ABB

review

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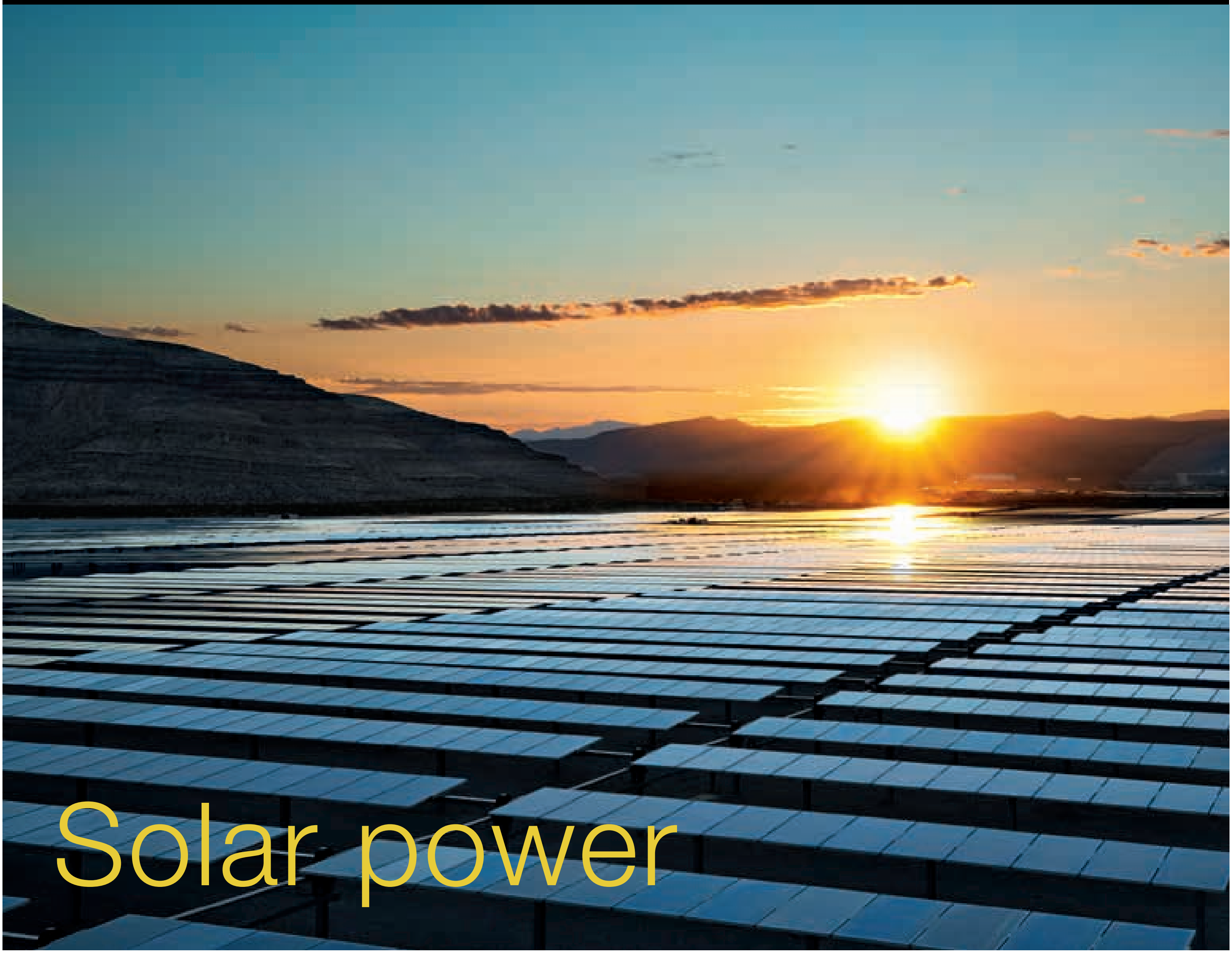
The corporate technical journal



Solar power

From being an experimental technology just some years ago, solar energy has gone through a stunning learning curve and is now able to compete without subsidies in an increasing number of markets. Solar panels have become a common sight on buildings and ground installations such as the Totana plant near Murcia (Spain) shown on the front cover of this edition of ABB Review. This installation was delivered by ABB and produces 2.2 GWh/year.

At the time of press, the world's first solar-powered airplane, Solar Impulse 2, was attempting to fly around the world. The plane is shown here and on page 5, and the project is presented in "A soaring vision" on page 16.

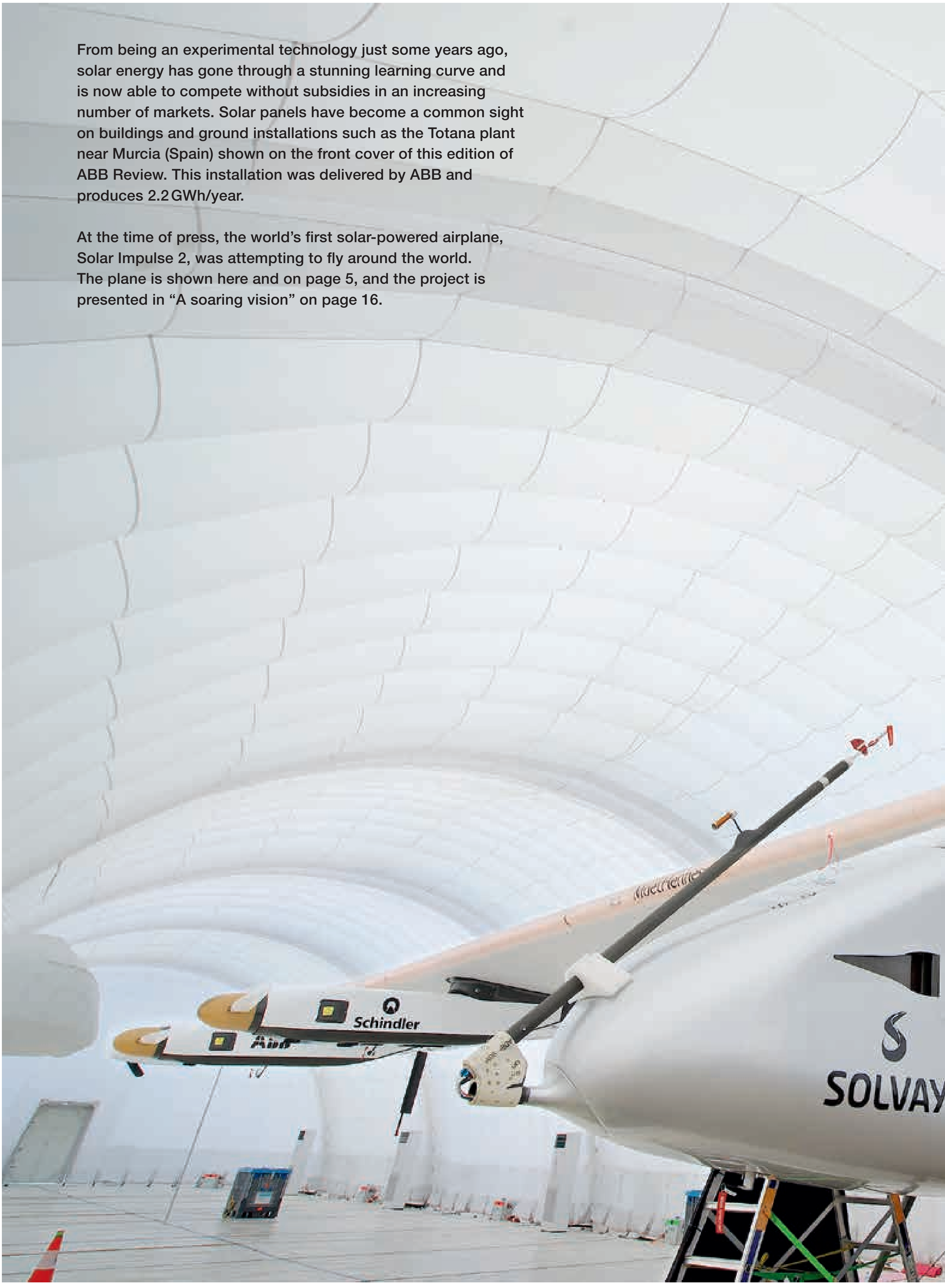


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ABB and solar energy

Claes Rytoft

Dear Reader,

In September 2014, ABB presented its Next Level Strategy, charting the company's plans for growth for the period 2015 to 2020. An important part of this strategy is a commitment to ecologically sustainable technologies.

Sustainability can be approached from numerous angles, ranging from choice of materials across energy efficiency to human safety. ABB's R&D activities are working on all of these aspects. The present issue of ABB Review, however, focusses on one particular and highly visible contribution to sustainability in energy: photovoltaics.

Photovoltaics is a rapidly growing part of the global energy mix. It is inherently scalable, clean, and is under favorable conditions already able to compete without subsidies. Although ABB does not manufacture the actual photovoltaic panels, the company offers all other parts of the value chain ranging across inverters, transformers, protection and control and is proud to be the only company able to supply this complete range. ABB's position was further consolidated by the acquisition of the company, Power One, in 2013.

This issue of ABB Review features an interview with Michael Liebreich, chairman and founder of Bloomberg New Energy and leading expert on photovoltaics, who thought provokingly presents his vision of the future of the technology and what it will take to get there.

The subsequent articles look at a selection of the numerous products and technologies ABB offers to support the photovoltaic value chain. Besides the more mainstream articles looking at different contributions to and aspects of grid connectivity, some more unorthodox applications are also covered, such as irrigation using solar powered pumps. The least orthodox of photovoltaic applications is an airplane. ABB is proud to be part of the Solar Impulse team, whose experimental plane is at the time of writing making a journey around the world powered entirely by solar-generated electricity.

Photovoltaics has come a long way from the largely experimental technology it was only some years ago. I trust that this edition of ABB Review will present you with insights and food for thought on this exciting source of energy and how it can be harnessed, connected to the grid and integrated with other forms of generation.

I would like to use this opportunity to remind you that besides the print version, ABB Review is available electronically, both as a pdf and as an app for tablet devices. Please visit www.abb.com/abbreview for more information.

Enjoy your reading

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Chief Technology Officer and
Group Senior Vice President
ABB Group


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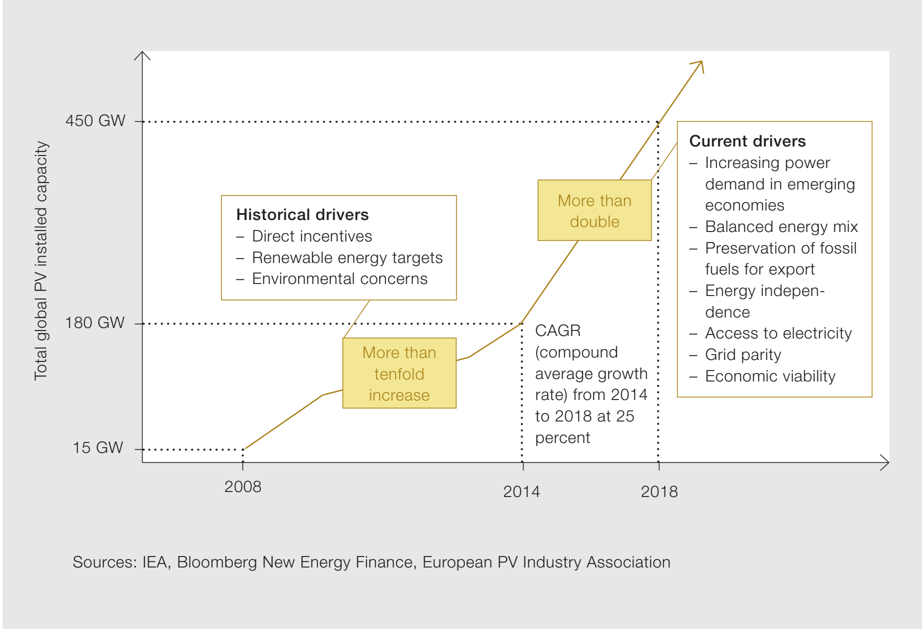
From source to socket

ABB is at the forefront of photovoltaics

ALEX LEVRAN – Over the past 10 years, global photovoltaic capacity has grown at a steady double-digit rate. The worldwide installed base has expanded more than tenfold from approximately 15 GW in 2008 to above 170 GW at the end of 2014. In 2014, total annual investment exceeded $83 billion. And this trend is set to continue: ABB expects that in the next three years the worldwide installed base of solar power systems will surpass 400 GW.

Title picture
An ABB field service engineer at the Apex Nevada Solar facility, near Las Vegas, NV, United States.

1 The PV market continues to experience solid growth with a shift in drivers.



In its early years, expansion of the photovoltaic market was fueled by government incentives and subsidies, particularly in Europe where governments set renewable energy targets as a percentage of the total generated energy. The targets were designed to enable non-carbon-emitting sources to displace carbon-emitting generation from the energy supply, thus reducing overall carbon emissions → 1.

Market maturity

With the market now maturing, government incentives will increasingly be displaced by the technology's inherent competitiveness as the prime driver of the sector's continuing growth. Over the past five years, the cost of installed solar power systems has declined by over 70 percent. The leveled cost of energy (LCOE) for solar electric power in many parts of the world has fallen to at least so-called grid parity[1] levels, if not further.

Europe was the first region to witness a large-scale emergence of photovoltaic power, thanks to feed-in tariffs (FIT) combined with subsidies to support the fledgling technology.

In the past few years, markets have grown very quickly in the United States, China, Japan, India and Australia. Industry expectations are that in the near future, market expansion will also occur in emerging countries in the Middle East, Africa and South America. The global solar market is now well established in the domain of residential, commercial roof-top, and utility-scale ground-installed applications.

Although steep price erosion has been adversely impacting profitability, there are clear signs that the industry is migrating toward profitable growth through global expansion.

> Over the past five years, the cost of installed solar power systems has declined by over 70 percent.

ABB's commitment to this sector aligns with the vision of its group CEO, Ulrich Spiesshofer: "We need to run the world without consuming the earth."

A complete range

Thanks to the 2013 acquisition of Power-One, the world's second largest inverter manufacturer, ABB now has an installed base of over 18.5 GW of solar energy supplied by over 1.5 million photovoltaic inverters. In addition, the company has installed 66 full power plants delivering more than 1.2 GW of solar power in 14 different countries. ABB has over 350 MW of solar power under full operation and maintenance (O&M) contracts at 55 different sites. With the additional acquisition of Powercorp, the company is delivering leading edge technology for the integration of renewable energy into microgrids.

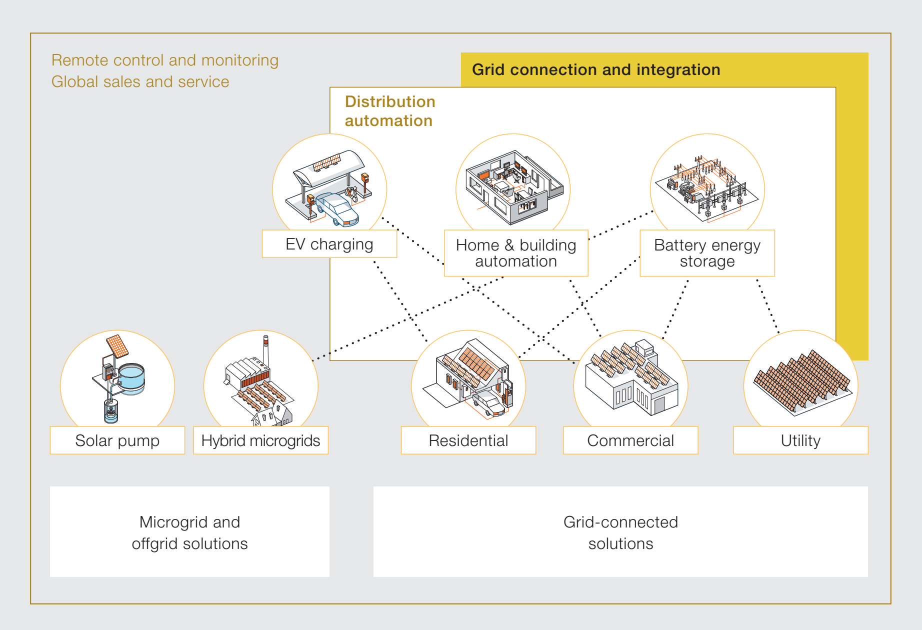
ABB is the only company that provides a complete range of electrical components connecting photovoltaic panels to the grid. The company has a broad portfolio of products, solutions and services that support all three market segments: residential, commercial and utility on a global scale.

For residential and commercial markets, ABB has developed a global low-voltage product portfolio that includes combiner boxes, AC and DC switches and breakers, contactors, fuse disconnects, current sensing, surge protection devices and rapid shutdown, as well as energy meters. The company has a global offering of single-phase and three-phase in-

Footnote

1 Grid parity is understood as the equivalent price per unit of electricity that could be bought from the local utility.

2 ABB offers the most comprehensive value proposition in the solar industry.



verters as well as a wide range of monitoring systems. ABB's portfolio includes storage platforms for the fulfillment of household energy self-sufficiency and independency.

For global utility markets, ABB offers solar inverters; medium- and high-voltage transformers; medium- and high-voltage switchgear with medium-voltage reclosers and vacuum circuit breakers; and substations. The company also offers high-voltage direct current (HVDC) transmission systems for the efficient transmission of power over long distances, and flexible AC transmission systems (FACTS) for reactive power support and active power control. ABB offers a full range of battery energy storage solutions from 25 kW to 70 MW and active voltage regulation devices for medium- and high-voltage applications. In addition to the products and components, the company also delivers full engineering system design, electrical balance of plant and simulation capabilities.

ABB's comprehensive monitoring systems include distribution grid automation, forecasting, load and demand planning solutions. The company offers total life-cycle support at every stage for any solar installation that includes tailored service contracts covering all equipment and solutions. ABB strives to help customers achieve a maximum return on investment through improved capacity, efficiency and reliability.

ABB is also well positioned to address the challenges posed by solar energy as its penetration in energy systems continues to grow. The expanding installed base of distributed generation in the worldwide solar market creates challenges for utilities to maintain stability of the grid. The industry is seeing continued demand to upgrade grid connectivity standards. In addition, improving the stability of grid storage – both at distributed and centralized levels – will become a very important element in the near future.

The company is providing solutions and services that will allow the solar industry to continue to grow and flourish as ABB expands its global reach → 2.

ABB is the only company that provides a complete range of electrical components connecting photovoltaic panels to the grid.

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A place in the sun

Challenges and perspectives for the future of solar

Michael Liebreich, Chairman of the advisory board and founder of Bloomberg New Energy Finance, discusses solar energy with ABB Review.

ABB Review: The concept of deriving electricity from sunlight has been around since Becquerel, but only in the last decade or so has it taken a significant and growing share of the overall energy market. Is this just the beginning? What is driving the ongoing changes?

Michael Liebreich: I started New Energy Finance 11 years ago because I was convinced we were on the brink of a clean energy revolution. One of the main reasons for my confidence was that was that I have an almost religious belief in experience curves. The key clean energy technologies – wind, solar, electric vehicle batteries – are all benefitting from steep experience curves, while conventional energy is limited by resource availability and environmental limits.

Another important game changer has been the very low cost of controls and software. Even if you go back 15 or 20 years, trying to manage a solar farm – or even worse, a set of distributed solar panels on rooftops – would have been hugely expensive. You would have been writing customized communication software and renting dedicated phone lines. Now, of course, all that is Internet based and costs next to nothing.

This progress is not going to stop. Solar power is now seeing costs in the 6 to 8 cents/kWh range for good projects, before any subsidies. The cheapest we have seen is 5.84 cents/kWh on a project announced this year in Dubai. Solar electricity has moved from the era of 50 cents/kWh to 30 cents, to 20 cents, to 10 cents and now below even that.

Just to put those prices into perspective, what are the comparable prices for non-renewable sources?

Let us consider, for example, the United States. The price of electricity from natural gas there is low, around 6 cents/kWh; so at 8 cents/kWh, solar is not quite competitive without subsidies. But apply the investment tax credit and solar can come down to 5 cents/kWh. Solar can also help to manage the demand peak because it is almost ideally timed to meet the needs of air conditioning. But of course you still need to meet your night-time demand, as well as demand when the weather is bad or during the winter.

Experience curves have been a massive driving force in advancing clean energies.

Although we are talking about solar, it is also worth noting that wind energy is seeing unsubsidized prices in the United States at 4 cents/kWh – so cheaper even than gas-produced electricity.

This poses a real challenge for coal. If you've got a fully depreciated coal-fired power station, and you allow it to chuck out whatever pollutants it wants, then you can produce at prices of 3 or 4 cents/kWh. But as soon as you tighten that up, even if you just get rid of the SO_x and NO_x, coal can be 5 to 8 cents/kWh, and that is before you take into account any climate costs. But then, if you include the costs of asthma caused by coal dust and particulates, the cost of mercury, the cost of damage to roads from coal trucks and so on, coal is completely uncompetitive. It's a very bizarre and unstable situation that one-third of the world's energy comes from coal, and yet the writing is absolutely on the wall for the coal sector. In the developed world we are seeing a surge of coal plant retirements, and in the developing world the build rate is dropping away. By 2030 we think we will be seeing net removal of coal generating capacity, rather than additions.

Will the cost of solar power continue to fall, and if so, what are the implications?

The 6 to 8 cents/kWh of today will continue to fall to even lower levels as the industry expands – we think it will hit 4 cents/kWh between 2030 and 2040, but it could be sooner – until we exponentially approach almost free power at the point of generation.

Of course you then have to get all that cheap, clean power to the user – at the exact time it is needed. On a system level there will have to be major changes when you look at the architecture required to integrate wind and solar power. This includes demand management, interconnections and storage. We are seeing the emergence of a completely different type of electricity system, built around flexibility. Frankly it plays to the strength of ABB to build those systems.

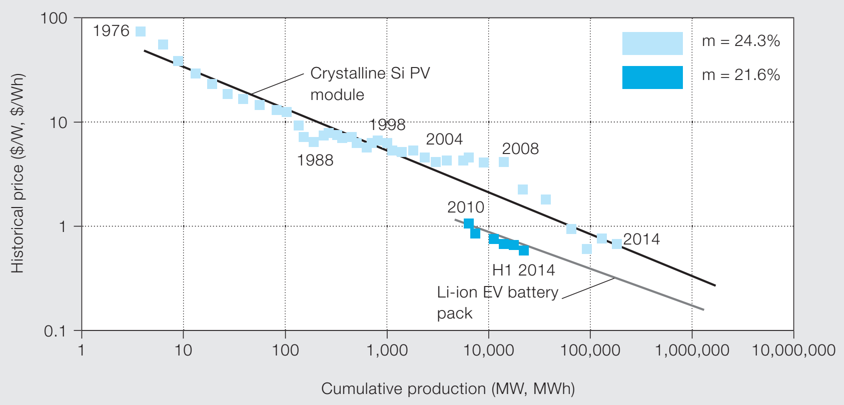
In terms of the total solar power that we can commercially harness, is there an upper limit?

It is very early to talk about hitting a limit as we're still at a very low penetration of solar, less than 1 percent of global electricity. Additionally electricity is only a minority of overall power consumed. There is also transportation and heat, whether in homes, commercial property or industrial processes. Of course electricity as a whole is penetrating these other areas, but it still only accounts for less than one-third of total energy demand. So we are far from any sort of saturation in terms of what the system can absorb.

As the percentage of variable renewable power grows, my working hypothesis is that engineers are incredibly brilliant and there is no fundamental upper limit. If we keep on investing in storage, interconnection between systems and demand management, we can continue adding capacity. For example, everybody is very

The driver for solar investment can no longer be idealism about the environment and the tools to achieve it can no longer be subsidies.

1 Lithium-ion EV battery experience curve compared with solar PV experience curve



Sources: Bloomberg New Energy Finance Note, Maycock, Battery University, MIIT

excited about the concept of storage. They've all discovered that the sun doesn't shine at night and therefore we need batteries. Batteries will go through the same experience curve that solar has seen, but right now they are still costly ➔ 1. So is that bad news for solar?

Well, first of all, there is a lot more electricity demand during the day than during the night. You can match a huge amount of solar power to daytime demand, and in most markets that means building out solar for many more years without having to worry about nighttime. Then, before having to add day-night storage, you can shift demand around, using demand management strategies or even thermal storage. For example, you could chill your freezers and refrigerators during the day when the sun is shining and let them coast through at night.

From the ABB perspective, when looking at cost reductions, there is so much potential that can be unlocked through looking at the whole electricity delivery chain as a system rather than as a collection of individual products. ABB is in the unique position to be able to offer the entire value chain.

Where do you see the major challenges and changes to face solar power in the next decade (both technological and policy)?

The driver can no longer be green idealism and the tools to achieve it can no longer be subsidies. The motivation needs to be improved system performance, in terms of cost, pollution and resilience, and the means have to be more nuanced. The transition to a greater usage of solar electricity has to be acceptable to the pockets of consumers and of industry ➔ 2.

