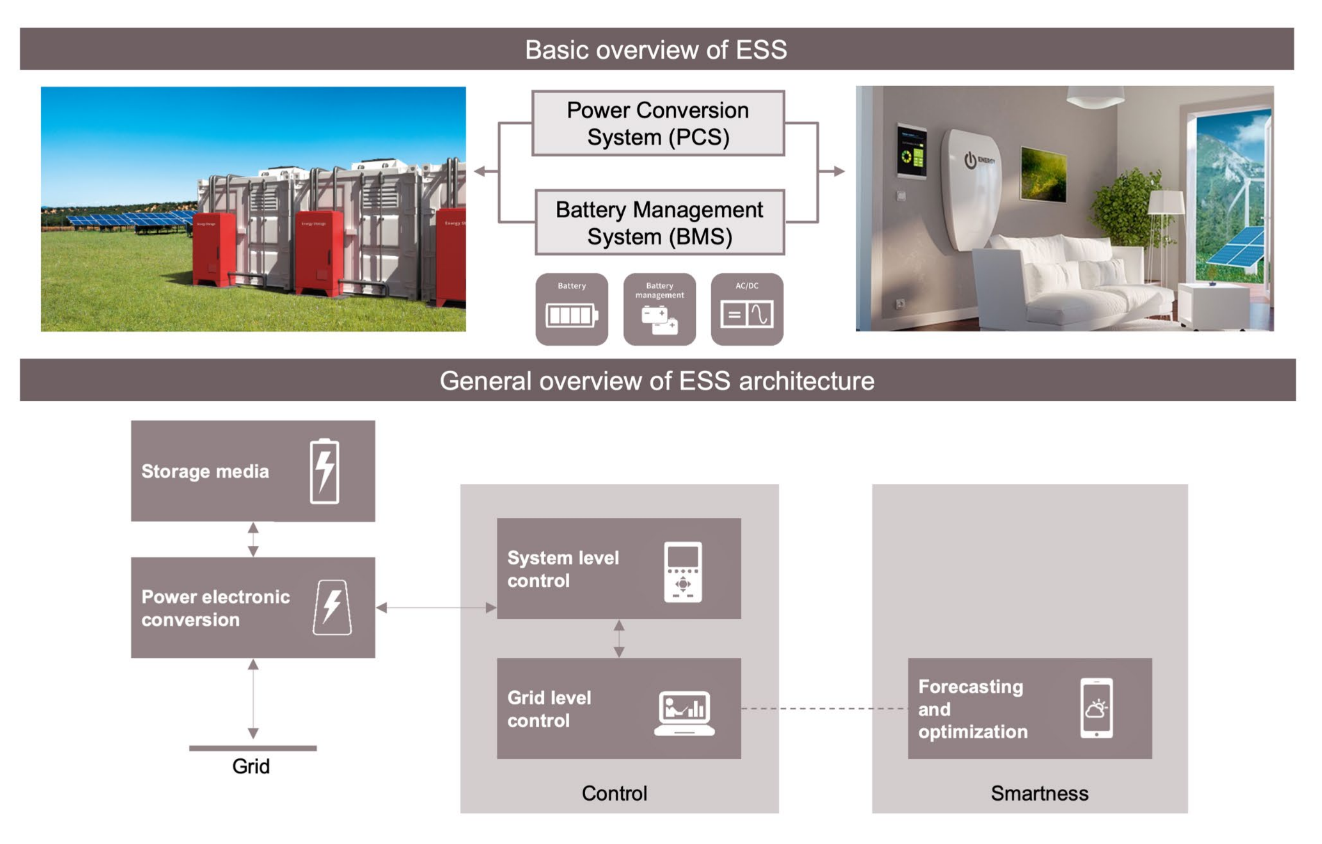

Figure 11 **Regardless of dimension, an ESS follows the same basic structure, integrating with local/national systems via communication links.**

Summary

Despite the seemingly varied applications, solar inverters, wind turbine converters and ESS solutions have a lot in common. They typically operate up to the voltage and current extremes of existing silicon switch technology, and benefit from the efficiency improvements wide-bandgap SiC switches and diodes are offering. Reliability, robustness and a long operational lifetime is also a key requirement, since access to much of the commercial and utility equipment is limited due to location and variability in weather. Infineon’s continued commitment to improving its IGBTs and MOSFETs, along with the development of innovative packaging techniques, provides its customers with a trustworthy partner that understands the unique challenges faced in these applications. On top of this, their control of both the frontend and backend manufacturing processes, including new technologies such as SiC, ensures that only a single partner is involved. Looking beyond power, Infineon rounds out their offering with the other necessary solutions, from battery management to sensing, control and communications, making them an ideal and informed partner across the range of renewable energy applications.

Notes and references

[1] https://commons.wikimedia.org/wiki/File:UK_electricity_production_by_source.png by absolutelypuremilk is licensed under https://creativecommons.org/licenses/by-sa/4.0/deed.en
[2] https://www.nationalgrid.com/group/about-us/what-we-do/uk-principal-operations
[3] https://www.enelx.com/en/questions-and-answers/eindustry/what-is-demand-side-management
[4] http://news.bbc.co.uk/2/hi/uk_news/magazine/6981356.stm
[5] https://hornsdalepowerreserve.com.au/
[6] https://www.utilitydive.com/news/report-teslas-australian-battery-project-steps-in-after-coal-units-fail/513870/
[7] https://electrek.co/2018/05/11/tesla-giant-battery-australia-reduced-grid-service-cost/
[8] https://www.solarpowerportal.co.uk/blogs/uk_battery_storage_capacity_could_reach_70_growth_in_2019_as_business_model
[9] https://www.teslarati.com/tesla-virtual-power-plant-residential-solar-powerwall-2-south-australia/
[10] https://de.wikipedia.org/wiki/Offshore-Windpark#Wartung_und_Reparatur

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