If you look, for example, at the German feed-in tariffs, they sent a very clear signal and were very effective in advancing solar. The problem was that they removed price signals from the electricity market, and thus removed price as a driver of competition for developers and technology providers. What happens in such situations is that people focus on lobbying and winning business through mechanisms other than price competition. And unsurprisingly, that's not an efficient way to do it. Ultimately it costs too much and something has to change. In Spain the reaction to this caused retroactive changes that stopped the market dead in its tracks. Even Germany is shifting to reverse auctions after it became clear high power costs were affecting Germany's competitiveness. Everybody is still very committed to Energiewende (Energy Transition), but the initial feed-in structures are being replaced by something more economically efficient. In the United Kingdom we are introducing a contract for difference (CFD) system requiring reverse auctions – which has already proven to bring the price down.

So government subsidy and support is good at the start-up stage, but should be reduced later?

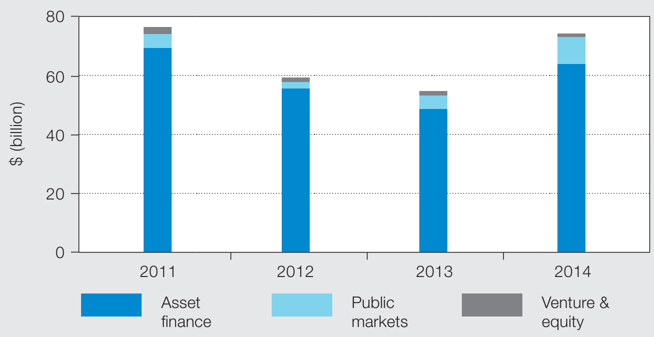
Absolutely. When solar is less than one percent of the electricity market – and I hate to say this – but if you share that extra cost over the rest of the electricity market, then it doesn't hurt much and it doesn't matter. But if solar advances to 3, 5 or even 12 percent, which is easily achievable in sunny countries, then you can no longer afford that level of waste.

As for industry, even if you are in a market with excessive subsidy levels, it's always better to be a low-cost provider: It is the only way you can really control your destiny and not be at the mercy of policy changes.

If governments should not subsidize, what role should they be playing?

Their primary role should be concerned with energy security – making sure that the system doesn't fall over – whether that's because of technical instability or because of geopolitics. After that governments must support where necessary but not beyond. They shouldn't try to force the incumbent energy providers to lead the transition to clean energy (but should let them do it if they want to). They should open up the market to new players and new business models. If you look at Germany, where solar has progressed most rapidly, the big utilities own 80 or 90 percent of gas, coal and nuclear, but only 5 to 10 percent of renewable energy. Why? Because incumbents didn't have the incentive to go in and do it. You see the same in California. The utilities are responding and trying to catch up, but they are only doing it because there is a competitive threat from new players. So governments need to ensure new players have access to the market. An example is the capacity market. If you put into place a capacity mar-

2 Investment in solar power



Source: Bloomberg New Energy Finance

Solar is better and cheaper than kerosene and can charge your phone as well as giving you light.

ket, you need to ensure you are not keeping out new players or solutions, which is very hard.

Are the main challenges facing the solar industry largely universal, or are there significant differences between countries and continents?

Solar is moving beyond its traditional core markets such as Germany, Japan and the United States and into places such as Chile, South Africa, North Africa and Thailand. Solar is now really happening all around the world. As prices are coming down, we are seeing a lot of places – especially in developing countries – that traditionally have high prices for electricity and low supply reliability. Solar is suddenly becoming very attractive and competitive in such markets. This is where the energy access piece comes in. You can easily install solar in locations that were previously off-grid. Solar is better and cheaper than kerosene and can charge your phone as well as giving you light. Solar is an enabler of rural development, especially in countries that were traditionally forced to import fossil fuels using expensive foreign currencies ➔ 3.

What are the main remaining barriers to the further spread of solar energy?

One of these is electricity subsidies. In places like India you are looking at artificially depressed electricity prices of 3, 4 or 5 cents. At that level, you can't recover the costs of building capacity. Another barrier is regulatory, protecting incumbent energy providers and their business models. A third barrier is about the physical limitations on the grid. Are we going to produce too much electricity when it's sunny and not enough when it isn't?

Where do you see the future of solar PV? In distributed rooftop installations, or in large ground-mounted PV power plants?

The answer is both. I don't think we need to prioritize one over the other.

Governments must support where necessary but not beyond.

We will get to the point that we will have a very high penetration of rooftop installations at grid parity. But will that cover all electricity demand? No. The area of solar rooftops is too small to meet all power demand. There will always be a wholesale market for electricity.

With rooftop generation growing nevertheless, we sometimes hear such terms as grid defection – meaning people will seek to become autonomous in terms of energy and remove their grid connection. Is grid defection a threat to utilities?

I'm not a big believer in grid defection. It will happen in some very niche situations such as very remote locations in the Australian Outback or libertarians who want to live by themselves. There are a number of reasons why most users will want to stay connected to the grid.

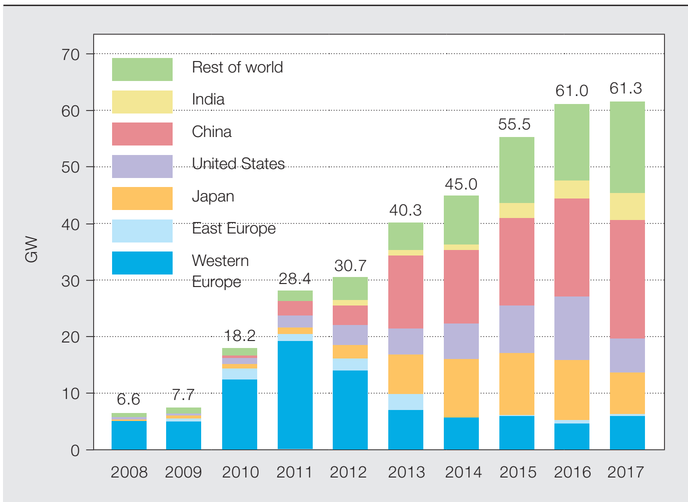
The first is, I have solar panels on my own roof, but when I put the dishwasher and kettle on at the same time, I've got to source that power from somewhere. Retaining the connection to the grid enables me to meet those peaks – as well as those days when there is no sun – more cheaply than investing in huge amounts of storage.

Second, if I have correctly sized the installation to meet my needs during the most demanding time of year, I'm going to be generating a big surplus during the rest of the year. Why not sell it? But for that I still need a wire. Third, what happens if my system fails? The grid can provide backup.

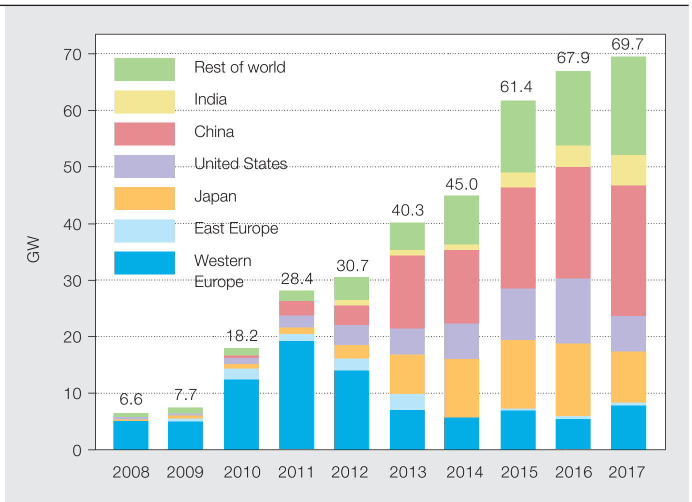
Finally, if you go off grid, your system needs to be a completely self-managed mini-grid, and that's not easy. I want my utility to help me manage it, to tell me when I need to clean my solar panels or maintain my fuel cell, and so on. So even for a well-designed system there are many services ranging from maintenance to supply security that a utility can provide. The utility can charge clients for these services, but not for bulk electricity.

So what we are going to see is load defection, meaning the user buys less power from the utility, both because of energy efficiency and because he or she self-generates power. Utilities will change their business model from charging for electricity to charging for services. If they

3 PV new build per annum



3a PV new build by year, historical and forecast to 2017 (conservative)



3b PV new build by year, historical and forecast to 2017 (optimistic)

Source: Bloomberg New Energy Finance
Note: A conservative and optimistic forecast has been developed for each country. It is unlikely that all countries will come in at the conservative or optimistic end, so for the global forecast, conservative is the sum of conservative country forecasts + 25% of the sum of optimistic-conservative forecasts. Global optimistic forecast is the sum of conservative country forecasts + 75% of the sum of optimistic-conservative forecasts.

don't do this, then yes, you'll see grid defection.

Looking beyond the scope of solar for a moment and considering other renewable energies, be they wind, hydro, biomass, geothermal or even some of the more experimental forms such as wave and tidal power, do you see these as competitors or partners of solar?

They are very much partners. We need to recognize the value of electricity in terms of when it can be delivered. Solar is fairly readily available during the day, but leaves an important supply gap in the evening, meaning you've got to look at what demand it can best meet. Hydro is dispatchable. You might even be able to use pumped storage, but even if you can't, you can collect water in a reservoir during the day and use it during the night, or during a few weeks when there's a wind lull.

Geothermal power is very interesting where you can do it. Biogas is working quite well. Tidal power is very predictable, though expensive. Wave power is at a much earlier stage of its development. I'm skeptical about the ability to drive costs down to levels anywhere close to what we see with solar and wind. You have to put an enormous amount of concrete and steel into the sea for a relatively modest power yield.

Where do you see the main strengths of ABB in serving and advancing solar energy?

It is all about ABB's extraordinary strength in engineering. So first of all we are talking about leading-edge components, ranging from photovoltaic inverters and low-voltage products to high-voltage direct current (HVDC) and communication equipment. ABB has huge technological competence at the product level.

Utilities will change their business model from charging for electricity to charging for services.

Secondly, I see ABB's competence at the system level. Whether you're talking about load balancing, designing a minigrid or providing other system-level services, there are relatively few players out there who are really able to deliver that. For example, startups might be very good at providing one component but will find it very difficult to provide a higher level of knowledge, reassurance and distributed services across a city, grid or multiple grids.

The third element lies in the company's reputation. One of the challenges is that the mainstream – be it the business reader of the Financial Times or the energy ministries of medium-sized countries – is not, on the whole, up-to-date about the technology and its costs. There is a knowledge lag. ABB has an exceptional role to play in reassuring policy makers and decision makers that clean energy is no longer about high-risk pioneering technology, but about robust, resilient, proven solutions.

Which is exactly what ABB Review is about and why we are producing this issue dedicated to solar.

To move on to a less mainstream topic, ABB is supporting Solar Impulse 2, a solar-powered plane attempting to fly around the world. Obviously aviation is not one of the primary fields of application of solar energy, but do you think we will ever see a commercial solar-powered flight?

Obviously solar planes are not going to be a major target market for solar technology any time soon. Solar Impulse is really an exercise in pushing the boundaries of technology and also the boundaries of human thinking by saying to people, "Look, this is possible." And it is doing a great job.

Can it ever work as a commercial offering? Solar Impulse 2 is very slow. It is taking something like 15 hours to fly across

Every generation had to win its energy supply and we had a period where we almost forgot that.

the Gulf of Arabia, 6 days to cross the Pacific. But who knows? Maybe commercial freight flights, possibly configured as a drone or a blimp could take the entire fuel costs out of the shipping equation.

Probably a better way to use solar to power flights would be to use it to create synthetic fuel, either through direct catalysis or from solar-powered electricity. But who knows? Had you looked at telecom companies in 1975, you would never have forecast Facebook, Skype and so on. So I'll rule nothing out.

Another form of transportation in which solar has a more direct part to play is electric vehicles.

I'm very bullish about electric vehicles. As I said earlier, I am a strong believer in the experience curve. Electric-vehicle batteries are seeing the same sort of cost curve as photovoltaics. But having said that, I don't think we're going to be seeing equally rapid penetration in all segments and countries where we now see combustion vehicles. The batteries are a major cost factor and this favors adoption in the sectors seeing the highest annual mileage, but range is an issue. So someone with a long daily commute is going to be a more attractive target than someone using their car either occasionally or for long random journeys to places where you don't know if you can get your battery charged.

Let us conclude this interview with something more philosophical: One interesting consequence of solar power is that normal people are choosing to add PV panels to their own houses and offices. Electricity generation is no longer something that happens in remote locations, of which we as consumers have only a vague awareness, but has become something tangible. Do you think this is changing the way we think about and value energy?

Absolutely. We easily take energy for granted, but actually it has to be won, has to be converted, has to be delivered. Each generation has to secure its energy supply. It looks like as if are coming out of a period in which we could almost forget that fact; everything was so easy.

The new technologies are making us look afresh at how we win our energy, look afresh at our rooftops, our garbage, our insulation and so on. Energy is moving out of our deserts and ports, and into our homes and our communities. I met a chap in India who was selling solar energy to local stalls in a village market. Stallholders could for a few Rupees get an LED lightbulb and a wire back to this chap's battery, which he was recharging every day with his solar panels. The stallholders were happy and the guy had created a good business. It was a fantastic service provision and a fantastic innovation. But actually all he had done was reinvent the electric utility.

It is also accelerating because the new technologies are building on each other. This Indian entrepreneur could only create his business because of the interaction of LED and solar. If he had tried to do it with a filament lightbulb, the solar panel would have been so huge that he wouldn't have fit on his roof. The revolution of solar technology is going to drive the emergence of super-efficient appliances and vice versa. The Clean Energy Ministerial launched the Global Lighting and Energy Access Partnership prize (Global LEAP) for highly efficient appliances, and one of the first winners was a television set that runs on just 6 W. That's less than a lightbulb.

Marshall McLuhan, the philosopher who coined the phrase "the medium is the message," also said "the 'message' of any medium or technology is the change of scale or pace or pattern that it introduces into human affairs." Well, it looks like solar power and these other new technologies carry an incredibly important message for us all.

Thank you for this interview and sharing your enthusiasm with us.

This interview was conducted for ABB Review by Erika Velazquez, Alex Levran and Andreas Moglestue. For inquiries please contact erika.velazquez@ch.abb.com

Michael Liebreich

Michael Liebreich is chairman of the advisory board and founder of Bloomberg New Energy Finance, the world's leading provider of information on clean energy to investors, energy companies and governments. He leads a team of about 200 around the world, just under half of them in London, comprising journalists, researchers, analysts and sales and marketing departments. Michael founded the company as New Energy Finance in 2004, selling it to Bloomberg in 2009.

Michael is a frequent commentator in the press, on TV and on radio on issues of energy, development and economics. He serves on the UN Secretary General's High-Level Group on Sustainable Energy for All and formerly on the World Economic Forum's Global Agenda Council for the New Energy Architecture. He is a Visiting Professor at Imperial College London, Board Member of Transport for London and Chairman of a Medical Charity funding research on colorectal illness.

Michael earned his MA in engineering from Cambridge University, winning the Riccardo Prize for Thermodynamics, and an MBA from Harvard Graduate School of Business, where he was a Harkness Fellow and Baker Scholar.

Michael Liebreich

- Founder and Chairman of the Advisory Board, Bloomberg New Energy Finance
- Advisory Board Member, UN Sustainable Energy for All
- Founder, Finance for Resilience
- Board Member, Transport for London
- Visiting Professor, Imperial College Energy Futures Lab
- Chairman, St Mark's Hospital Foundation

A soaring vision

Propelled only by the sun's energy, the airplane Solar Impulse 2 sets out to demonstrate the promise of alternatives to fossil fuel

ERIKA VELAZQUEZ – The attempted around-the-world journey of a solar-powered plane is pushing the boundaries of energy management and conversion. To demonstrate the enormous potential of renewable energy and pioneering spirit, Swiss aviators Bertrand Piccard and André Borschberg have built the first-ever aircraft capable of using only solar energy to fly both day and night, thus able to cross continents and oceans. As a global leader for supplying technologies to enable energy efficiency, sustainable transportation and renewable energy, ABB was a natural choice to form an innovation and technology alliance with the Solar Impulse project. ABB brings its technical expertise to this attempted flight around the world, which uses only energy supplied by a plane's solar panels and onboard battery systems. ABB engineers have overseen a multitude of technical challenges that include improving control systems for ground operations, component testing, enhancing the battery systems and troubleshooting throughout the journey.

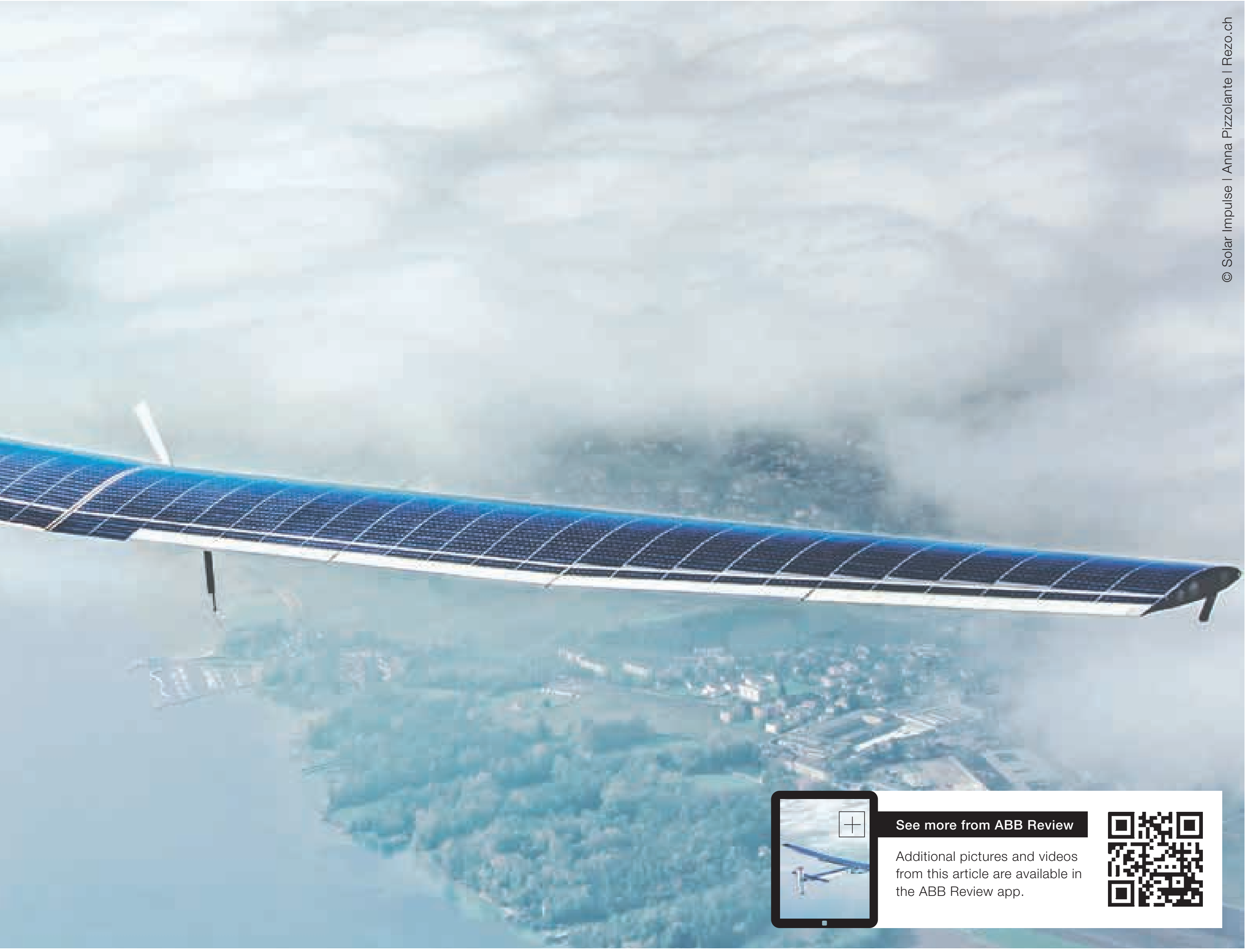


ABB and Solar Impulse formed their alliance to advance a shared vision of decoupling economic growth from environmental impact by increasing the use of renewable energy.

Borschberg and Piccard have been flying increasingly ambitious solar-powered missions to draw attention to the possibilities for clean energy. In 2013, they made a record-setting journey across the United States, from California to New York, using their first ultralight aircraft Solar Impulse 1. The plane, which had a cruising speed of about 53 km/h, also completed a 26-hour overnight flight in 2010, and flew from Switzerland to Morocco in 2012.

Title picture
Solar Impulse 2 flying over Switzerland during a test flight

The pilots unveiled Solar Impulse 2 in April 2014. On its debut flight in Switzerland in June 2014, the plane reached a maximum altitude of 1,680 m and flew at an average ground speed of 55.6 km/h.

The cooperation and exchange of expertise and experience between ABB's engineers and the Solar Impulse team has enabled a unique opportunity to showcase renewable energy.

The new carbon-fiber plane is covered in 17,248 solar cells that provide clean energy to the aircraft's four electric motors → 1–2.

During the day the solar cells recharge four lithium batteries, thus assuring a steady stream of power for nonstop flight day and night.

The latest journey

Solar Impulse 2 began its attempted 35,000 km journey around the world in March 2015 in Abu Dhabi. By the time the mission is set to conclude in Abu Dhabi in July 2015, the plane will have made 12 stops – in Oman, India, Myanmar, China, the United States, and either North Africa or Europe → 3.

Flying at speeds between 50 and 100 km/h, the journey is anticipated to take 500 hours flight time, over the

1 Solar Impulse 2 at a glance

The plane's external dimensions feature a length of 21.85 m, a height of 6.4 m and a wingspan of 72 m. The wingspan, wider than a Boeing 747 jumbo jet, minimizes induced drag and provides a maximum surface area for solar cells.

The frame of Solar Impulse 2 is constructed with lightweight, thin materials, such as carbon fiber and honeycomb sandwich panels that reduce the weight of a carbon layer from 80 g/m² to 25 g/m², only one-third as much as a sheet of printer paper.

The plane's upper wing surface is covered with high-efficiency solar cells and the lower surface is constructed with a high-strength, flexible skin, an innovation borrowed from techniques developed by sail makers for racing boats competing for the America's Cup. The 140 carbon-fiber ribs are spaced at 50 cm intervals to give the wing its aerodynamic cross section and also maintain its rigidity. The aircraft features 17,248 monocrystalline silicon solar cells, each 135 µm thick and mounted on the wings, fuselage and horizontal tailplane, providing the best compromise between lightness, flexibility and efficiency.

Energy gained from the solar cells is stored in lithium polymer batteries optimized to have a density of 260 Wh/kg.

The batteries are insulated by high-density foam and mounted in the four engine nacelles, with a system to control charging thresholds and temperature. Their total mass amounts to 633 kg or just over one-quarter of the aircraft's all-up weight.

The aircraft is equipped with four brushless, sensorless motors, each generating 13 kW (17.4 hp), mounted below the wings and fitted with a reduction gear limiting the rotation speed of a 4 m diameter, two-bladed propeller to 525 rpm. The entire system is 94 percent efficient, setting a record for energy efficiency.

The plane climbs to 8,500 m during the day to gather as much sun energy as possible, and descends to 1,500 m at night in order to conserve energy, coasting more like a glider, and therefore using much less stored energy from the batteries than it would if it would keep a constant altitude.

The aircraft flies at an average speed of 70 km/h, with a takeoff speed of 44 km/h and has a maximum cruising altitude of 8,500 m. Minimum speed is 36 km/h at sea level and 57 km/h at maximum altitude. Maximum speed is 90 km/h at sea level and 140 km/h at maximum altitude.

course of five months, crossing four continents and two oceans.

Engineering

ABB's engineers were able to bring specific know-how to the project in areas such as testing procedures and protocols as well as specific knowledge of power electronics and cooling. Component testing was done for functionality, temperature and pressure performance.

One responsibility of the ABB engineers on the project was to improve the control system for Solar Impulse's balloon-like mobile hangar, which is used to house the plane during unscheduled landings or if a local airport cannot host the plane. The mobile hangar is an inflatable structure made specifically for the plane, consisting of several modules that are then connected together and dragged over the plane → 4. Each module has a double layer of fabric with ABB fans in between that inflate the hangar.

Increased reliability was achieved by incorporating ABB relays and circuit breakers into the existing system. The system was made redundant with a switchover unit that is connected to an alternative power supply. An upgrade was made in current measuring relays that activate an alarm in the event of a failure of any of the fans.

The ABB engineers also developed the cockpit battery charger that is used to charge an additional small lithium battery located behind the pilot. The cockpit battery is used as an emergency power supply for the plane's avionics and powers the essential electronic devices (navigation, communication, etc.) in case of electric power loss in the plane. This important battery is also charged exclusively with sun power as well, before and during the flight, and kept at a 100 percent charge over the long flight segments. If the plane is ever left without solar power for the motors, the cockpit battery enables communication and navigation, and all the electronics that help fly the plane, as the plane can glide for a long time after the engines are disabled.

Increased reliability was achieved by incorporating ABB relays and circuit breakers into the existing system.

ABB engineers were also involved in testing the plane's electrical system, including certain aspects of the plane's battery management system and maximum power point tracking (MPPT) devices that reap as much power as possible regardless of atmospheric conditions from the collection of solar cells forming a solar skin over the plane's wings.

The plane's eight MPPT devices are critical, since failure of just one during certain legs of the flight – for example, the five-day, nonstop flight between China and Hawaii – would make it impossible to charge batteries enough during daylight while running the motors sufficiently to reach maximum altitude.

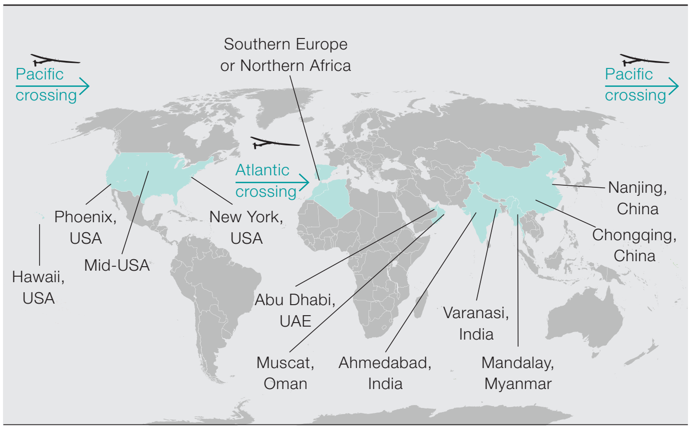
Functional component testing to ensure that all devices are fully operational before installation was a crucial aspect of the ABB engineers' involvement. For example, the plane's warning panel, which monitors all devices for faults and triggers the annunciator panel and enables the alarms to warn the pilot when there is an issue with an onboard device, is made up of over 1,000 components.

Initial testing showed that the board was too sensitive to the relays' mechanical bounces. Follow-up debugging of the circuit required four days of work on the annunciator panel (from the entire electrical and propulsion team). Only after a stable solution was designed, manufactured, and retested was the device mounted on the plane. A working alarm system is absolutely critical because it needs to alert the pilot, who then might have only 10 seconds to react to save either his life or the mission. Testing was also conducted on the pilot monitoring devices that measure pulse and oxygen level.

The last project undertaken was designing a media system that enhanced the direct recording from the onboard cam-

2 Solar Impulse 2 is equipped with four brushless, sensorless motors mounted below the wings.

3 Flight plan of Solar Impulse 2's intended around-the-world journey



4 Solar Impulse 2's mobile hangar can be used to house the plane during unscheduled landings.

era to high-quality 1080p. This project required the integration and interfacing of a number of components as well as cooling the media system adequately.

A true partnership

The cooperation and exchange of expertise and experience between ABB's engineers and the Solar Impulse team has enabled a unique opportunity to showcase renewable energy.

"The flight will test technology and human ingenuity to the limit, and that's another important reason why ABB is part of this adventure – because we are constantly pushing the boundaries of technology and ingenuity to serve our customers while minimizing environmental impact," says Ulrich Spiesshofer, ABB's CEO. "While our groundbreaking innovations and technologies tend to be hidden behind walls, buried underground, or located deep under the sea, Solar Impulse is literally a flying ambassador for technological innovation and its potential to improve the world."

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Balancing act

Microgrid optimization control stabilizes production in solar and hybrid microgrids

CELINE MAHIEUX, ALEXANDRE OUDALOV – Traditionally, remote, off-grid microgrids have relied on diesel generators to produce electricity. Diesel oil is usually delivered by conventional land or sea transport, which results in transportation costs and a higher cost of electricity for end consumers. But with the environmental benefits and increasing cost-competitiveness of renewable energy, it is now more and more common to find solar photovoltaic and wind power integrated with diesel generators to form a hybrid microgrid. Energy storage devices such as flywheels and lithium-ion battery systems may also be included. Accommodating fluctuations in photovoltaic production and coordinating the operation of the diesel generators, feeder loads, energy storage and grid stabilization devices in response to these fluctuations is a tricky task that requires an advanced control system.

1 What is a microgrid?

A microgrid is a smaller version of a larger (macro) power grid. It is a collection of power generation sources, loads and energy storage devices that operate as a single unit and are kept in balance by a control system. Some types of microgrids are connected to the surrounding power (macro) grid; in addition to generating their own power, microgrids can also receive power from, or transfer power to, the main grid. Other types of microgrids are self-sufficient – they are "off grid" or "islanded" and have to generate their own power.

Microgrids are suitable for a wide variety of different applications. They are the obvious solution for islands like the Azores or Canaries and for communities in remote locations like the Australian outback, as well as for research stations in far-off places like the Antarctic. Military bases, university campuses, mines, onshore oil and gas fields, theme parks and tourist resorts are other typical applications, as are rural electrification programs in countries lacking power.

It is becoming increasingly common for traditional off-grid microgrid generators – usually powered by diesel oil – to be supplemented by one or more solar power plants and a number of wind turbines → 1–2. The microgrid might also include energy storage devices like flywheels and lithium-ion battery systems. Flywheels can provide instantaneous power to the microgrid to counteract variations in output caused by passing clouds or sudden changes in wind speed. Battery systems store energy in larger amounts and over longer periods to handle energy time shifts. They can store solar energy produced during the day when demand is low and release it in the evening when demand is high.

The challenge of integrating solar photovoltaics (PV) with diesel generators has two aspects: handling fluctuations in the photovoltaic production level, and coordinating the operation of the diesel generators, feeder loads, energy storage and grid stabilization devices in response to these fluctuations. This requires an advanced control system that can connect and disconnect generators and loads, provide set points to generators and charge or discharge the flywheel or battery system. By doing this, the control system will maintain maximum PV penetration, reduce operating costs and keep the microgrid stable.

ABB microgrid solution

ABB's Microgrid Plus System™ is a distributed control platform that automates and manages microgrids that consist of fossil-fueled generators and renewable energy generation from one or more sources. It also integrates other micro- grid components such as energy storage and grid stabilization systems, and distribution feeders. Further, it connects and communicates with the adjoining power grid, if there is one → 3–4.

The Microgrid Plus System is designed to work with ABB's other microgrid product – the PowerStore™ flywheel-based or battery-based grid stabilization and energy storage system. Together, these two technologies calculate the most economical microgrid configuration that achieves a proper balance of supply and demand – one that maximizes renewable penetration (up to 100 percent), reduces the operating cost and maintains the highest level of power quality, grid stability and reliability of power supply.

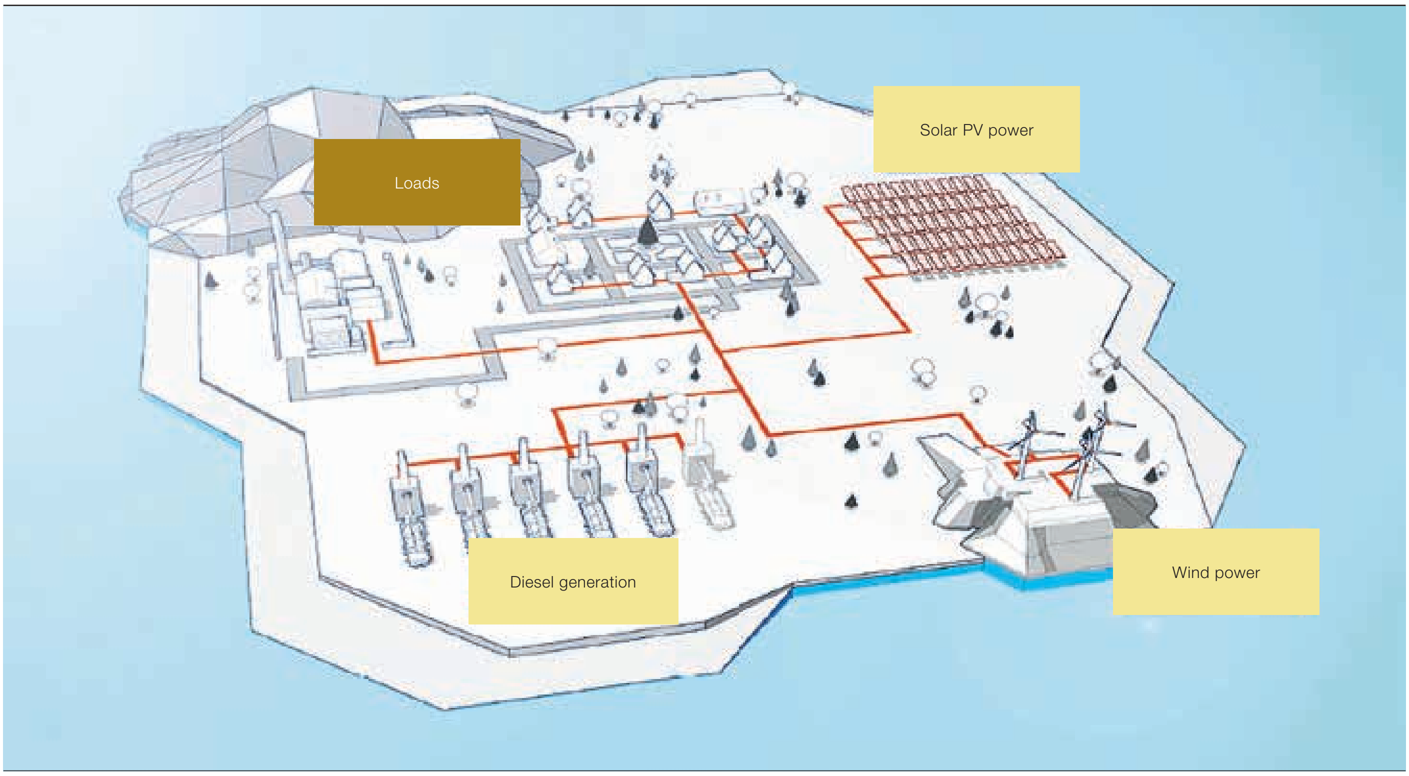
ABB's MGC600 controllers are the building blocks of the Microgrid Plus System. They enable communication between all the electrical devices in the microgrid and use the data communicated by the devices to make local decisions that work cohesively for the benefit of the whole microgrid. The range of MGC600 controllers is comprehensive in scope and uses a common hardware platform that runs different types of firmware according to the electrical device concerned → 5.

It is becoming increasingly common for traditional off-grid microgrid generators to be supplemented by solar power plants, wind turbines and energy storage devices like flywheels and lithium-ion battery systems.

These firmware packages contain the core control logic of the MGC600. They work in harmony with one another within the Microgrid Plus System. For instance, the PV control and monitoring system (MGC600-P) schedules and controls the PV plant in conjunction with the controllers that control the diesel generators (MGC600-G) and energy storage system (MGC600-E).

Title picture
Microgrids may comprise a mixture of diesel generators, solar power, wind turbines, battery or flywheel storage units and the electrical devices to connect them all together. How can such a disparate collection of equipment be effectively controlled and coordinated? Shown are the PV panels, and diesel and flywheel containers at Marble Bar, Western Australia.

2 A typical microgrid



Comprehensive functionality

The MGC600 has a number of unique features and benefits that improve the availability of the microgrid and reduce its consumption of fossil fuel by maximizing the penetration of renewable energy generation:

- Automatic starting and stopping of the PV generator
- Active power limitation based on the generator's optimal load
- Active power limitation based on system step load
- PV generator control for islanded mode or grid connection
- Active power limitation sharing between multiple PV generators

The MGC600-P monitors and controls the PV generator either with a PV plant controller or with an inverter. It provides manufacturer-independent control and monitoring to allow different makes of inverters and plant controllers to be integrated into the microgrid system. For low- and medium-penetration systems (ie, those without storage and stabilization devices), the MGC600-P monitors the power output of the fossil fuel generators via an MGC600-G controller. Based on the load levels of the fossil fuel generators, the MGC600-P determines whether the power limitation set point of the PV plant should be increased or decreased. This enables the fossil fuel generators to run at their optimal load, while ensuring that the maximum amount of renewable energy is utilized.

Control strategy examples

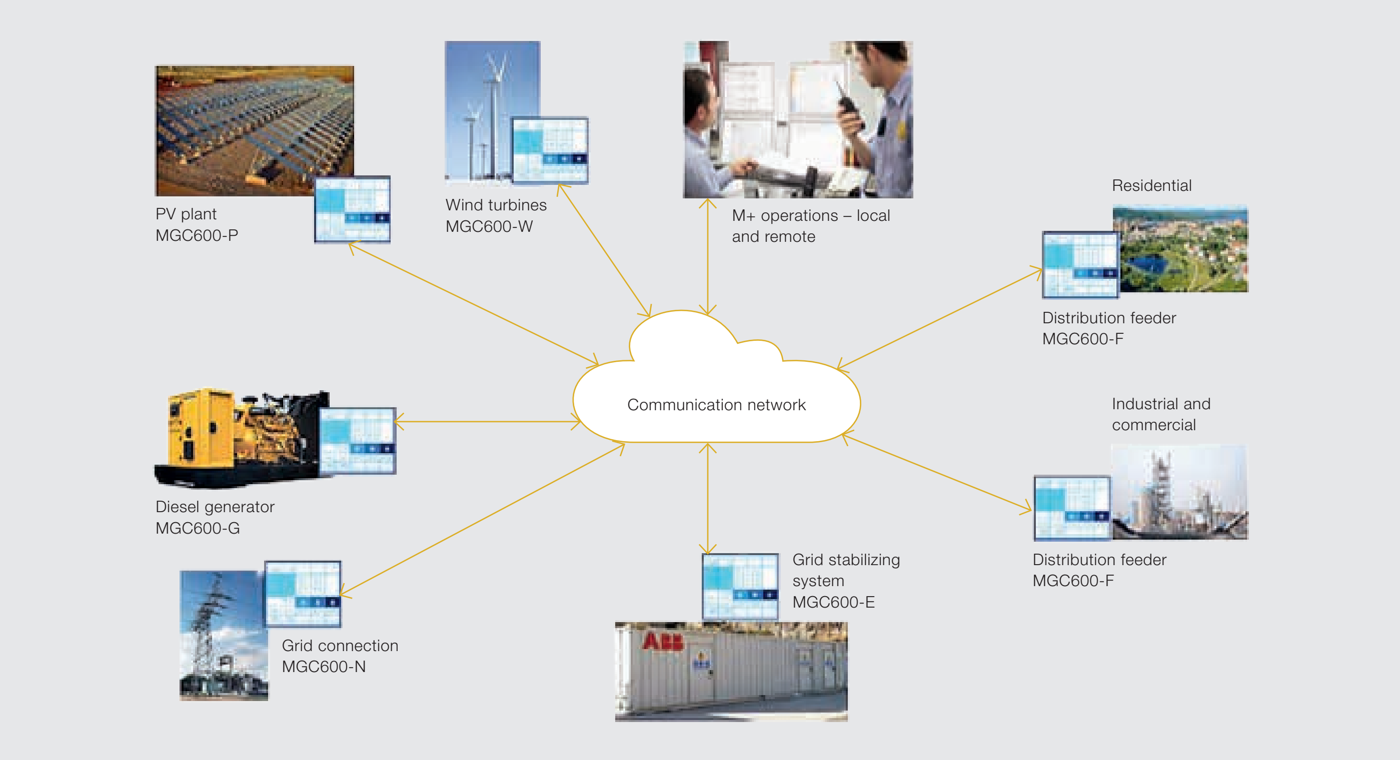
The Microgrid Plus System has a long and successful record of operating in various types of microgrids. The following two theoretical case studies illustrate how different levels of solar PV penetration require different control strategies. These, in turn, necessitate a control system that has the flexibility and functionality to accommodate different control strategies and to integrate varying levels of renewable energy.

In the first case study, the microgrid owner wants to reduce exposure to diesel price volatility and the high cost of running the microgrid on fossil fuel. A PV power plant has been integrated into the microgrid; it has the capacity to cover almost 100 percent of instantaneous grid demand at maximum production. However, because solar PV is intermittent in nature, the diesel generator must run in parallel to the PV plant to provide system frequency and voltage references. In this particular case the increased generation of solar PV could drive diesel generator output to a very low level. Diesel generator suppliers usually advise that the generator should not operate below 20 to 30 percent of its nominal capacity for more than a few hours, as doing so may damage the engine. Load sharing coordination between the solar PV system and diesel generator is, therefore, necessary.

An advanced control system that can connect and disconnect generators and loads, provide set points to generators and charge or discharge the flywheel or battery system is needed.

In a Microgrid Plus solution, both the PV system and the diesel generator are equipped with MGC600 controllers: the MGC600-P for the PV system and the MGC600-G for the generator. These two

3 The Microgrid Plus System with MGC controllers operations and PowerStore example



sets of controllers exchange information with each other in real time. Based on the load levels of the fossil fuel generators, the MGC600-P automatically adjusts the set point and enables the generators to run at their optimal load, while ensuring the maximum amount of renewable energy is utilized by the microgrid.

If the microgrid connects to a larger power grid, the grid operator may not accept reverse power flow, ie, not allow power from the microgrid to be transferred into the transmission or distribution network. In this case the microgrid will most probably run with the diesel generator switched off. The MGC600-P controller that controls the solar PV plant will coordinate a power infeed from the main power grid with an MGC600-N controller at the point of common coupling.

In the second case study, the production capacity of solar PV in the microgrid is substantial and exceeds demand during the peak production hours. However, solar PV peak production and local load peaks do not always occur at the same time. The evening peak, when demand is usually the highest, does not coincide with PV production, which occurs during daylight. The solution to this quandary is to store some of the PV energy produced during the day for use during the evening when the PV plant has stopped production. This can be done with a lithium-ion battery system. The cost of these has fallen significantly in recent years and many different studies and manufacturers' data forecast further cost reductions in the near future.

The addition of an energy storage system to the microgrid means that the microgrid control system now has an additional component to manage. This is not a difficulty for the distributed control concept of the Microgrid Plus System: It is easy to install a dedicated MGC600-E controller for the energy storage system that exchanges information with the other controllers in the Microgrid Plus System. The MGC600-E controller continuously informs the other controllers about its status and the battery state of charge and state of health, while receiving critical operational information from the diesel generator, solar PV and network controllers.

Stable operation with PowerStore

ABB's PowerStore is a compact and versatile flywheel-based stabilizing generator that reduces instabilities in microgrids or weak grids due to fluctuations in solar PV power output caused by passing clouds. It is able to operate in a grid support mode for large networks or in virtual generator mode for isolated microgrids.

> ABB's Microgrid Plus System is a distributed control platform that automates and manages microgrids that consist of fossil-fueled generators and renewable energy generation from one or more sources.

The Microgrid Plus System also integrates energy storage and grid stabilization systems, and distribution feeders. Further, it can connect and communicate with the adjoining power grid.

4 ABB's microgrid expertise

ABB offers turnkey solutions for, and has references for, all types of microgrid requirements: Greenfield hybrid power plants consisting of renewable and diesel power generation; the integration of renewable energy generation with an existing fuel-based microgrid; optimizing the performance of an unstable microgrid that combines renewable energy and fossil fuel generation; stabilizing the connection of an existing renewable energy plant to a weak power grid; and power grid stabilization.

ABB has 25 years of experience developing microgrid technologies and has delivered more than 80 microgrid solutions worldwide – more than any other supplier.

5 The MGC600 controller range uses a common hardware platform that runs different types of firmware according to the electrical device concerned.

Firmware/controller	Description
Diesel generator (MGC600-G)	Controls, monitors and interfaces with diesel generators
Distribution feeder (MGC600-F)	Controls, monitors and interfaces with feeders and their protection relays
Photovoltaic solar (MGC600-P)	Controls, monitors and interfaces with solar array inverters
Single/multiple load (MGC600-L)	Controls, monitors and interfaces with large loads like crushers, boilers, etc.
Energy storage system (MGC600-E)	Controls, monitors and interfaces with battery-based ABB PowerStore
Network connection of microgrid (MGC600-N)	Controls, monitors and interfaces with other microgrids or larger grids
Wind turbine (MGC600-W)	Controls, monitors and interfaces with wind turbines

→ 6 shows how stable power output is ensured by a quick power injection and the efficient absorption capability of PowerStore. The power fluctuations are caused by variations in solar PV generator output due to passing clouds. Two diesel generators ("Gen 2" and "Gen 4") are involved in power balancing but the speed of the solar PV output variation causes stress to their prime movers, which results in faster wearing and more maintenance. PowerStore intervenes precisely during these short variations and helps the diesel generators ramp up and down in a sparing mode.

In addition, → 6 illustrates how MGC600 controllers coordinate their actions. For instance, Gen 2 is switched on and off by the MGC600-G controller in accordance with PowerStore's state of charge and power output, which is reported by the MGC600-P. In other words, when repetitive solar PV fluctuations are detected and PowerStore's state of charge is getting low after assisting Gen 4 (green curve), Gen 2 is switched on. Then both generators share the power balancing control while PowerStore is recharging.

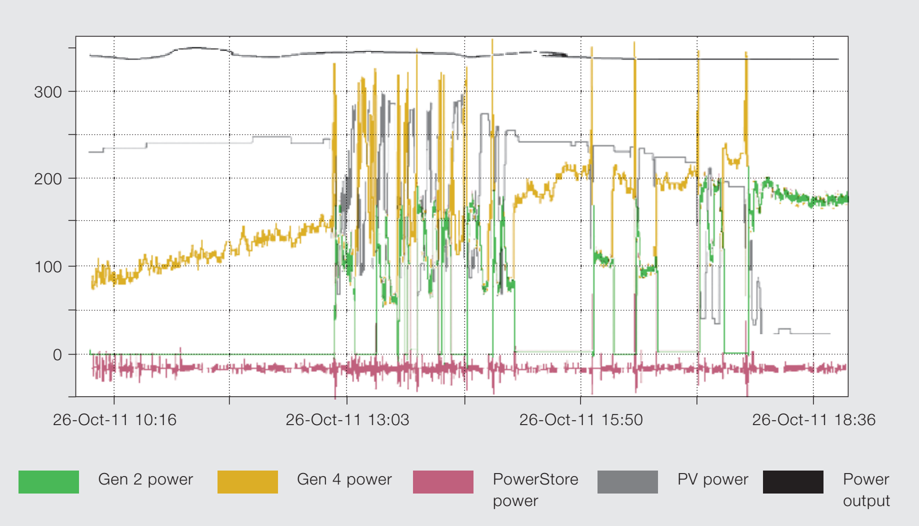
Advanced control functions

Several advanced control functions are included in ABB's microgrid optimization products.

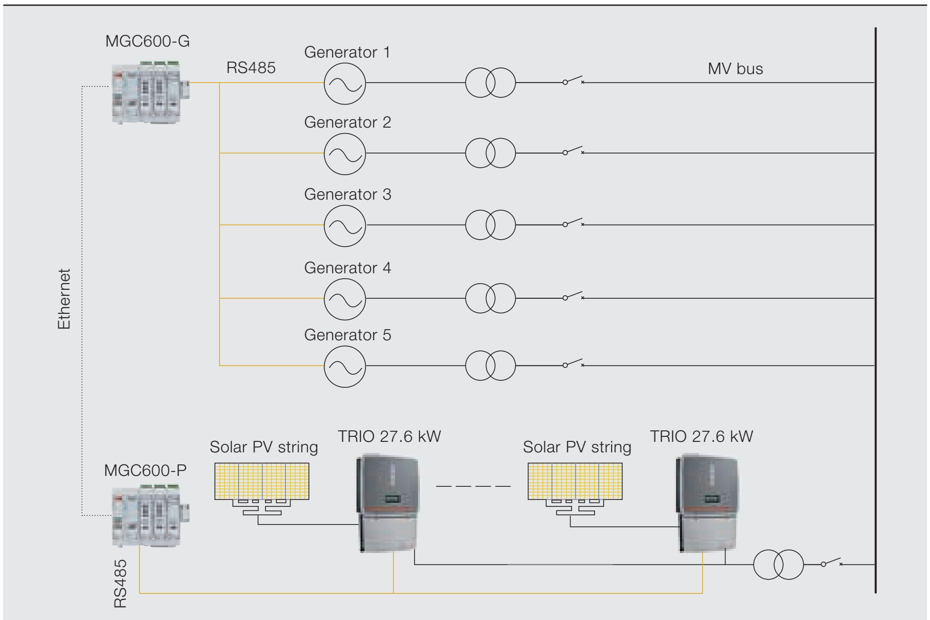
Cloud tracking

In order to guarantee the stable and economic operation of a microgrid with a high penetration of solar PV, ABB has developed algorithms that track the movement of clouds in the vicinity of the microgrid. The algorithms predict the time of arrival and duration of cloud cover over the PV plant, and calculate the expected fall and subsequent rise in output (ramp rates). Very large ramp rates of solar PV can cause instability if they exceed the ramp rate capability of the diesel generator. Accurate short-term prediction of solar PV ramp rates will allow a proactive control action and reduce the effects of disturbance. If there is not enough energy stored in the battery system to cover the shortfall in PV production, a single generator or several generators can be scheduled in advance for start-up. If production shortfalls are long, then an optimal amount of energy could even be purchased from the market (for grid-tied microgrids) during low-cost tariff hours, stored in the battery system

6 Power generation profiles in an isolated microgrid



7 ABB's low-cost and low-complexity control concept to save fuel in PV/diesel microgrids



PowerStore is a compact and versatile stabilizing generator that reduces instabilities in microgrids or weak grids due to fluctuations in solar PV power output caused by passing clouds.

MGC600 controllers are the building blocks of the Microgrid Plus System.

and then released during the day to meet contracted quotas.

Hybrid energy storage

A hybrid energy storage system made up of various energy storage technologies with different characteristics (cycle life, response speed, efficiency, cost and so on) can potentially help integrate larger-scale solar PV at a lower total cost than if the technologies were deployed separately. ABB is analyzing the advantages and disadvantages of such a system and is developing control solutions for it.

Diesel fuel-saving solution

ABB is developing a low-cost and low-complexity control solution to save fuel in PV/diesel microgrids with a capacity ranging from a few hundred kilowatts up to a couple of megawatts. One MGC600-G controller will coordinate several small-scale diesel generators and a single MGC600-P controller will manage several small-scale solar PV inverters → 7.

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A bright future

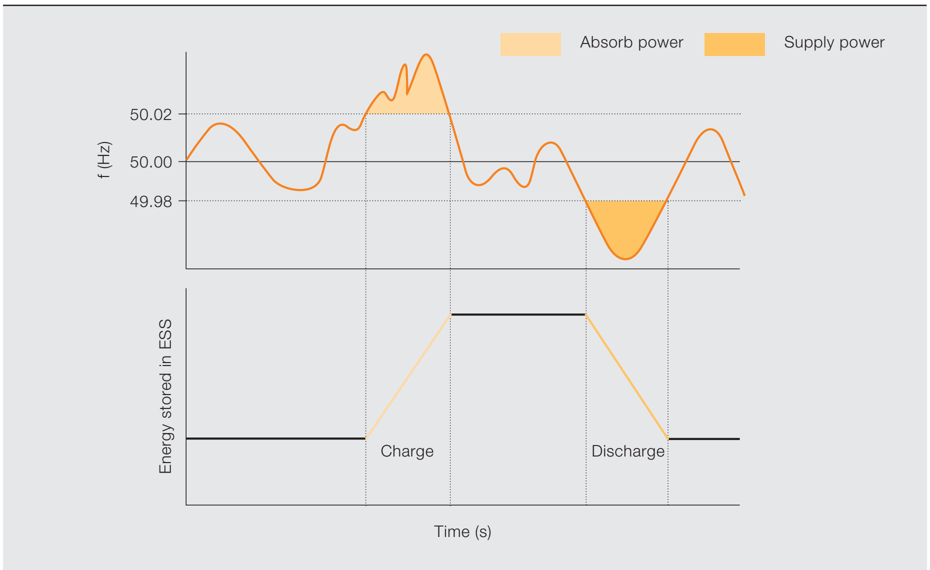
Energy storage transforms the solar paradigm

PAOLO CASINI, DARIO CICIO – The amount of solar radiation that reaches the Earth's surface is more than enough to supply the world's total energy needs. However, matching the intermittent availability of this energy source with demand can present a challenge, especially in the early morning and evening hours when solar energy sources do not produce enough power to meet demand. This challenge can be overcome by energy storage: Coupling solar energy sources with energy storage can eliminate the unpredictable nature of solar power, transforming it into a highly controllable and easily dispatchable source of power. From distributed storage systems to large centralized solutions, ABB has the domain know-how and energy storage solutions needed to enable precise control and connection of solar power installations.

Title picture
The energy the Earth receives from the sun is more than enough to meet the world's power needs. But how can this energy be stored so power needs can be met when the sun is not shining?

Placing energy storage adjacent to the solar PV systems enables precise control over when and how much power will dispatched on to the network.

1 Frequency regulation mode



Strategically placed, local solar power generators not only reduce greenhouse gas emissions, but they also enhance grid reliability and security: Placing smaller, distributed generation sources close to the load makes the grid more resilient against outages and power quality disruptions, which benefits both local utilities and end users. There are economic benefits to be had too if the consumer can generate and consume his own power and thus avoid utility charges.

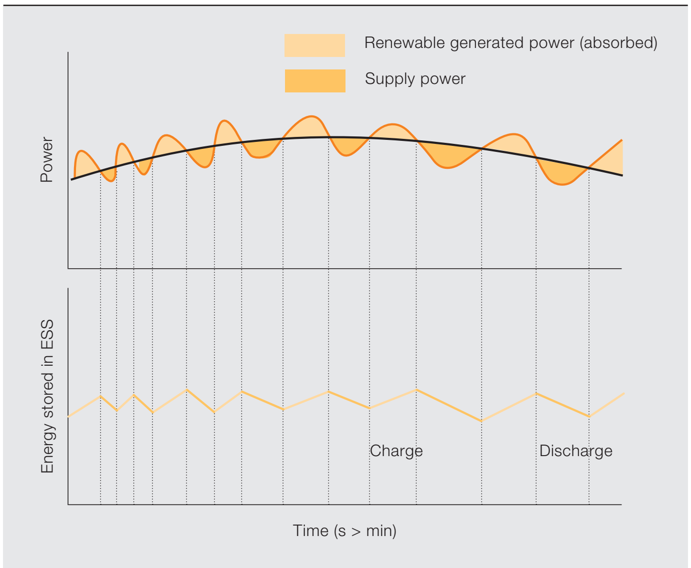
However, in order to fully realize the potential and value of solar power, its intermittent nature must somehow be overcome. One major tool for doing this is the energy storage system (ESS). Placing energy storage adjacent to the solar photovoltaic (PV) systems enables precise control over when and how much power will be dispatched on to the network. Energy storage can also enable smooth power output, which improves power quality for the end users. Further, an ESS allows for more efficient use of the power generated from the distributed solar plants.

PV energy storage helps save even more by making the solar PV plant a reliable source of power when the customer's usage is at its highest. At these times, energy that was stored by the ESS during low demand periods can be used, thus avoiding hefty peak demand charges.

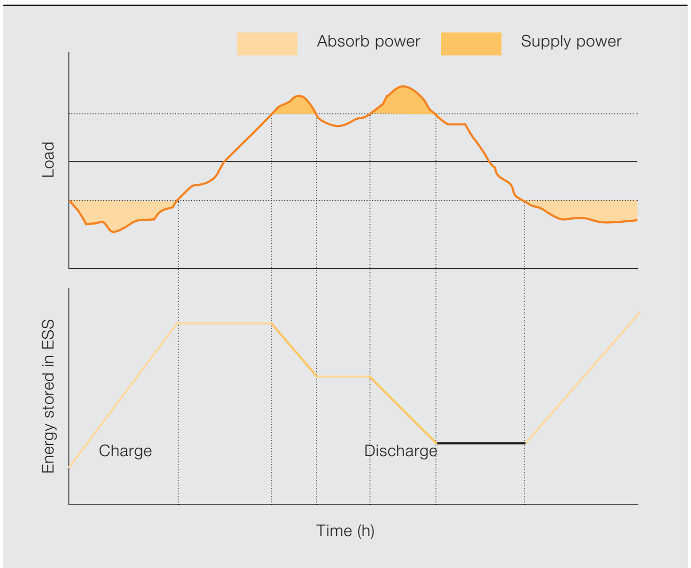
ABB's community storage solutions are designed for all these cases and can be used in applications ranging from 25 kW to multi-megawatts. For example, ABB's integrated energy storage module (ESM) comprises a transformer, low- and medium-voltage switchgear, and automation equipment such as inverters. This unique design provides a quick, simple installation with a high level of safety for the equipment and operators. The choice of

Coupling energy storage with utility-scale solar PV allows the unpredictable and variable solar plant to become an easily controllable resource that can be dispatched to provide second-by-second frequency regulation in real time.

2 Capacity firming mode



3 Load-shifting mode



which lithium-ion battery technology to use in a particular ESM is based on the application's specific requirements.

Utility-scale solar energy

The increasing demand for power sources that emit less carbon and are more sustainable is driving utility-scale solar power generation growth at an unprecedented rate. However, the electrical grid was designed to deliver a planned and stable supply of power from centrally located power sources, via the transmission and distribution lines, to end users. Engineers carefully plan and constantly recalibrate the grid to ensure that power is available where it is needed at the precise moment it is needed. Adding energy sources that are variable, intermittent and distributed throughout the transmission and distribution network requires significant additional control and precision to make sure demand and supply are aligned.

ESS for frequency regulation

System operators often use large-scale generation facilities to not only provide bulk power to the end users, but also to provide the ancillary services needed to maintain the integrity of the electrical grid. One of the more pertinent of these services is real-time frequency regulation. Around the world, the electrical grid needs to operate at either 50 or 60 Hz in order to ensure the facilities and critical equipment used in manufacturing are properly powered. This requires instant and continuous balancing of electricity supply with demand. This is difficult enough to do with traditional, predictable and easily dispatchable generators, but the task becomes extremely complex indeed when solar sources, with their inherent variability, are added to the mix.

Further, as more utility-scale solar plants are brought online and more coal-based plants shut down, the easily controllable resources that provide such grid services become fewer. However, coupling energy storage with utility-scale PV allows the unpredictable and variable solar plant to also become a more easily controllable resource that can be dispatched to provide second-by-second frequency regulation in real time. When used in combination with solar, the ESS is charged or discharged in response to an increase or decrease of grid frequency → 1. This approach to frequency regulation is a particularly attractive option due to its rapid response time and emission-free operation.

ESS for capacity firming and ramping support

In order to maintain the integrity of the electrical grid and ensure power quality, voltage and frequency must constantly be kept at specified levels. However, with utility-scale PV plants, the ability to maintain these levels can be quickly compromised by the passing of clouds, an abrupt change in the weather or a crack in a solar PV panel. These variations can cause rapid fluctuation of the PV power output – resulting in deviations in frequency and voltage. Even a second of cloud coverage can cause the voltage to drop, de-

By quickly absorbing or injecting power in response to grid control signals, the ESS can ensure that the correct frequency and voltage levels are maintained.

4 ABB's EssPro PCS container and cabinet enclosure configurations

stabilizing the local network. The sudden drop in voltage and power can also cause deviations in frequency levels, disrupting the overall operating characteristics of the grid. By quickly absorbing or injecting power in response to grid control signals, the ESS can ensure that the correct frequency and voltage levels are maintained ➔ 2. Not only can energy storage provide this capacity firming for the PV system, but it can also make sure that the PV power output increases and decreases at a rate specified by the grid operators to ensure that the PV plant abides by local grid codes.

By coupling solar power with energy storage, the ESS can charge when generation is higher than demand and discharge when demand begins to spike, yet the sun is setting.

ESS helps network reliability through load shifting

In areas with a high penetration of solar generation, the local utility network is susceptible to resource adequacy issues when demand and PV generation are out of balance – specifically, in the early morning and evening hours when demand begins to increase but solar sources are not producing enough power to accommodate this demand. This is where energy storage can help the system operator maintain grid integrity through load-shifting capabilities. By coupling solar power with energy storage, the ESS can charge when generation is higher than demand and discharge when demand begins to spike, yet the sun is setting ➔ 3.

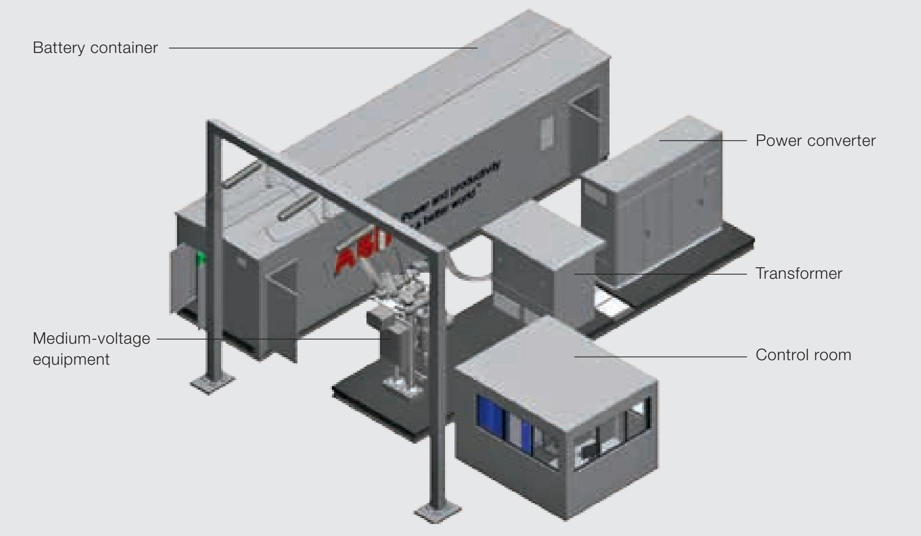
ESS for utility-scale solar performance improvement

Strategically placed ESSs can increase operational performance and grid reliability, and better integrate utility-scale solar generation. From power conversion systems (PCSs) to fully integrated and turnkey battery ESSs, ABB's EssPro™ energy storage solutions help to ensure the high performance of solar plants and to maintain grid reliability and efficiency ➔ 4.

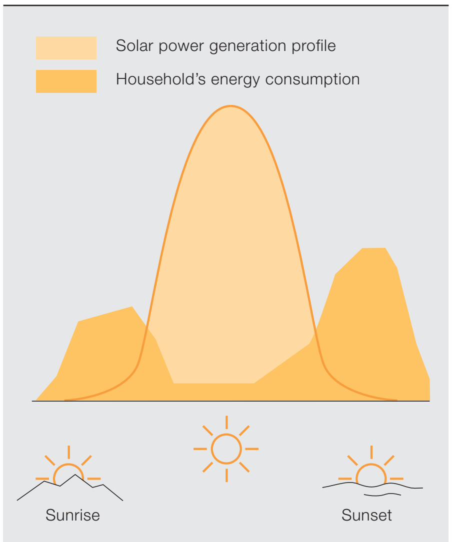
ABB's EssPro PCS links the ESS's battery to the electrical grid and converts the stored energy from DC to AC that is compatible with the utility network. In addition to the conversion technology, the system also provides the controls needed to help maximize the PV plant's operational performance.

ABB's EssPro Grid integrated, turnkey ESSs are available for power requirements ranging from hundreds of kilowatts to tens of megawatts and are

5 Example of a 1 MW, 15-minute layout of ABB's EssPro Grid



6 Residential PV demand and supply match poorly.



ready for connection to medium- or high-voltage grids ➔ 5. Based on ABB's broad experience in electrical utility grids and in-depth knowledge of battery technologies, the EssPro Grid combines advanced controls and algorithms with the storage technology best suited for the application to maximize the performance of the ESS.

Residential-scale solar energy storage

The record growth experienced by the solar market worldwide since 2004 was initiated by the introduction of the feed-in tariff (FIT) scheme in Germany. For years, the FIT ensured remuneration for every solar kWh injected into the grid at a tariff substantially higher than the retail electricity price – without the necessity of a match between what was injected and the actual demand of the household, either in terms of energy balance or in terms of power equivalence at any given time. But this landscape is now changing, driven by the increased penetration of distributed generation further exacerbating associated grid instability issues; the approaching parity of self-generation costs and retail energy costs; and the diminution of incentives.

The new solar energy keywords are self-consumption (the consumption by the household of locally produced solar energy) and self-sufficiency (the capability to autonomously meet the energy demand of the household). To achieve these two aims, the misalignment between the daily solar power profile and the household demand must be overcome ➔ 6. This is achieved by the addition of an energy storage capability to the traditional PV system.

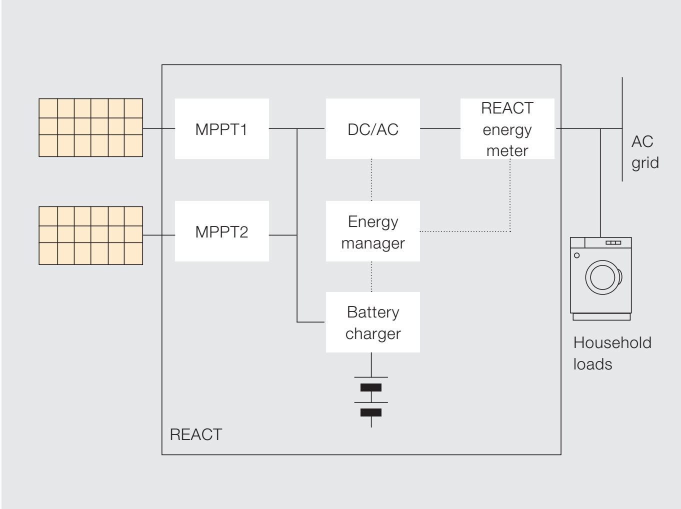
> The misalignment between the daily solar power profile and the household demand is overcome by the addition of an energy storage capability to the traditional PV system.

REACT

Practicality and cost make electrochemical batteries the best way to store excess solar energy. But the unplanned addition of batteries to a PV plant – even if it could bring self-sufficiency – would most likely result in a very doubtful financial return. An economically sustainable residential PV/storage solution is, instead, the result of a compromise between the size of the installed battery bank and the levels of self-consumption and self-sufficiency the household can achieve with the addition of a tailored energy management strategy.

7 ABB's REACT has battery storage in the left compartment and electronics in the right.

8 A typical REACT layout: A dedicated energy meter delivers real-time feedback on self-consumption and self-sufficiency.



ABB's residential energy storage system REACT (renewable energy accumulator and conversion technology) → 7 is designed to realize this trade-off in the best possible way. A REACT system comprises a grid-tied PV inverter (up to 5 kW) fed from a DC link – to which the maximum power point tracking (MPPT) trackers (connected to the PV array) and a bidirectional battery charger are connected → 8. Though its integrated DC-link architecture is the best cost solution for new installations, it can also be used to retrofit existing PV plants as an AC-link battery charger by simply not connecting the PV array to its input.

The energy storage section of a REACT system is made of lithium-ion batteries with a modular architecture that allows the system to expand from its native 2 kWh up to 6 kWh (field upgradable). An onboard load management system allows interaction with selected loads/appliances, thus boosting the energy independence of the household by up to 60 percent in the basic system configuration.

The choice of lithium-ion batteries is driven by their favorable expected cost profile in coming years, size/capacity performance, charge/discharge power rating, efficiency and longevity (more than twice that of other current technologies).

The future is bright

The addition of an energy storage capability to a PV installation, no matter what size, helps overcome the intermittent nature of solar power and brings it into line with more traditional energy sources in terms of dispatchability, stability, controllability, etc. The continued development of storage technology is essential to speed the journey toward self-consumption, self-sufficiency and the flawless integration of solar sources into electrical power grids worldwide.

The new solar energy keywords are self-consumption and self-sufficiency.

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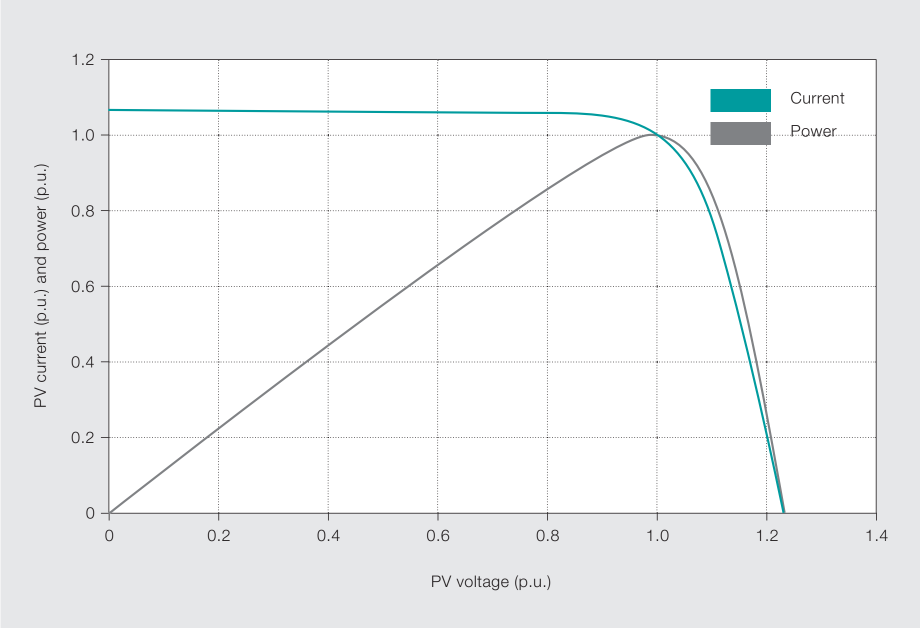
Evolving solutions

Technology trends and design targets for next-generation photovoltaic inverters

JUHA HUUSARI, PAOLO CASINI – Photovoltaic power conversion is a relatively new application area in the world of power electronics. Early photovoltaic conversion technologies were based on motor drives and only recently has the industry seen solutions developed solely for photovoltaic conversion. To maintain a strong presence in today's photovoltaic business, companies must be able to adapt to a constantly evolving market and also be visionary, focusing on key technologies to ensure cutting-edge designs for tomorrow's needs. ABB, with its strong background in power electronics, is not only a leading supplier of photovoltaic products, but also a forerunner in next-generation photovoltaic conversion technology.

1 Characteristic behavior of a photovoltaic power source



Widely adopted feed-in tariffs and other incentives that helped lower the cost of photovoltaic (PV) modules led to a boom in the PV industry between 2006 and 2011, particularly in Europe [1]. However, the sharp reduction of financial incentives has forced the market to adapt – meaning cost has become a key target for new product launches. Research, too, has had to adapt. ABB has been vigorously investigating new developments for PV applications, particularly in PV power conversion systems.

PV power conversion

PV power conversion essentially means efficient and controlled delivery of the electrical energy from the PV modules into the load of the system (in small-scale residential applications, such as heating or lighting) or into the transmission grid (in larger-scale applications). The sun's radiated energy reaching the face of the Earth is captured by the semiconductor junction within a PV cell that generates charge carriers, ie, electrical current, into the system. By its nature the PV cell is intuitively seen as a current source, unlike most electric power sources, which have voltage-source characteristics. This, in turn, requires appropriate measures to reliably control the power generation. Early converters intended for PV applications inherently provided suboptimal performance and even the scientific community struggled to accept the paradigm change with PV conversion control principles [2]. Such performance flaws have since been eliminated.

Due to its nonlinear semiconductor nature, the PV generator yields its maximum output power only when the generator is forced to operate at a specific voltage level → 1. Furthermore, environmental conditions, such as the temperature of the PV cells within the generator as well as the intensity of the arriving irradiation drastically change the electrical properties and the generated power of the PV generator. The generated power increases as a function of decreasing cell temperature and increasing irradiation intensity. Therefore, in regions like northern Europe a PV generator may produce peak power during cold, early spring mornings.

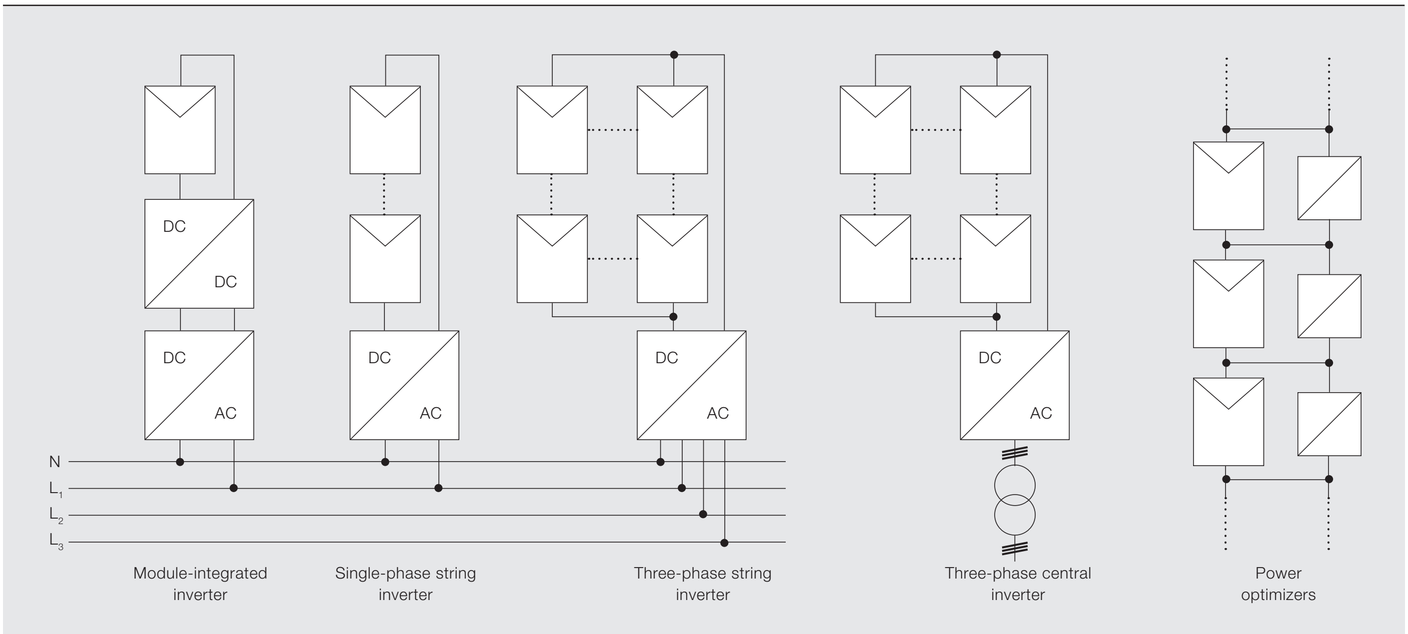
> By its nature the PV cell is intuitively seen as a current source, unlike most electric power sources, which have voltage-source characteristics.

The intermittent behavior of the PV generator is supervised by the power electronic converter processing the generated power of the PV generator. Through a feature known as maximum power point tracking (MPPT), the converter monitors the output power of the generator, adjusting it constantly to the desired level by changing the voltage level of the generator.

The basic building block of a PV generator is the PV cell, roughly 15 cm × 15 cm, with a thickness on the order of 100 µm. A single PV cell typically generates a couple of watts at voltages below a single volt, depending on the size and technology used. Most of the cells are silicon (Si) based, but the entire family comprises other conventional semiconductor materials, such as gallium-nitride (GaN), indium-phosphide (InP) and copper-indium-gallium-diselenide (CIGS), as well as more exotic – namely, organic and dye-sensitized – materials.

Title picture
A 181-kWp PV installation on the roof of ABB factory in Helsinki, Finland.

2 Conceptual photovoltaic power processing converters



Individual cells are joined in a series arrangement to create a PV module (also referred to as PV panel), comprising two to 96 PV cells. This is done because power processing is more feasible with higher voltage levels. PV modules typically range from 5 to 350 W; the large-scale systems are realized with larger, high-power modules. The PV modules are connected in series to form the fundamental unit, a PV string. Due to safety regulations, the maximum voltage of the PV string versus Earth is limited (1,000 V/1,500 V in the European Union; 600 V in the United States), which in turn defines the string's maximum power. One PV string rated for 1,000 V usually provides a nominal DC power of 5 kW. Thus, commercial PV inverters for multiple strings are typically rated for multiples of 5 kW.

The power converters processing the generated power are typically categorized as follows: micro-inverters, generally interfacing one to four PV modules into the AC grid; string inverters, 1- to 3-phase inverters interfacing one to 20 PV strings; and, finally, 3-phase central inverters usually rated above 100 kVA → 2. In addition, there is a niche group of power optimizers that are add-on, low-power DC-DC converters intended to fine-tune the generated power in existing PV strings. Excluding power optimizers, ABB provides converters and solutions for all of these application areas.

Plant-level features

Traditionally, PV installations were realized with the highest possible inverter rating relative to installation size: Small installations with micro-inverters and, respectively, larger systems with high-power inverter stations. This concept is changing as the industry experiences a trend of high-power systems being built with string inverters. The factors driving this include higher power output as distributed inverters perform fine-granular maximum-power extraction as well as lower installation costs. In addition, during inverter failures only a restricted part of the installation stops producing power. As a result, the importance of string inverters is increasing.

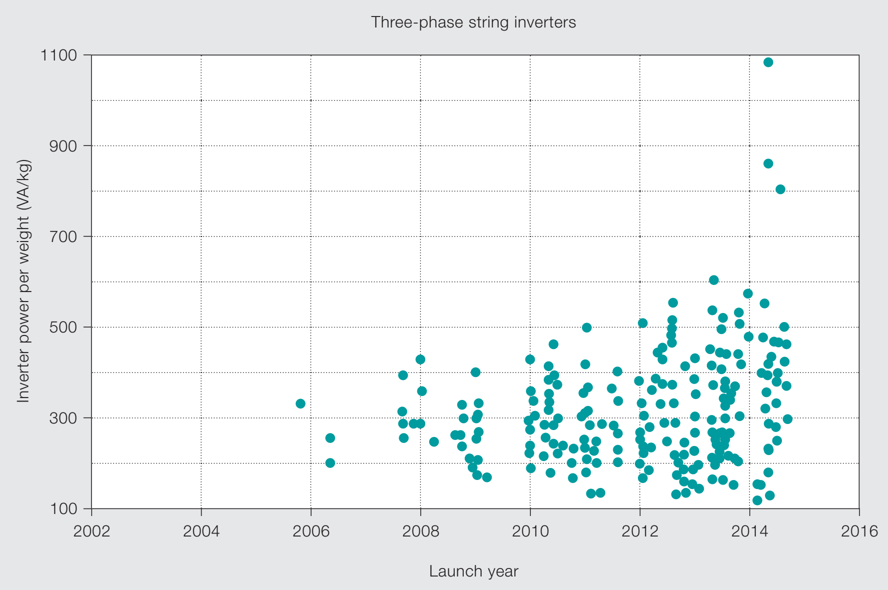
Another interesting development emerging in PV applications for larger systems is the inclusion of environmental measurement data to enhance near-future prediction and power output. Through monitoring, eg, the cloud movement near the PV power plant, the centralized controller can, in advance, guide the inverter(s) within the plant to adjust their operation, ie, to improve the MPPT operation. Additionally, this information can be used to predict the available short-term power, benefitting the grid operator.

A modern-day feature that has emerged in PV applications is the connection to various distributed data services, in which the inverter contains a connection to the information network to store and share

Through monitoring, eg, the cloud movement near the PV power plant, the centralized controller can, in advance, guide the inverter(s) within the plant to adjust their operation, ie, to improve the MPPT operation.

The heart of a PV inverter is the bridge of fast-switching semiconductor devices that, together with passive energy-storage elements, enable power processing.

3 Evolution of power density in wall-mountable, transformerless PV inverters



relevant information, such as historical energy output. Again, such information aids the grid operator in dealing with demand-power balancing.

Emerging semiconductor devices

The heart of a PV inverter is the bridge of fast-switching semiconductor devices that, together with passive energy-storage elements, enable power processing. While the clear majority of PV inverters utilize Si devices, lately the industry has seen the emergence of silicon carbide (SiC) devices. Able to withstand higher voltages and temperatures and to switch faster than Si counterparts, the SiC device enables more compact and more efficient power processing converters [3]. However, SiC technology is expensive and the long-term reliability of SiC components remains an open question. These drawbacks notwithstanding, SiC devices can be seen as an integral part of PV inverters in the coming years, as demonstrated through ABB's research [4] as well as products utilizing SiC technology.

The benefits of GaN technology compared with SiC are still being debated within the industry. It is claimed that GaN devices enable ultrafast switching action, thereby providing greater benefits in efficiency and power density. However, practical demonstrators validating these claims are yet to be announced.

While SiC devices are already technologically mature, GaN devices are not. At present, there are only a handful of GaN products on the market and, furthermore, no high-current power modules are available. This is also due to the property of the lateral GaN semiconductor junction, which makes paralleling many GaN chips difficult, thus hindering the production of high-current modules. With single-packaged GaN chips it is possible to reach power levels of roughly 20 to 30 kW; at higher power levels modules are required.

Power density in string inverters

Over the past 10 years, the design targets for PV string inverters have been changing dramatically. The first-generation designs targeted high energy yield with multiple isolated MPPT converters. The second-generation designs maximized conversion efficiency, followed by third-generation single-stage systems. Current design targets are now lower cost and higher power density. Each of these posed different challenges to power electronics designers.

The power density concerns arise from various needs: For safety reasons, the industry has adopted a weight limit of 75 kg for each cabinet to be carried by two people. For wall mounting, there are also limits regarding the weight capacity of the mounting structure and the wall itself. Another driver is the lower transportation cost per installed Watt.

The evolution of the power density of commercial wall-mountable, transformerless three-phase PV string inverters weighing less than 75 kg shows that inverter manufacturers are putting increasing effort into maximizing the power density → 3.

The power density of PV string inverters has definite limitations. Typically the passive filtering elements make up a significant part of the system weight, but the heat transfer solution, the enclosure itself and various protection devices also add considerable weight. Many of these restrictions cannot be changed – for example, the enclosure thickness and the use of certain protective means are defined in standards (eg, in IEC 62109). The higher the power level, the bulkier the protection means becomes, thus resulting in a heavier enclosure to support the weight and to provide an adequate ingress protection (IP) rating.

A modern-day feature that has emerged in PV applications is the connection to various cloud services.

The challenge of reaching a higher power density will push designers to look for more innovative system solutions and foster the use of next-generation semiconductor components.

Utility-scale PV solutions

Although technological developments have been seen throughout the entire PV industry, the utility segment has had the most impressive pace of innovation. Since the early stages of the modern PV market the evolution of utility-scale PV inverters has been driven by the optimization of the PV plant's production efficiency and total cost of ownership (TCO), that is, the summation of the initial capital expenditure (capex) and the operational expenditures (opex) sustained during the life of the plant.

Most of the efforts by the inverter industry in the past 10 years have been aimed at improving the inverter's power conversion performance, which has resulted in increased efficiency values up to 98 percent weighted and 99 percent peak. But the unavoidable asymptotical efficiency trend and the modest incremental gain of the financial return in relation to the added cost of better-performing topologies and control techniques has gradually brought attention to the reduction of the TCO.

Innovation at the inverter level is seen as a means to drive down the cost of the balance of system (BOS), which represents 60 percent of the cost of a utility PV plant, compared with less than 10 percent of the cost incidence of the inverter itself. A few years ago the progressive adoption of the 1,000 V system voltage from the 600 V system voltage allowed a 25 percent reduction of the DC BOS. The PV industry is today on the verge of a similar change with the upcoming 1,500 V module technology, which will revolutionize the utility inverter offering by requiring a significant review of the electronic and electromechanical components and topologies deployed in PV inverters.

The other component of the TCO is operation cost. The typical annual operation and maintenance cost of a PV plant is roughly equal to 1.5 percent of its initial capex cost and a significant part of it is represented by the maintenance required by traditional air-cooled PV inverters, especially when installed in remote and hostile conditions. Throughout the 20 years of expected field life the opex becomes a major contributor to the cost of the plant. Combining the need to reduce maintenance costs with reduced logistic costs and ease of installation creates another driver for the evolution of utility-scale inverters' mechanical packaging. The sudden switch to outdoor inverter enclosures in several utility portfolios was the initial move in this direction that will continue with the development of innovative, low-cost maintenance cooling solutions. The traditional air cooling of IP20 inverters, with their periodic maintenance to clean air filters and decontaminate electronics exposed to the direct air flow, is gradually moving to sealed-enclosure solutions IP54 or IP65 rated with liquid or 2-phase cooling solutions.

An additional benefit of smarter packaging and cooling technologies is increased power density, which results in reduced logistics and installation costs. This is particularly important as utility demand shifts to emerging markets, where installations are needed in remote areas.

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Life-cycle automation and services

A holistic approach to photovoltaic plant automation, operation and maintenance

ADRIAN TIMBUS, MARC ANTOINE, LUIS DOMINGUEZ – The photovoltaic power industry is rapidly growing, with worldwide installations expected to grow by 60 to 66 GW in 2017 [1]. ABB is deeply involved in this growth, applying a holistic approach to photovoltaic generation projects that encompass the entire plant life cycle as well as the two stages of photovoltaic generation projects. The first stage is to design the solution, select the equipment and build the plant. The second is to ensure that the plant produces the maximum amount of power, and that its equipment is managed efficiently to minimize operation and maintenance costs. This holistic approach is a culmination of ABB's expertise in providing technologies for solar power applications and the company's vast service and maintenance resources.

1 ABB's photovoltaic power plant offering

As a leading provider of photovoltaic (PV) power plant technologies, ABB partners with and guides owners and investors. ABB performs feasibility studies and analyzes the project's profitability; designs, engineers and optimizes plants; provides project management; and supplies electrical and automation systems. Through its comprehensive operation and maintenance (O&M) offering, which includes an advanced remote monitoring and service concept, ABB ensures that each plant maximizes production while protecting its assets.

ABB's scalable power and automation solutions for PV power plants are designed for rapid deployment. They are pre-assembled, factory-tested and containerized to enable short lead times and easy installation. With the exception of the solar panels, which ABB does not manufacture, the solutions consist entirely of ABB products, designed specifically for PV applications. These are seamlessly integrated to deliver the highest levels of reliability and efficiency and the lowest levels of plant energy consumption. ABB has delivered more than 100 integrated electrical and automation solutions for PV power plants, with a combined generating capacity of around 1,000 MW.

ABB's technologies for photovoltaic (PV) power plants are designed to maximize plant performance and provide owners with a rapid return on investment and long plant operating life. From electrical balance of plant (EBoP), to control systems and power management, to production forecasting and remote monitoring and services, ABB's PV power generation technologies seek to ensure maximum power production at minimal cost → 1.

World-leading plant automation system

Symphony® Plus for Solar, ABB's automation system for PV power plants, is a versatile and scalable monitoring and control system. As its name suggests, it is part of ABB's Symphony Plus platform, the total plant automation solution for the power and water industries. Symphony Plus is the latest generation of the Symphony family of distributed control systems which, with more than 6,500 operating installations, is one of the most widely used plant automation platforms in the world.

Symphony Plus for Solar monitors and collects data from the critical components of the plant. These include the panel strings, transformation centers (each of which contains inverters, transformers, medium-voltage switchgear and low-voltage switchboards), the grid connection and the meteorological stations. The system supports a broad range of communication protocols, enabling it to connect and exchange data with all of the components. Equipped with a real-time database and historian, it acquires and stores all relevant plant data, either on-site or at an ABB remote service center.

> Symphony Plus for Solar improves the return on investment with comprehensive O&M services.

Using the IEC 61850 communication protocol, Symphony Plus for Solar monitors and controls substation equipment and integrates generation and electrical components into a single information system.

One of the main differentiators of the Symphony Plus platform is that it is designed to last the operating life of the plant. Through ABB's "evolution without obsolescence" life-cycle policy, each generation of the Symphony Plus family builds on and enhances its predecessor, adding new technologies and new functionalities to meet the evolving performance objectives of its users. An investment in Symphony Plus hardware and software is thus protected throughout the life cycle of the plant.

Power management

Power management functionality is key to faciliting the grid connection of PV plants. Symphony Plus' high-performance controller connects to all relevant actuators (inverters, tracking systems and – if applicable – capacitor banks, STATCOMs[1] or energy storage), and performs real-time calculations to regulate the plant's power production in accordance with the specifications. Accessing all relevant plant information, it dispatches set points to the inverters. It also ensures that plant management and control is in accordance with the local grid code requirements, controls the production ramp rate, and provides power factor and voltage control at the point of connection to the grid.

Production forecasting

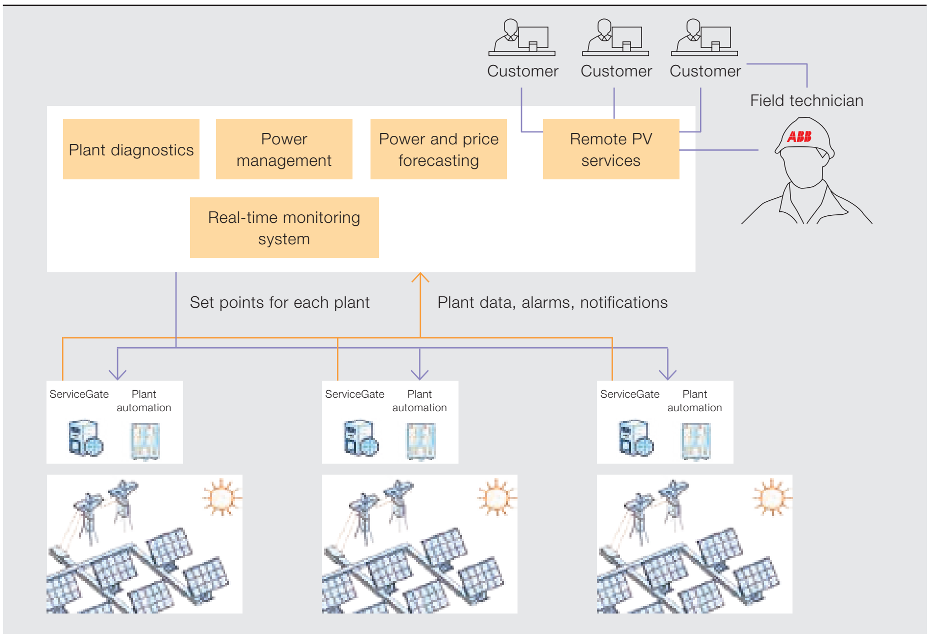
As PV plants grow larger, the ability to forecast power production has become an increasingly important factor in plant profitability. ABB provides a flexible production forecasting solution that uses data from the panels, strings and invert-

Title picture
Operation and maintenance services are one of the key components of ABB's photovoltaic offering, allowing plant operators to minimize operation and maintenance costs.

Footnote
1 Static synchronous compensators

ABB provides a flexible production forecasting solution to predict plant output.

2 Architecture of Symphony Plus for Solar



3 Alarms and notifications in the remote portal

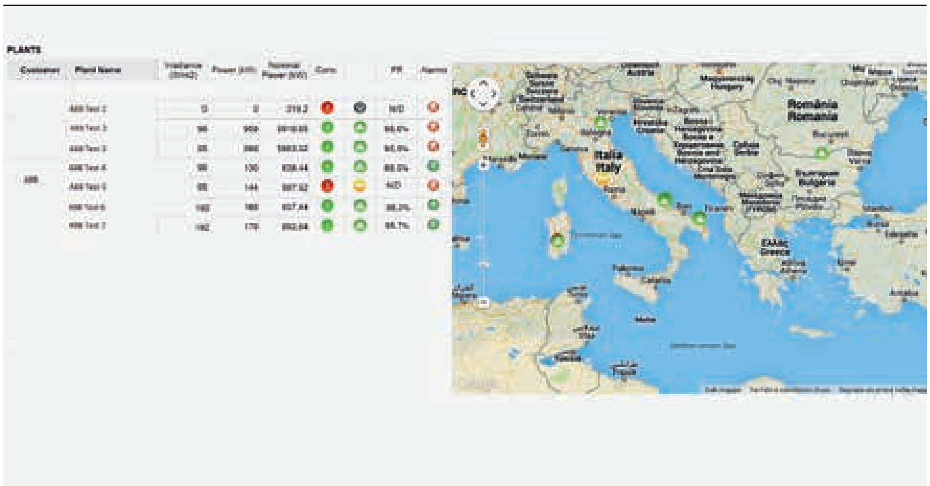
ers, as well as historical production and meteorological information, to predict plant output. The forecasting horizon spans from hours ahead (typically 6 h ahead, with a time resolution of 15 min) to days ahead (typically one week, with hourly resolution).

ABB has also developed algorithms that track the movement of clouds in the vicinity of the PV plant. Using advanced image processing and computer vision techniques as well as optical and physical models, the algorithms predict the time of arrival and duration of cloud cover over the plant, and calculate the expected drop in output power. If the plant is equipped with an energy storage system, optimization of power balancing is achieved by using the accurate short-term prediction of power fluctuations caused by cloud coverage.

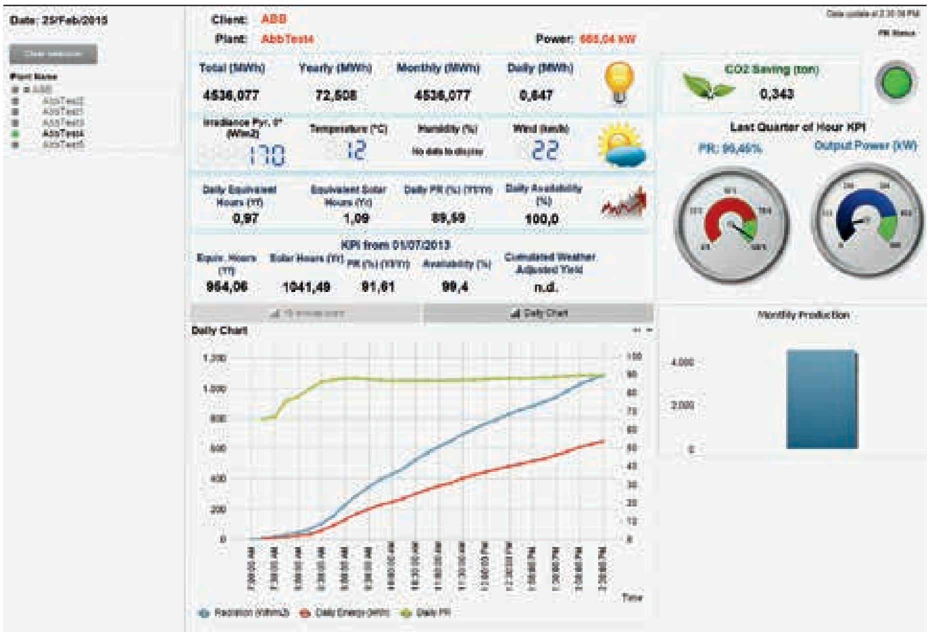
Remote monitoring and control

Plant owners need to minimize operation and maintenance (O&M) costs by being able to quickly identify underperforming components. They require predictive maintenance to reduce downtime, extend equipment life cycles and evaluate the impact of equipment failure. They also expect quick access to service engineers and product experts.

ABB's remote monitoring, operations and service platform for PV power plants delivers on all these fronts. Symphony Plus for Solar comprises three main components: a remote-enabled interface called Symphony Plus ServiceGate, 4 Overview display using maps



5 KPI dashboard



Symphony Plus for Solar comprises three main components: a remote-enabled interface, a remote service center and a dedicated Web portal.

ABB's remote service center, and a dedicated Web portal → 2. The platform can be used for a single plant or a fleet of PV or other renewable energy plants.

ServiceGate provides a high-speed and secure data transmission connection between the plant automation systems and an ABB remote service center. It supports system configuration, health checks and system diagnostics, as well as remote operations of plant equipment.

The data from ServiceGate is received by, and stored at, ABB's remote service center, which is equipped with a dedicated hardware platform and configurable software. It runs the processing and monitoring software and advanced applications, and stores the results displayed in the dedicated Web portal. Unlike other monitoring systems on the market, ABB's system enables real-time plant operations through an ergonomic human-machine interface (HMI). Moreover, an optimized power management function is also available at the fleet level to control the production of the entire fleet at the best economic running point. The service center is manned 24 hours a day by accredited engineers, ready to react at all times to any field problems.

The Web portal has a dedicated interface through which the PV plant communicates with the external world. All plants in the fleet can be managed through the same Web portal, which can be accessed by authorized users anytime, anywhere using a PC or mobile device. The log-in provides different levels of authorization based on roles defined in IEC 62351.

Key features of the Web portal include alarms and notifications, dynamic presentation of collected data, predictive maintenance, production forecasting, production and performance cockpits, a reporting and ticketing system, and health checks.

Alarms and notifications

Besides receiving standard alarms from the plant such as faulty inverters and plant equipment, users can generate their own alarms for situations like "low KPI value." When an alarm is activated the platform conducts a preliminary diagnosis of possible operating failures and immediately notifies the responsible personnel by SMS or email → 3.

6 Plant performance report

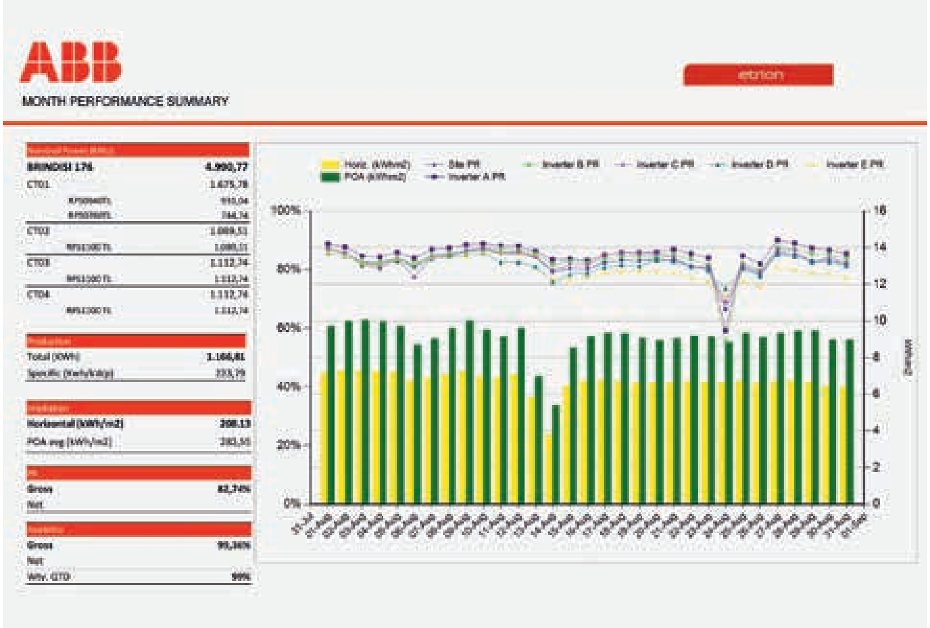


ABB is currently using the remote service platform to monitor and control more than 50 PV power plants worldwide.

Maps with dynamic data

Maps show the geographical location of the fleet plants with icons. An adjoining frame contains a list of the plants in the fleet and uses dynamic traffic lights and icons to show the status of contractual KPIs, the presence of open maintenance tickets and the status of the plant's connection to ServiceGate → 4.

Predictive maintenance

The remote service platform contains a set of tools to detect and correct the most common reasons for underperforming assets. The tools analyze the plant in small sections (typically individual strings) to pinpoint local problems at an early stage before they develop into larger production problems. They detect soiling (dust accumulation on the modules); total and partial shading of strings; and aging, which analyzes the efficiency of the PV modules over time to determine the loss in performance caused by degradation.

Production and performance cockpits

Other applications that monitor and analyze plant production include performance ratio monitoring, which is a real-time cockpit for monitoring plant production and KPIs (based on QlikView technology) → 5; equipment condition trending that monitors the performance of critical plant equipment in real time; and fleet analysis, which provides a historical data dashboard for comparing and analyzing fleet performance.

Reporting and ticketing system

The remote service platform stores data from the PV plants, and the Web portal uses the data to, for example, automatically generate: reports on production, interventions and actions by operators; an O&M log book that collects tickets relating to O&M activities and tracks operators' actions; and executive-level reports with information necessary to manage the plants → 6.

Health checks

The remote service platform also performs equipment health checks. These consist of fingerprint diagnostics, which monitor and assess equipment performance and identify reliability issues. They are available for plant assets, including the automation system (hardware and software), cyber security settings, and electrical process equipment. The fingerprints are used to start a continuous optimization process by identifying necessary improvements and a schedule for their implementation.

ABB is currently using the remote service platform to monitor and control more than 50 PV power plants worldwide. These plants range in size from less than 1 MW to more than 100 MW, and include single plants and entire fleets. High customer satisfaction and a large number of renewal contracts indicate that ABB's holistic approach to PV power production is producing real benefits and measurable value for customers.

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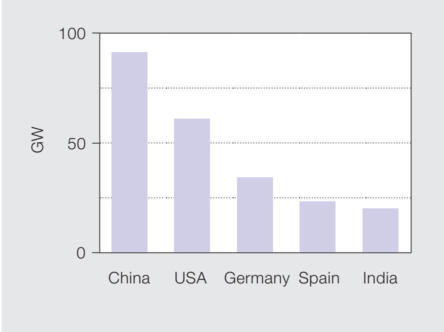
Putting it all together

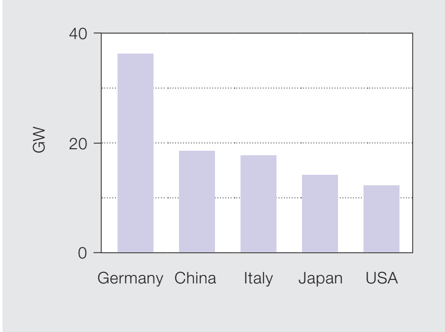
Integrating distributed renewable energies into the grid

JOCHEN KREUSEL – More than ten years ago the new renewable sources of electric energy – sun and wind – began to make their way into the electric power supply system. At that time, they were seen as two additional primary energy sources that could be connected to the existing systems without making any fundamental changes. Today, these new renewable energies have, in some countries, become the largest generation subsector. In light of the significant cost reductions of the past years further acceleration of this growth is expected. But the approach of connecting renewable energies to the existing systems is too shortsighted. Instead, electric power supply systems must be further developed to integrate new sources on a larger scale. With its high scalability, photovoltaics is the strongest driver of this change, affecting all areas of supply and utilization along the electric energy value chain. ABB's in-depth knowledge of renewable power generation technologies and comprehensive experience with grid codes and utility practices in use around the world enables it to provide the full range of products, systems, solutions, services and consultant capabilities to serve the renewable energy industry.

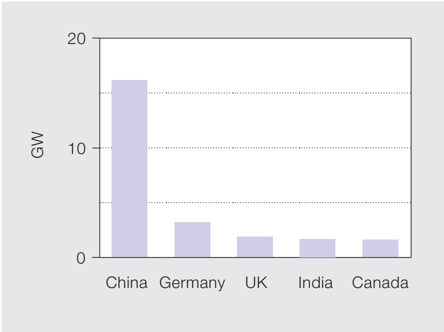
1 Wind and solar energy – top five countries in terms of installed and new capacity in 2013



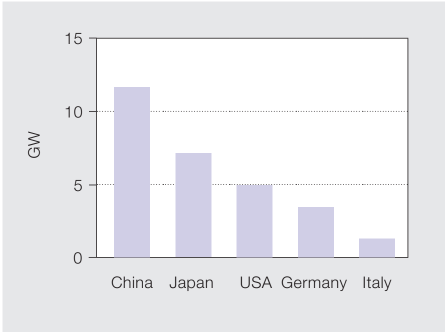
1a Wind: installed capacity, 2013



1b PV: installed capacity, 2013



1c Wind: new capacity, 2013



1d PV: new capacity, 2013

Sources: Wind: Bundesverband Windenergie e.V., Deutschland; Photovoltaics: IEA-PVPS, IDAE, PV News, BSW, IWR

Since the end of the 20th century, an increasing number of countries have been promoting the use of wind and solar energy. Denmark has been a pioneer in this field, and by 2011, was supplying more than 40 percent of its electric energy demand with renewable sources – three-quarters of which was wind energy. Germany is also being watched closely as the first large industrial country attempting to transform its electricity supply with a strict focus on new renewable sources.

➔ 1 shows the five leading countries in the world in terms of installed capacity and new wind and solar capacity in 2013. Countries from all regions are active, and some of the early pioneers – recognizable by their high installed capacities – have been overtaken by other countries. Today, the new renewable energies are a global reality, no longer dependent on the support from individual countries.

Title picture
The shift to renewable power sources makes the reliable delivery of power a bigger challenge than ever before. ABB's comprehensive wind and solar power offering is helping to meet this challenge.

The strongest driver of this change is photovoltaics, which – after the significant cost reductions at the end of the last decade – has reached or fallen below grid parity in a number of countries. That is, photovoltaics has achieved competitive end-consumer prices in low-voltage grids. ➔ 2 shows the development of the generation costs of photovoltaic (PV) power compared with household electricity prices in Germany. Photovoltaics is an economical option for meeting the demand of individual households, provided that the grid usage fee is largely energy-based. This makes it independent from direct subsidiaries for a large scope of applications as long as it reduces the owner's own demand.

Remote generation, distributed generation and volatility affect all areas of electric power supply and utilization.

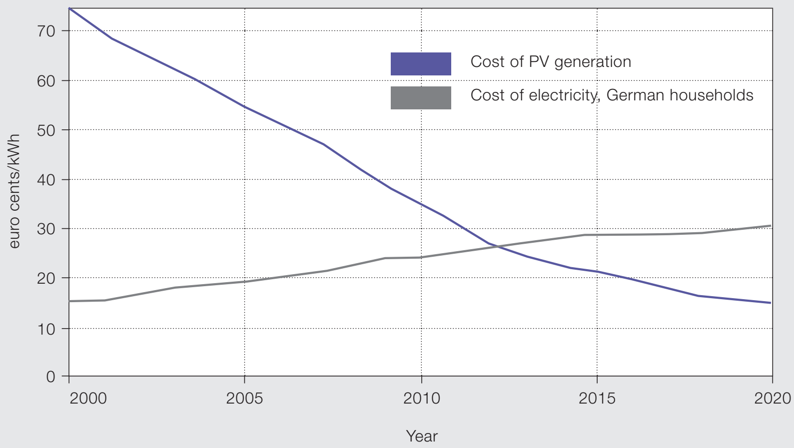
New renewable energy sources and system integration

New renewable energies have three main features that fundamentally change the electric power supply system: remote generation, distributed generation and volatility.

Remote generation
The share of remote generation of renewable energy is much higher than with power plant systems in which a regional balance of generation and demand is preferred for both economic and technical reasons. This development is mainly driven by the heavily location-dependent sources of wind and water and can lead to very large generation units or clusters.

Distributed generation
The growth of distributed generation is primarily driven by photovoltaics and combined heat and power generation (CHP). For photovoltaics, this is mainly due to the relatively low economies of scale in terms of costs combined with economic performance, relative to the end-consumer prices in a low-voltage grid. CHP must be distributed in order to provide the heat close to the consumer.

2 PV generation costs* compared with household consumer prices in Germany



* 1 euro is equal to about $1.05.

Source: www.solarwirtschaft.de, Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety of Germany (Leitstudie 2010), BSW Solar (PV-Roadmap)

The rising share of renewable energies is influencing the operation of conventional power plants.

Very small PV systems in particular can lead to a considerable share of the generation being covered by a very large number of smaller units feeding energy into the distribution networks.

Volatility

Volatility is mainly introduced to the electric power supply system by wind and solar energy, both of which lead to faster, larger and, especially in the case of wind energy, less predictable fluctuations than before.

Remote generation, distributed generation and volatility affect all areas of electric power supply and utilization. An overview of these areas, including the influence of new loads as drivers for change, is given in ➔ 3.

Conventional provision of electric power

The rising share of renewable energies is influencing the operation of conventional power plants. The increased frequent use of power plants originally intended as base-load plants for loads following operation with steep power output gradients poses a great technical challenge. Using Germany as an example, the effects of this change were investigated in detail in [1]. The study concluded that already in 2015 power gradients of up to 15 GW/h are expected for the conventional power generation park.

Another factor influencing the operation of conventional power plants is that, as wind and solar energy have no variable costs, they will always be placed at the lower end of the merit order in an energy-only market. This means they displace conventional generation, reducing the utilization of conventional power plants and making fixed-cost coverage more difficult.

These economic effects mean that building and operating conventional power plants is no longer attractive. But as conventional generating capacity is indispensable both as backup for periods of low renewable power output and for power system control, suitable adaptations of the market design are now being discussed. ABB is deeply involved in the discussions and is helping to shape the modern electric power supply system.

Transmission level

In transmission networks, remote generation leads to increased capacity requirements. Additionally, the volatility of the generation – particularly in combination with the low number of full-load hours of the renewable energies – increases transmission requirements. Expanding the interconnected power system represents the most cost-efficient option to match volatile generation and consumption [2].

The benefit of regional expansion for the integration of a very high share of renewable energies into the electric power supply is illustrated in ➔ 4, using the expansion of the European interconnected power system to North Africa and the Middle East as an example.

The increasing variety of operating conditions in the distribution networks increases the information requirements.

3 Effects of the main drivers for change on different parts of the electric energy supply and utilization value chain

Driver	System affected				
	Conventional generation	Transmission	Distribution	System operation	Application
Remote generation		– Long-distance transmission – FACTS[1] – Overlay grid/ HVDC		– Stabilization with FACTS[1]	
Distributed generation			– Automation – Voltage regulation	– Communication – Control – Virtual power plants	
Volatile generation	– Part-load capability – Flexibility	– Trans-regional leveling – Overlay grid/ HVDC – Bulk storage	– Distributed storage	– Load management – Virtual power plants – PMU/WAMS[2]	– Storage (in applications) – Demand response
New loads (eg, e-mobility)			– Charging infrastructure	– Demand response	

1 FACTS: flexible alternating current transmission systems
2 PMU/WAMS: phasor measurement unit/wide-area monitoring systems

→ 4 shows the costs for an additional MWh generated from renewable sources in Europe, provided that the European energy-political goals are met and that further cost reductions for the plants are used. The cost advantage is a result of significantly more ideal locations in North Africa and the Middle East compared with Europe. The costs for the additional required transmission capacity are taken into account. This cost advantage directly benefits the plant operators, and requires no special support apart from reliable framework conditions. The other cost advantage shown in → 4 is based on a better balance of renewable energy supply and demand resulting from the complementary seasonal variations of wind and consumption in Europe and the regions south of the Mediterranean Sea. This cost reduction requires suitable consideration in the market design.

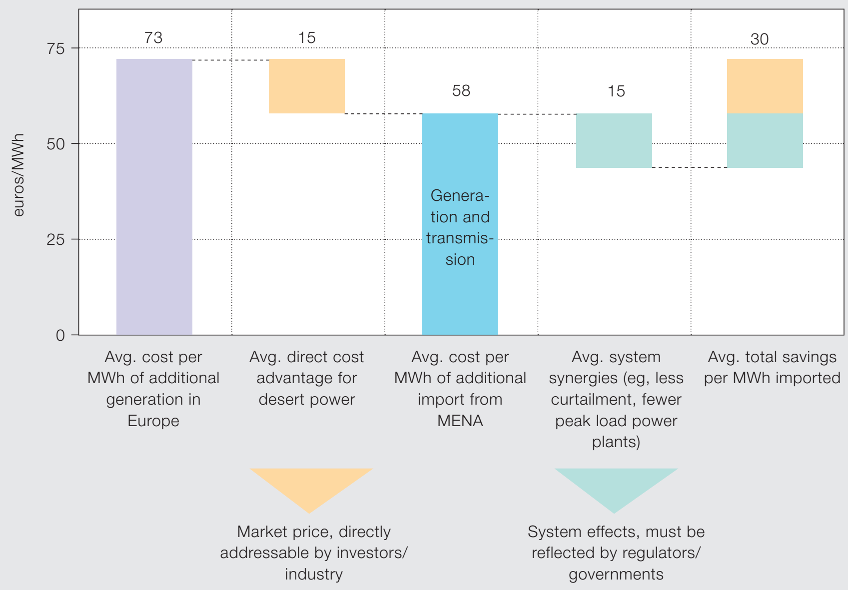
The transmission systems required under the circumstances described in → 4 will presumably be different from those of the past. Considering the large transmission distances combined with the often fundamentally changing load flow situations due to the high infeed peaks from the renewable sources, a superimposed transmission level (overlay grid) based on high-voltage direct current (HVDC) transmission technology appears sensible. A key component for this is the HVDC circuit breaker developed by ABB [4].

Distribution level

The changes occurring in the distribution networks are manifold. In many cases, an increase in distributed generation requires a reinforcement of the grids. However, especially in rural grids with relatively long transmission lines, voltage support problems occur first. As this is not caused by the one load situation the network has been designed for, but by the multitude of operating conditions between feeding and extracting power, the traditional solution of manually adapting the transformation ratio of the local distribution transformer is no longer sufficient → 5. In such cases, the often significantly more expensive grid reinforcement can be postponed or even entirely avoided by installing a voltage regulator such as a voltage-controlled distribution transformer (see, eg, [5,6]).

The increasing variety of operating conditions in the distribution networks increases the information requirements. This leads to an at least partial automation of the distribution substations, which thus far have been minimally monitored or remotely controlled. Distributed generation as well as e-mobility (due to the mobile nature of the consumers) will lead

4 **Reducing the costs* for renewable energy by integrating the power supply systems of Europe, North Africa and the Middle East** [3]



* 1 euro is equal to about $1.05.

Note: cost of MENA (Middle East and North Africa) exports arriving in Europe includes cost of transmission losses
Source: Dii, Fraunhofer ISI

Expanding the interconnected power system represents the most cost-efficient option to match volatile generation and consumption.

Due to the volatile power output associated with renewable energies, the short-term demand response is gaining in importance.

to an insufficient capacity of distribution networks in some situations. This means that measurement and control will be required – and as every technical system, including measurements, can be faulty, the solution will be to transfer well-known approaches from the transmission networks, such as state estimation, to the distribution level and into the secondary distribution systems.

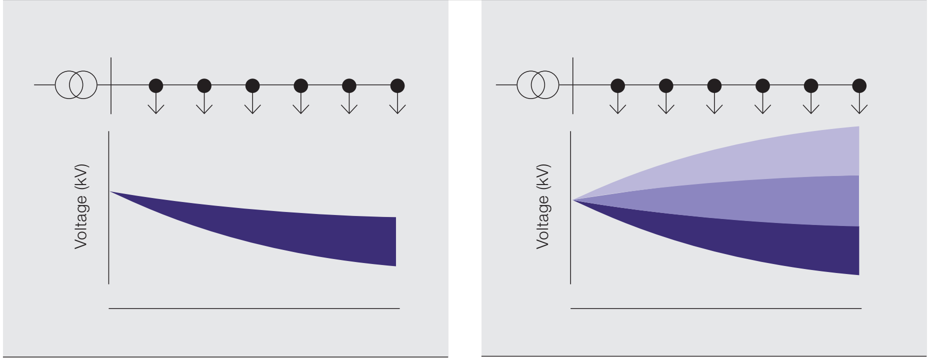
If the grid is unable to offer sufficient capacity for all situations, possible congestion must be proactively detected and resolved – a task that is not new in the electric power supply domain. In fact, it is common practice in the coordination between (large-scale) power plants and system operators. Hence, the solutions for this electric power supply area must be largely standardized and automated. An example of predictive distribution network operation, which also takes the requirements of the deregulated market into account, has been developed and successfully taken into operation within the scope of the MeRegio E-energy project in Germany [7].

Consumption

Due to the volatile power output associated with renewable energies, the short-term demand response is gaining in importance. Demand-response measures, particularly those involving loads with inherent storage, may contribute to this. The requirements associated with the balancing of loads and generation for different time domains, the solutions commonly used today and the solutions expected in the future are shown in → 6. This clearly shows that demand response can make an important contribution especially in the first 15 min. This is an important period because it is sufficiently long enough to ramp up power plants with fast startup capability when generation capacity is suddenly lacking. Whether demand response can help in the very short time frame in which the rotating mass of power plants has a stabilizing

A holistic approach considering the supply of electric energy as well as of heating and cooling is essential for the utilization of demand-side flexibility options.

5 Change of the voltage support task in distribution networks with increasing distributed generation (schematically)



5a Past: Distribution; voltage is decreasing along the LV lines and voltage band can be guaranteed by a fixed setting of the distribution transformer

5b Now and in the future: Distribution and feed-in, resulting in a broader variation of voltage at the end of the line, possibly requiring on-load voltage adjustments

effect today depends on whether an autonomous reaction of the load to imbalances between generation and consumption can be achieved. After 15 min the use of demand response is only realistic for selected applications.

Demand response is particularly suitable for heating and cooling applications as thermal energy storage can in most cases be implemented at a relatively low cost. Hence, a holistic approach considering the supply of electric energy as well as of heating and cooling is essential for the utilization of demand-side flexibility options.

Future conventional generation will require plants that can be operated economically even at low loads and in frequently and fast-changing load situations. The transmission networks will have to take over more long-distance transmission tasks with strongly varying load flow situations compared with the past. To compensate for the volatility of the new renewable sources, wide-area interconnected systems such as those proposed for the region Europe-North Africa-Middle East within the scope of the Desertec concept can be an option.

Storage options

Storage is another important building block for the integration of renewable energies. But due to the variety of applications and available solutions it is a highly complex topic, which requires a separate discussion. Energy storage is explored in more detail in "A bright future" on page 27 of this edition of ABB Review.

The transition from an electricity supply based on thermal power plants to a supply using new renewable energies as its main source will lead to a fundamental redesign of power systems.

The road ahead

The transition from an electricity supply based on thermal power plants to a supply using new renewable energies as its main source has technical implications in all areas of electric power supply and utilization and will lead to a fundamental redesign of power systems.

The consequences of the integration of distributed generation into the distribution networks will be particularly far-reaching, both quantitatively and qualitatively. First of all, an increase of grid capacity will be inevitable in many cases. As the combination of extracting power from and feeding power into the grid leads to a larger range of operating conditions, additional voltage monitoring and regulation will often be required. And finally it will no longer be sensible to design the distribution networks

6 Requirements for balancing generation and demand in different time domains and possible solutions today and in the future

Time domain	Task	Traditional solutions	New solutions for the future
<30 s	Instantaneous reserve, balancing of short-term variations	– Rotating mass of the power plants	– Battery storage – Renewable energy resources and load management may also contribute
<15 min	Minute reserve, balancing of short-term variations	– Hydropower plants – Power plants on the grid – Fast start-up power plants	– Load management – Battery storage
1-3 d	Balancing of diurnal variations of the residual load	– Pumped storage – Power plants (fuel storage)	– Pumped storage – Load management (selected applications)
Weeks to months	Balancing of annual variations of the residual load	– Power plants (fuel storage) – Water reservoir (natural inflow)	– Water reservoir (natural inflow) – Expansion of interconnected power system

One of the most significant changes in the system management will be the integration of a very large number of distributed units, both on the generation and the consumption side.

for rare extreme situations – this is mainly due to the low number of full-load hours associated with solar energy and because of e-mobility. Thus monitoring and control down to the secondary distribution level will be necessary.

Balancing loads and generation will become more difficult in systems with a strongly varying primary energy supply that is not storable. Besides the proven, but landscape-profile-dependent pumped storage plants, battery storage facilities can contribute in the short term, eg, for frequency stabilization and peak shaving. In the long term, ie, mainly for the compensation of seasonal variations, the system boundaries will likely be expanded by extending the interconnected systems or interconnecting other systems such as heat and gas supply.

The most significant changes in the system management will be the integration of a very large number of distributed units on both the generation and the consumption side, as well as achieving frequency control with a decreasing number of rotating masses acting as stabilizing elements.

The greatest challenges in the necessary further development of the systems are – from a more organizational perspective – the coordination of the required measures in all system areas and – from a technical perspective – the development of suitable storage, the operation of the system without rotating masses and the integration of large numbers of distributed units into the system management. With its commitment to innovation, ABB continues to drive the growth of renewables, paving the way for the new electric power supply system.

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A growing need

Affordable irrigation with ABB's solar pump drive

FILIPPO PAGANI – It is no secret that the world's thirst for water and energy continues to rise dramatically. But did you know that half of the world's energy is used to operate pumps? With agriculture's reliance on irrigation, which depends on water pumps, it is no wonder that so much energy is dedicated to this field. But plugging into a reliable or affordable local power grid to operate a water pump is not always an option in many parts of the world. And so, ABB has turned to the sun to develop an innovative solution that uses solar power as a reliable energy source for pumping water. The ABB solar pump drive, designed to use maximum power point tracking and conventional drive technologies, enables water pumps to run at maximum power proportional to the available solar power.

1 ABB's solar pump drive system includes either an ACS355 drive or an ACSM1 drive.

1a ACS355 general machinery drive

1b ACSM1

Solar pumping systems are increasingly being adopted for use in a variety of applications. For example, the systems are being used in community water supplies, fish farming and agriculture, forestry, and wastewater treatment engineering. These systems are also more frequently being used for municipal engineering, city parks, resorts, and even fountains in residential areas – and, of course, for irrigation.

In some countries many small- and medium-sized farms are either off-grid or receive only a few hours of electricity each day. Often, the farmers' only alternative is to run irrigation pumps with diesel generators, which are costly to operate – especially as water demand rises during the growing season, causing fuel prices to spike. Now, solar energy is playing an important role in the irrigation sector for agriculture around the world.

Title picture

An Indian pump supplier has incorporated ABB's ACS355 solar pump drive into its pump technology, enabling independence from the electricity grid and from diesel fuel.

Solar pump drive

In 2011, ABB developed a solution that combines ABB drives with solar panels and a maximum power point tracking (MPPT) system that controls the pump through solar radiation. Pump operators, such as farmers, can then benefit from the maximum amount of pump output over the course of the day. Compared with diesel generator pumps, the ABB solar pump drive is environmentally friendly and has a long lifetime and low maintenance costs. It is independent from the grid and produces no pollution or noise.

The power range for the solar pump drive was recently extended from 0.37 to 18.5 kW up to 45 kW. This increased power range enables the use of the solar pump drives in larger pump applications such as high-power pumps in agriculture and solar desalination.

In some countries many small- and medium-sized farms are either off-grid or receive only a few hours of electricity each day.

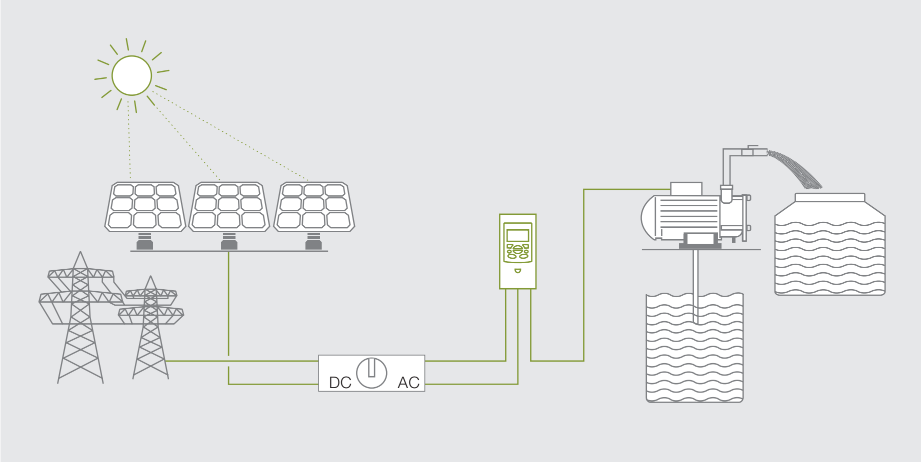
The complete system consists of four components: a photovoltaic (PV) panel, a drive, a motor and a pump. The ABB solar pump drive system uses a PV panel as its power source, which is connected to the direct-current (DC) connectors of an ACS355 or an ACSM1 drive ➔ 1. The drive is connected to the motor that runs the pump ➔ 2.

Maximum power with dual supply

The ABB drives provide uninterrupted flow, even during drastic changes in irradiation, thanks to the MPPT algorithm. Built-in MPPT functionality is also important for reliability when the equipment is installed at remote sites where maintenance is minimal. Users can monitor the pump remotely, from anywhere. Embedded, pump-specific features such as dry-run detection and sensorless flow calculation are used to protect and monitor the pumping station. The drive is designed to automatically shut down to prevent equipment damage from running the pump dry. Sensorless flow measurement gives a direct indica-

In 2011, ABB developed a solution that combines ABB drives with solar panels and an MPPT system that controls the pump through solar radiation.

2 The ABB solar pump drive



tion of the performance, allowing the end user to measure system performance based on flow rather than on electrical parameters.

After dawn, when the sunlight is sufficiently intense to power up the drive, the drive automatically starts the motor and runs the pump to draw water. At sunset, the drive turns off the motor and the water flow ceases. When equipped with a changeover switch, it is possible to run the drive from the grid – for example, during the night or when maximum flow is required and not enough solar power is available.

Compact and beneficial

The solar pump drive is preprogrammed for specific pump applications with minimal parameter settings required. Other benefits include: long pump life, elimination of restarting during DC voltage variations, and automatic fault-reset and auto-start. The solution is also free of other restrictions that can impact productivity, such as load shedding, electricity supply cuts and increased energy prices, as well as burnt motors often caused by voltage fluctuations.

A number of ABB's low-voltage components such as relays, terminal blocks and contactors are also used in the solution, including PV-S miniature circuit breakers, which are specially designed to safely extinguish dangerous DC arcs in PV applications.

Driving success

The ABB solar pump drive has been a success in India, where ABB already has thousands of installations.

In some Indian states the government funds as much as 86 percent of the cost of solar pumps as a long-term investment in the country's agricultural output and sustainability.

There is demand for the solution in, for example, Asia, South America and Africa as well: Only around 6 percent of cultivated land in sub-Saharan Africa is currently equipped for irrigation. Even in countries that do not subsidize renewables, a number of financing alternatives including rental programs, cooperatives with shared ownership and micro-loans are making solar water pumps economical for smaller off-grid farms.

With the world's growing demand for both water and energy, and environmental pressures showing no signs of easing, solar pumping is a viable short-term as well as long-term solution. ABB is paving the way for increased use of renewable energy sources around the world.

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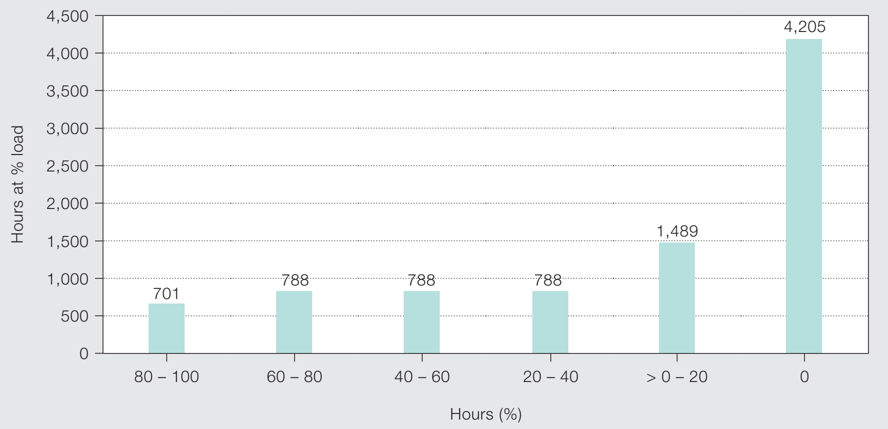
Transforming revenue

ABB's technology cuts transformer losses

PATRICK ROHAN, TERO KALLIOMAA – Although transformers have a high efficiency – typically above 99 percent – the industry-wide energy losses from transformers are significant simply due to the huge number installed. This is one reason why environmental performance legislation is increasingly regulating transformer performance. Just as important is the cost of these losses to operators: In a utility-scale solar power installation, every Watt of power lost is one that cannot be sold. Indeed, during the hours of darkness, energy often has to be purchased to keep the transformer energized, unless it can be disconnected from the network. The obvious question then arises: How can operators reduce losses and maximize the return on investment from their transformer fleet?

1 Most solar farms operate significantly below their peak output most of the time. Example data for a solar plant at latitude 45.3 °N.



The European Union Ecodesign Directive, effective July 2015, provides consistent EU-wide rules for improving the environmental performance of energy-related products. A transformer is one such product and the directive requires all transformers placed on the market to comply with strict new design specifications that explicitly address transformer losses. This trend toward the regulation of transformer losses is making owners and developers of solar plants pay closer attention to the overall costs of transformers – especially the fact that while the capital costs of the lower-loss transformers that are required to meet new efficiency directives may be slightly higher than those of "standard" transformers, the lifetime costs are lower. The lifetime cost should take into consideration not only the purchase price, installation costs, maintenance costs, etc. but also the future revenue not realized because of losses – a revenue loss that will be greater than the initial purchase price.

It makes financial sense to use lower-loss transformers: They cost slightly more to purchase, but increase lifetime revenues.

Transformer losses

Transformer efficiency is impacted by the inverter output: As the load increases, so does the transformer load loss. However, losses also arise when there is no load as energy is consumed when voltage is applied to magnetize the iron core. These losses are independent of the load and will be present as long as the transformer remains energized.

The collector network of a utility-scale solar plant, which includes transformers, is sized to the peak inverter output. But, averaged over a year, outputs usually do not exceed 20 to 30 percent of the peak value → 1. Geographical location and the technology employed – eg, tracking systems – cause production variation from site to site, therefore it is important to know what the average of the inverter output is so that transformer manufacturers can customize their designs to minimize whichever loss component has the greatest impact. In the case of solar plants, no-load losses become a significant proportion of total losses because of the lower average output.

Comparing the cost of losses

Solar farm owners seek to maximize their return on investment by operating as

Title picture
Even though they are generally very efficient, the sheer number of transformers in the field means that a substantial amount of energy is being lost. How can operators reduce these losses and get more from their fleet investments? Pictured is a solar MV station including a low-loss transformer and switchgear.

2 Example data for a transformer capital cost and performance (transformer prices are for illustration purposes only)

Transformer options					
Transformer	kVA	Voltage (V)	No-load loss (W)	Load loss (W)	Purchase price ($)
1: Regular grain-oriented steel	2,500	20,000/400	2,782	23,682	21,600
2: High-permeability steel	2,500	20,000/400	1,747	21,861	25,700

3 Energy comparison: The low-loss transformer results in increased annual revenue

Energy sales for both transformers							
Load factor (%)	Hours	Transformer 1			Transformer 2		
		Energy sales (MWh)	Price ($/MWh)	Energy sales ($)	Energy sales (MWh)	Price ($/MWh)	Energy sales ($)
100	701	1,733	130	225,349	1,735	130	225,609
80	788	1,563	130	203,138	1,564	130	203,363
60	788	1,174	130	152,565	1,175	130	152,739
40	788	783	130	101,800	784	130	101,937
20	1,489	739	130	96,037	740	130	96,253
0	4,205	-12	-65	-760	-7	-65	-477
Total				**778,128**			**779,424**

close to capacity as possible, while minimizing losses across the collector network. Capital investment aimed at lowering losses and increasing efficiency is decided upon depending on the calculated return. As an example of such an evaluation, two liquid-filled transformers can be compared: One using a grain-oriented steel that exhibits “standard” losses and a low-loss unit, using a high-quality, high-permeability steel that conforms to the new EU directive. The cost of future losses based on the loading profile shown earlier can be calculated for these two, assuming:

– The average price of energy sold is $130/MWh.
– The average price of the (nighttime) energy purchased is 50 percent of average selling price.

→ 2–3 compare the net energy sales for these two transformer types. Transformer 1 is the standard unit and has a cumulative total of 5,960 MWh available to sell, which would yield a revenue of $778,128. Transformer 2, which has lower losses and uses Hi-B core steel, has 5,992 MWh available to sell, resulting in a revenue of $779,424. Therefore, the lower-loss transformer increases revenue by $1,296 per year. This illustration is for a 2.5 MW installation, however the saving can be scaled up linearly for larger installations.

Note the negative energy sales during times of zero inverter output, indicating the solar site is purchasing power from the grid to energize the transformer and collector network → 3. This represents the no-load or core losses that are always present when the transformer is energized.

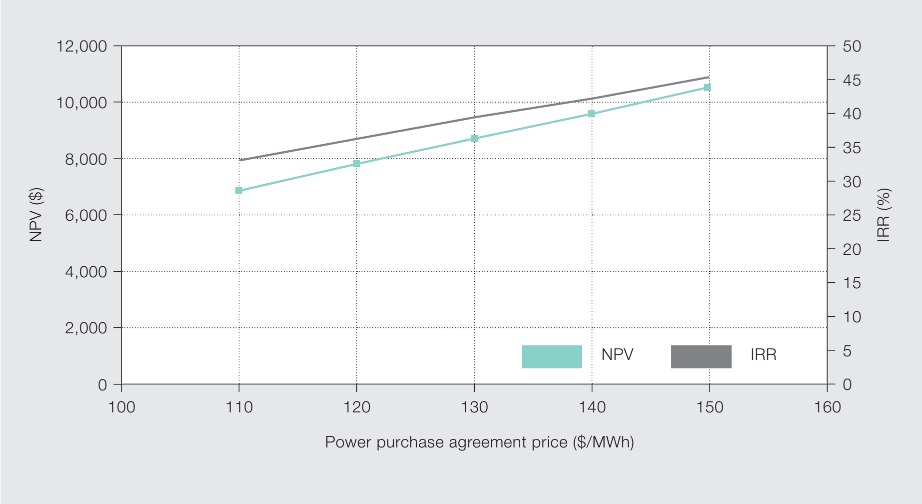
After the revenue calculation, the next step is to calculate if the additional purchase price for the lower-loss transformer is worth the investment. The calculation incorporates the initial purchase cost of the transformers and the increased annual revenue that can be achieved with the increased efficiency of the lower-loss transformer over its lifetime (assumed to be 20 years).

The financial argument for using lower-loss transformers can be examined more closely by calculating the NPV (net present value) and the IRR (internal rate of return), using an interest rate of 8 percent. The power purchase agreement (PPA) price sensitivity graph in → 4

Losses also arise when there is no load as energy is consumed when voltage is applied to magnetize the iron core.

Depending on the site's geographic location and the price paid for nighttime energy, it can also be worthwhile to consider switching the transformer out of the circuit altogether to save the nighttime energy cost.

4 The PPA price sensitivity graph shows an IRR and NPV of the additional investment at varying PPA prices.



shows an IRR and NPV of the additional investment at varying PPA prices. A $130/MWh PPA would yield an IRR of 39 percent and an NPV of $8,726. This means the additional cost for the lower-loss transformer is indeed a good investment.

Switching out to save

Depending on the site's geographic location and the price paid for nighttime energy, it can also be worthwhile to consider switching the transformer out of the circuit altogether to save the nighttime energy cost. This can be done with the help of medium-voltage (MV) switchgear.

In utility-scale solar plants, there is switchgear on the MV side of each of the transformers to protect them and the MV network from harm. The switchgear is either directly beside the transformer or further away in a collection station or grid connection substation, depending on the size and the design of the power plant. In order to break the current, the switchgear is equipped either with a fuse switch or a circuit breaker. While motorized fuse switches can be operated up to 1,000 times, the circuit breaker can be operated several thousand times.

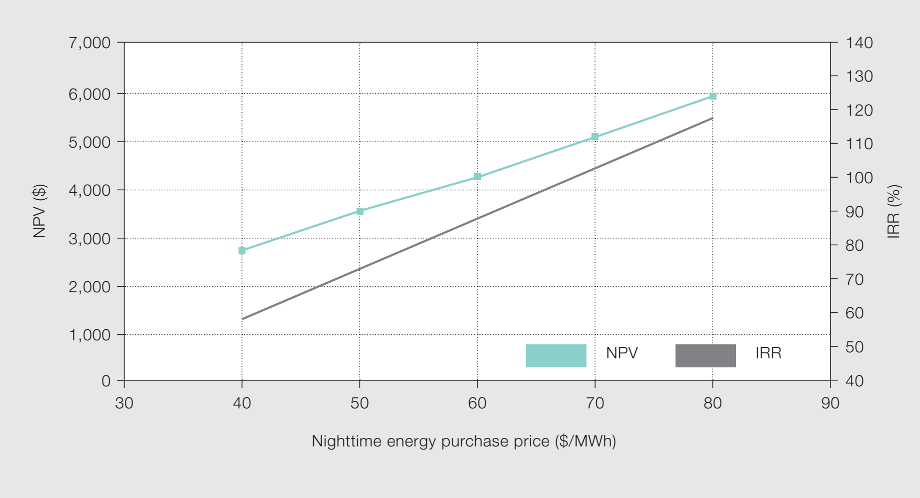
Equipping switchgear with motorized circuit breakers and remotely controlled protection relays allows automatic, or remotely operated, opening and closing schemes to de-energize the transformers. The additional investment required depends on the plant design and can involve simply changing fuses to circuit breakers, motorizing existing circuit breakers or adding motorized circuit breakers. The protection relays may also need to be changed or have communication equipment added to enable remote control of the circuit breaker.

Equipping switchgear with motorized circuit breakers and remotely controlled protection relays allows automatic, or remotely operated, opening and closing schemes to de-energize the transformers.

ABB has a wide selection of switchgear suitable for application in solar installations – for example, SafeRing/SafePlus or UniSec secondary switchgear. ABB's green policy ensures a focus on environmental factors during the manufacture and over the life span of the switchgears.

The savings achieved by doing this depends on the length of time each day the panels are not producing electricity and

5 Energy purchase price sensitivity of the additional investment for switchgear on NPV and IRR for the regular grain-oriented steel transformer, for the case where the existing circuit breaker is motorized



Savings are heavily dependent on facility design: If circuit breakers were already planned for, simply motorizing them would enable the operator to de-energize the transformers.

how many mechanical operations the circuit breakers can withstand. Obviously, in solar power plants, no electricity is produced at nighttime and to de-energize a transformer every night and re-energize it every morning over a 20-year lifetime, each circuit breaker would have to be operated 14,600 times. This poses a challenge because the circuit breakers in secondary switchgear are usually limited to a maximum of 10,000 mechanical operations.

In smaller power plants (under 10 MW), the solution is to either replace the circuit breaker after 10,000 operations or simply limit the number of operations to this figure over the transformer lifetime. In larger solar power plants, which utilize primary switchgear either in the collection stations or in the grid connection substation, it may be viable to invest in motor-operated circuit breakers that are capable of 30,000 mechanical operations. While more expensive, the number of circuit breakers required would be fewer because the primary switchgear in collection substations and grid connection substations is connected to several MV stations within the facility.

For example, ABB's UniSec secondary switchgear can be fitted with a circuit breaker capable of 10,000 operations at up to a 24 kV voltage level. A UniSec switchgear with a motorized vacuum circuit breaker could cost the site developer as little as $600 more than a nonmotorized option. However, the savings from de-energizing the transformers overnight would generate an additional $580 per year of energy savings, assuming energy costs of 65 $/MWh and that the transformer was de-energized during winter when the nights are longest and solar irradiation lowest. This adds up to 3,226 hours and 9 MWh energy savings annually in the case of Transformer 1 (compare with → 3). The return on the additional investment would be a 97 percent IRR and $4,750 NPV. Therefore, the additional investment in motorized circuit breakers would be worthwhile → 5.

Savings are heavily dependent on plant design: If circuit breakers were already planned for, simply motorizing them would enable the operator to de-energize the transformers. In installations with smaller transformers in which the fuse-switch option is viable, changing them to motorized circuit breakers may also be a good investment – depending on the energy costs.

ABB can offer support in both the internal power plant network design and the selection of the appropriate products to reach the most optimal solution from both the original investment and total cost of ownership point of view.

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Next-generation components

Advanced low-voltage components for next-generation 1,500 V DC utility-scale PV solar applications

ALLEN AUSTIN, FEDERICO MAI – Solar photovoltaics is the fastest growing renewable energy source in the world and ABB, a leading industry supplier, is committed to meeting the needs of this rapidly developing industry by providing a complete portfolio of products, systems and solutions for photovoltaics applications. To date it has met the challenge of the next-generation advanced component design by introducing a new line of 1,500 V DC low-voltage components that ensures safe processing of 1,500 V DC power, including reduced power losses, reduced number of poles, visible blade technology, integrated heat dissipating and advanced arc extinguishing technologies.

As the solar photovoltaic (PV) industry continues to become an increasingly important share of the energy mix, the balance of system component technology is continually evolving to help lower the cost of energy production. In the past few years, the industry has seen a tremendous jump from 600 V DC inputs to 1,000 V DC inputs, which represent the majority of utility-scale solar PV installations. The next step in this trend is systems with 1,500 V DC inputs, which, by increasing the voltage level, enable higher power output capability by up to 50 percent – thus decreasing system losses and balance-of-plant costs.

ABB has developed 1,500 V DC low-voltage components in order to process this new power. These components include switches, molded-case circuit breakers, contactors, surge protection devices and voltage/current sensors. Some components are rated up to 3,000 A / 1,500 V DC and carry various certifications, UL and IEC included.

Adapting to the solar market

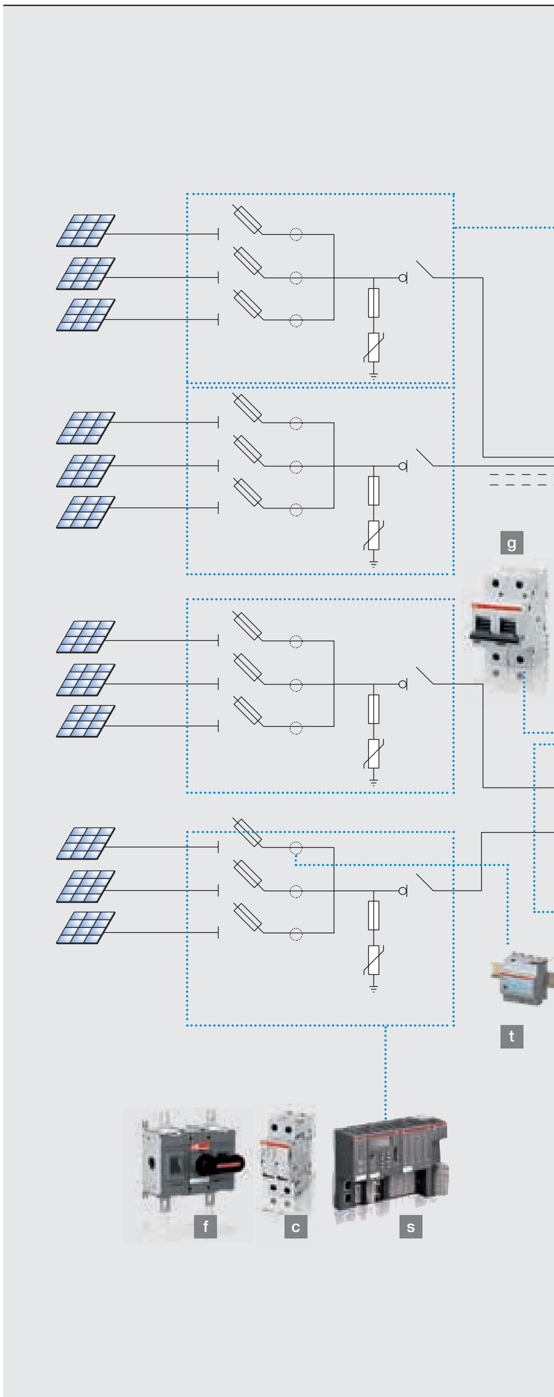
Clearly 1,500 V DC is not new – for instance it is used in rail applications – but adapting it to the solar market has brought certain challenges.

A major challenge has been the issue of higher voltage requirements affecting the design of the system and insulation requirements. Temperature is an additional aspect that has to be addressed with components in the PV plant having to operate at higher temperatures, often reaching 70° C. Additionally, components for the 1,500 V DC PV utility-scale installations may have to be designed for bidirectional current flow.

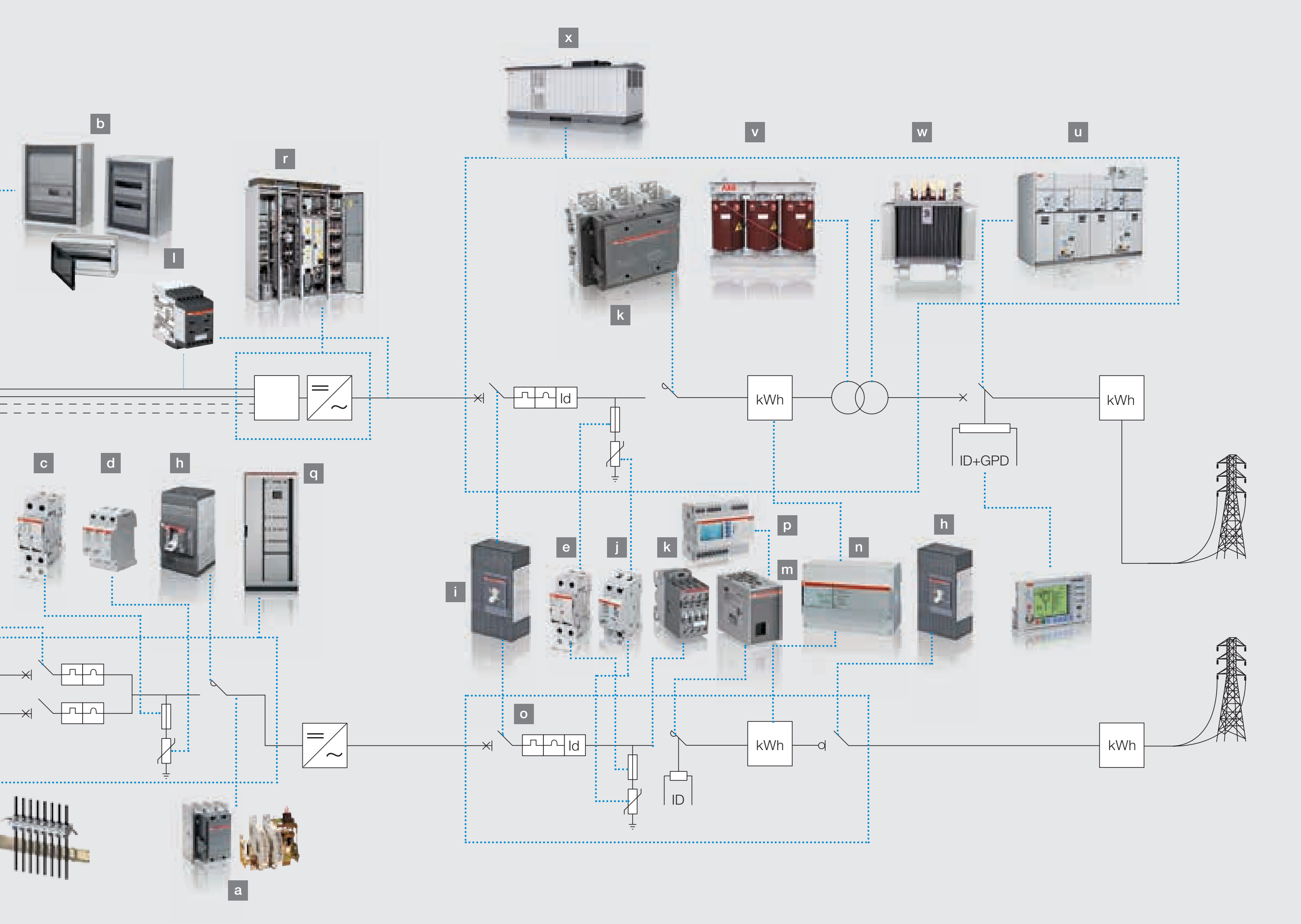
The new products also ensure safe processing of 1,500 V DC power, as well as reduced power losses, reduced number of poles, visible blade technology, integrated heat dissipating and advanced arc extinguishing technologies.

In addition to the increased voltage, the new products can also handle more current – up to 6,000 A depending on the device. This allows for utility-scale PV combiner boxes and inverters to handle more power. Some of the new products can handle two 1,500 V DC inputs simultaneously.

1 Example of photovoltaic applications: commercial 20



to 1,000 kW



Low-voltage products
a – Contactors: GAF series, IOR bar contactors
b – DC string boxes:
Switchboards: Gemini series,
Consumer units: Europa series
c – Fuse disconnectors: E 90 PV; Fuses: E 9F PV
d – Surge protective devices: OVR PV
e – Fuse disconnectors: E 90
f – Switches: OTDC series,
Miniature circuit-breaker disconnectors: S800 PV-M
g – Miniature circuit breakers: S800 PV-S
Miniature circuit breakers: S200 M UC Z
h – Switch disconnectors: Tmax PV

i – Molded-case circuit breakers: Tmax
j – Surge protective devices: OVR T1 / T2
k – Contactors: A and AF series
l – Insulation monitoring devices: CM-IWN
m – Power supplies
n – Energy meters: EQ meters
o – Residual current device blocks: DDA 200 B
Residual current devices: F202 PV B and F204 B
Miniature circuit breakers: S 200
p – CM-UFD.M22
q – ArTu switchboards

Solar inverters
r – Central inverters: PVS 800
Remote monitoring portal

String monitoring
s – PLC AC500
t – Current Measurement System (CMS)

Medium-voltage products
u – Secondary switchgear
v – Dry-type transformers
w – Liquid-type (oil-filled) transformers
x – Compact secondary substations

Already a leading supplier for all photovoltaic applications, ABB can now also provide advanced solar components to its customers that will allow them to begin their own next-generation 1,500 V DC PV utility-scale designs, thus enabling them to benefit from higher efficiency and reduced costs for their systems → 1.

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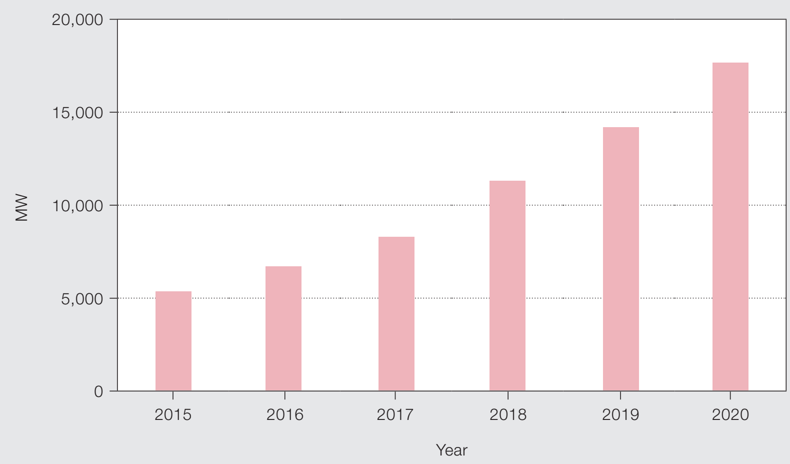
Self generation

Photovoltaics play an essential role in ABB's Active Site technology

LEONARDO BOTTI, PHILIP JUNEAU – What is the best way to connect rooftop photovoltaic panels, and how can users deploy them optimally? Photovoltaic technology has undergone a rapid transformation, both in terms of performance and cost, and is reaching the brink of competitiveness with conventional generation. Its installation is already viable without recourse to subsidies and incentives, and even with subsidy protection being decreased or abolished in many countries, the sector is continuing to see strong growth. However, the shift from conventional generation to solar generation is not just about replacing one source of power with another. It is also about a shift from centralized to distributed generation. With commercial, communal and industrial sites consuming and generating electricity as well as possibly having on-site storage, these sites are increasingly developing into microgrids. These microgrids need to be optimally managed and connected to the macrogrid. This is the role of ABB's Active Site technology.[1] This technology provides broad and comprehensive support for the emerging needs of the market. ABB provides an ideal solution for connecting and managing on-site photovoltaics (PV) using a broad range of state-of-the-art three-phase string inverters, including compact and outdoor devices and fast responding maximum power point tracking (MPPT).

1 Annual installed unsubsidized commercial and industrial PV



Source: IHS, BNEF

Subsidies for photovoltaics (PV) in the main European markets have become unviable and are being scaled down. Other mature markets will soon be seeing the same trend. But this is not bad news for solar energy generation. Significant cost reductions and rising retail tariffs have turned PV from a heavily subsidized and marginal technology into a mainstream and competitive source of power. Not only commercial users, but also residential households, are installing solar generation systems on their roofs to reduce their electrical bills. The self-consumption model, enabling residents to become "pro-sumers," means they can use energy generated on the premises, while also being able to either sell surplus or buy additional power as needed. Presently, such installations can be achieved without subsidies and can attain an IRR (internal rate of return) of more than 6 percent and a payback period of under 10 years (with an equipment life span double this). The figures are even more encouraging for commercial buildings and industrial complexes where the IRR can rise above 10 percent and the payback time fall below seven years – making them the best candidates to implement Active Site technology. Active Site can control and optimize the microgrid and its interface to the macrogrid, ensuring an optimization of energy usage and costs while permitting the microgrid to fully participate in the smart grid.

Title picture
Hospitals, campuses and factories, rather than being pure consumers of electricity, are increasingly also generating it. This picture of ABB's inverter factory in Helsinki, Finland shows the company is no exception. ABB's Active Site technology can help manage such sites and connect them to the grid.

Footnote
1 For more information regarding ABB's Active Site technology, please refer to "Active Site" on page 34 in ABB Review 4/2014.

In mature markets such as Europe and the United States the self-consumption model appears to work well, being financially viable and overall self-sustainable. Many analysis and research studies forecast that over 20 percent of electricity demand will be replaced by self-produced solar power by 2020 in these countries, thanks to over 60 GW of unsubsidized roof installations planned to occur within this timeframe ➔ 1.

In this scenario, with customer needs reaching a higher complexity level than ever before, competitiveness will be even more challenging for all energy providers, including the major utilities, whose role will shift from being energy providers to comprehensive energy service companies ➔ 2. Their ability to make this transition will be a key market success factor.

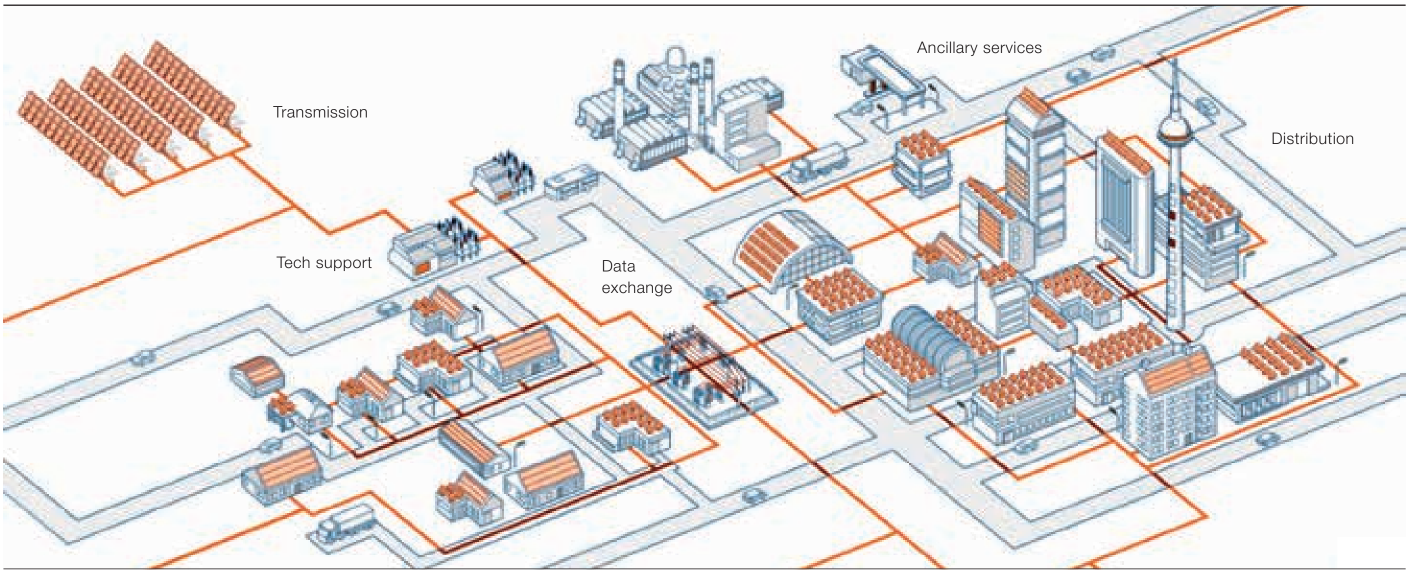
Presently, photovoltaic systems can be built without subsidies and can generate an IRR of more than 6 percent.

Enabling factors will be:
– Smart distribution capabilities (ability to master the technological complexity of the evolving grid)
– Expertise in energy management (experience in grid management as well as the necessary hardware and software tools)
– Technical prowess (expertise, professionalism and experience as well as recognition by customers and end users)

Distributed generation with PV

An electricity bill is an important expense at all consumption levels, from a single apartment to a large industrial complex. Being able to manage and control energy consumption is an important factor in cost control. On a commercial or industrial campus there are many different load profiles, characterized by individual buildings and objects. These profiles are

2 Energy services environment presenting the greatest potential for utilities



Power generation using small and flexible modules within the electrical grid is crucial to achieving a truly decentralized electrical system.

heavily influenced by factors such as the weather, hourly usage profiles, etc. To manage this users must first implement a process to measure, analyze and determine the demand and consumption profiles on an equipment or asset level. This is possible by harnessing the plethora of energy meters, sensors and other measurement components within the building automation system.

Combining this data can not only provide a detailed and precise overview of present load profiles, but also help better forecast future ones. With this detailed data available, and combined with other pertinent information about the site, determining the best on-site generation capability is a relatively small next step.

To use a real-life example, a small industrial plant in Italy is evaluated ➔ 3. The plant, which manufactures plastic enclosures, was seeking to improve its energy performance by installing a PV installation on its roof. Following a detailed analysis of the electricity demand and consumption, with over 10.6 GWh annual power expenditure, a profile was determined ➔ 3b.

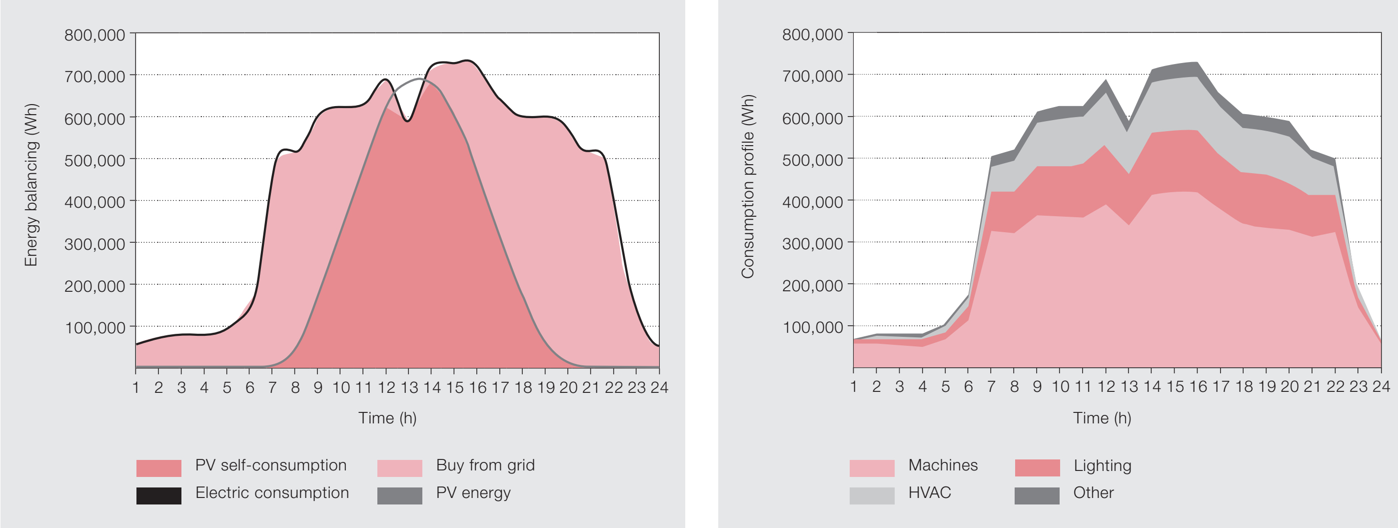
The shape of the curve is a good representation of the load activation time and perfectly matches solar availability ➔ 3a. Through simulations and analysis of all the different variables, ABB determined that the most effective solution was a 700 kW PV installation. This solution permits the site to consume 1.1 GWh/year and, assuming an electricity rate (taxes included) of 17 cents/kWh (0,156 EUR/kWh), results in a substantial savings of over $150,000/year (140.000 EUR/year) with a payback of slightly more than six years and an IRR of 11.5 percent. ABB's solution to achieving this goal is combining 24 units of TRIO-27.6-S2X and a single VSN-700-05 monitoring system, along with environmental sensors, low-voltage breakers and ancillary protections.

Local intelligence and virtual power plants

Power generation using small and flexible modules within the electrical grid is crucial to achieving a truly decentralized electrical system. An Active Site featuring distributed solar generation is the most effective way to attain this goal. Under certain conditions, such installations can become virtual power plants (VPPs), featuring a continuous exchange of data between microsites and the grid. VPPs enable the provision of system services in the transmission and distribution network (eg, control power in the so called "minute reserve capacity") configured by combining loads from end-use equipment with emergency generating units and distributed generation. The VPP aggregates the electrical output from a multitude of objects and makes this supply available to the distribution system. When requested, the VPP controls the immediate dispatch of electrical output to the connected plants, contributing to grid stability.

ABB's three-phase string inverters fitted in industrial campuses as well as in commercial buildings play a crucial role in

3 Real world example: factory in Italy



3a Daily energy balancing at site with local PV

3b Daily consumption profile for the site

bringing these Active Sites to the VPP level. Thanks to their multiple maximum power point tracking (MPPT), these inverters can maximize site production.

Looking at grid requirements in detail, the ABB inverter product lines PVI, TRIO and PRO provide a wide range of reactive power and fault ride through functions. Coupled with frequency/voltage management control, they make an important contribution to network stability. The benefits of VPPs for energy providers include:

- The option of “trimming” electrical demand peaks, thus securing a higher stability level for the energy production facilities. This indirectly provides consistent savings in terms of the additional costs otherwise required to meet higher peaks for short periods.
- Reduces the need for backup systems due to the lower consumption and the better energy flow management achieved. This allows closing legacy generation plants (capex reduction).
- Avoids replacement of old and/or obsolete power plants with new power generation facilities (capex avoidance). This is a critical item in many countries where massive investments are the main alternative.
- Reduces expenses on legacy grids by leveraging the Internet of Things with the use of applications (apps) via smart tablets and smartphones. Such end-user apps will help reduce general and administrative efforts.
- Extraordinary ability to perform real-time diagnostics when faults occur with the opportunity to perform effective preemptive interventions, thus saving on maintenance expenses (opex).

Communications

Optimizing a site’s self-consumption is the way to make the most of solar-based electricity, but to do so requires a continuous and reliable exchange of data between the different participants in the decentralized electrical system, namely generators, loads and the grid. ABB’s Active Site architecture bases its communication on multiple protocols to ensure that all possible inputs are analyzed and managed by the Active Site control system. The system’s communication connects loads, switches, sensors and meters and distributed solar generators. Algorithms and operating schemes provided by the grid operators balance the energy operation of the site with the aim of minimizing wastage and meeting network fluctuations. ABB solar inverters can communicate using a range of protocols including ModBus, TCP/IP and RS 485 as well as open gateways. They are fully integrated into the building automation system and can exchange data continuously with the overall Active Site energy management system.

PV installations are a vital part of ABB’s Active Site concept. Coupled with a company’s energy storage and building automation technologies, the PV installations have a vital part to play in energy independence and sustainability.

Algorithms and operating schemes provided by the grid operators balance the energy operation of the site with the aim of minimizing wastage and meeting network fluctuations.

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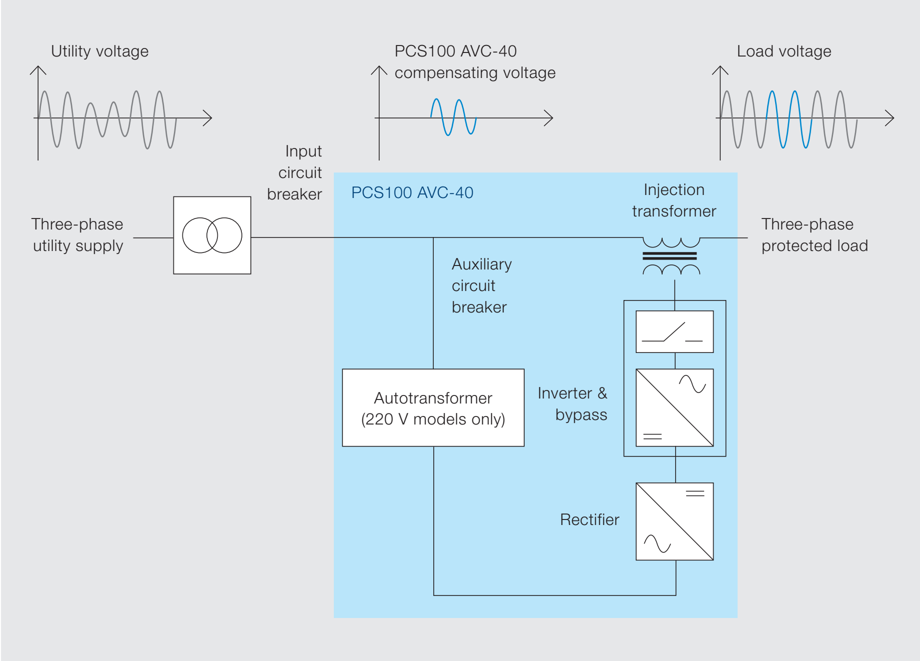
Steady as a rock

Two PCS100 AVC products now designed for different applications

DARIO ROZMAN – Even developed countries equipped with modern power networks are not immune to voltage problems. While outages may be rare, the voltage problems caused by weather, network faults or "digger-through-the-power-cable" type events are ever-present. With modern industry employing more and more automation, the sensitivity of processes to such power quality events is increasing. Even an event lasting less than a few cycles can cause processes to unexpectedly stop – potentially resulting in product damage, wastage and production shortages. In developing countries, or regions with a weak power supply, the main problem is poorly regulated voltage. Without the correct voltage, the reliable process operation may not be possible. If the voltage is low or imbalanced then the overheating of motors is a particular concern. ABB's PCS100 AVC products are designed to protect industry from voltage events, allowing companies to get on with what they do best.

1 PCS100 AVC-40 schematic



Often, industrial sites are located close together – for example, in an industrial park or in a particular area of a city. If one user in this cluster disrupts the utility voltage – by starting a large motor, for example – the others can be affected by power supply sag or fluctuation. Weather events or faults in other parts of the utility network can also cause the voltage to sag well below its nominal value and stay there for many cycles.

Such voltage variations can cause sensitive production equipment to stop. If a production line stops, it has to be restarted and this can be a complicated and very expensive exercise. Equipment damage caused by power quality events can be even more costly. Further, equipment can be very dependent on a stable power supply to deliver a good-quality end product.

It is best, then, for companies exposed to the risk of an uncertain power supply to invest in equipment that ensures a constant supply of clean, high-quality power – ABB's PCS100 Active Voltage Conditioner (AVC).

Title picture
ABB's PCS100 AVC corrects voltage sags or fluctuations and ensures a supply of high-quality power to critical loads.

The PCS100 AVC product

ABB has a variety of power protection products and the PCS100 AVC is unique among these. Specifically designed for industrial and large commercial applications, the PCS100 AVC is able to respond instantly to voltage sags and surges, correct for voltage imbalances and remove voltage flicker.

> The PCS100 AVC-40 responds to voltage sags or swells within several milliseconds and can inject up to 40 percent voltage correction.

The PCS100 AVC consists of two converters that are not in the current path between the load and the utility. Instead, the corrective voltage injection is achieved by means of a transformer winding placed between the utility and the sensitive load → 1–2. This configuration delivers a very efficient and effective voltage correction.

The PCS100 AVC does not require battery storage as it draws the additional current required to make up the correction voltage from the utility supply. Without the ongoing maintenance costs typically associated with batteries, the cost of ownership of PCS100 AVC systems is very low.

Furthermore, the PCS100 AVC contains a bypass system that, in the event of a fault within the PCS100 AVC, ensures that the load continues to be supplied from the utility.

The PCS100 AVC is available with ratings from 150 kVA to 3.6 MVA and is realized in a low-voltage switchgear cabinet → 3. It offers precise online voltage control, a proven and dependable converter platform, sophisticated control software and an efficiency of 99 percent. The PCS100 AVC product portfolio now has two products designed for different applications:

- The PCS100 AVC-40 – designed for customers who have a stable network, but one which may be susceptible to voltage sags caused by external factors such as weather, etc.
- The PCS100 AVC-20 for continuous voltage regulation. This product is ideal for customers whose network is weak and unstable.

The PCS100 AVC does not need batteries as it draws the additional current required to make up the correction voltage from the utility supply.

2 The PCS100 AVC

Each product is specifically engineered to fix different types of common utility power supply problems.

PCS100 AVC-40 Active Voltage Conditioner for sag correction

The PCS100 AVC-40 responds to voltage sags or swells within several milliseconds and can inject a voltage correction of up to 40 percent. For example, if a facility was faced with a voltage that sagged to 60 percent of its nominal value, the PCS100 AVC-40 would boost the voltage back to 100 percent. No lights would dim and no equipment would trip – business would go on as usual. This example applies to three-phase power; performance is even better for single-phase sags (the most common type): voltage sags down to 45 percent of the nominal voltage are fully corrected.

The PCS100 AVC contains an internal bypass system that, in the event of a fault with the AVC, ensures that the load is continually supplied from the utility.

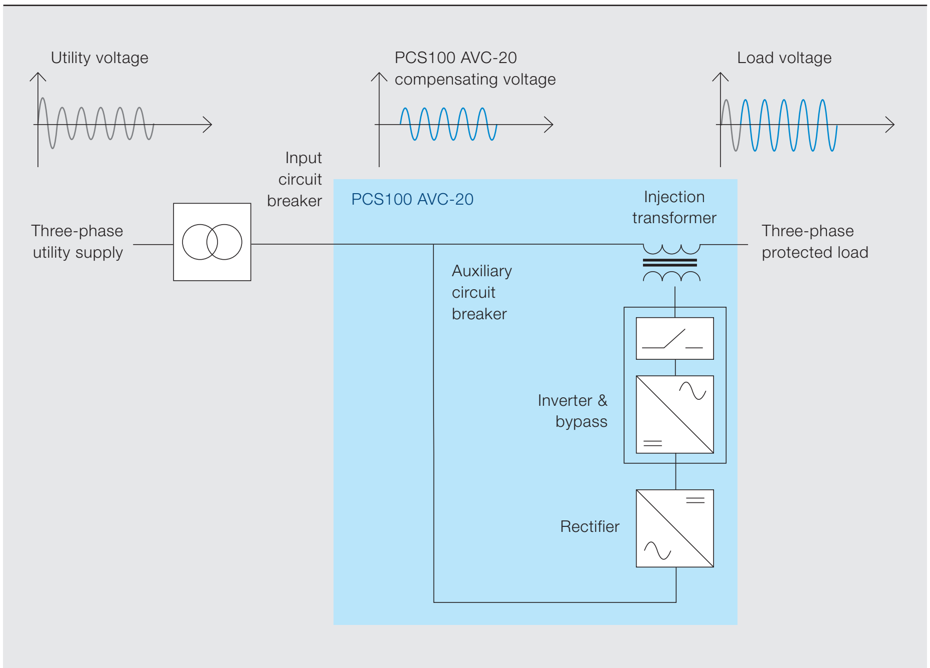
For three-phase sag events, the PCS100 AVC-40 can restore voltage that has sagged to 50 percent back to the 90 percent level, thus guaranteeing continued plant operation. The AVC can sustain this correction for 10 seconds. This performance amply covers the sag durations experienced by customers. Thus, plant operation is well protected against the two main aspects of voltage sags – depth and duration.

For single phase, the PCS100 AVC-40 can correct sags of up to 30 percent remaining voltage back to 90 percent, guaranteeing continued plant operation. The AVC can perform this correction for 10 seconds at this voltage level. Again this is more than covering the sag durations experienced by customers.

In addition, the PCS100 AVC-40 is able to continuously correct voltage fluctuations of ±10 percent in the mains voltage and even remove imbalances from the supply voltage.

The product is rated from 150 kVA to 3.6 MVA and is available for 220 V, 400 V and 480 V. Special voltages and powers up to several MVA are available as customized designs.

3 PCS100 AVC-20 schematic



Rated at up to 3 MVA, the PCS100 AVC-20 ensures continuous voltage regulation to 100 percent for voltage fluctuations of ±20 percent of the mains voltage. It also removes any imbalances from the supply voltage.

PCS100 AVC-20 Active Voltage Conditioner for voltage regulation

Rated at up to 3 MVA, the PCS100 AVC-20 ensures continuous voltage regulation to 100 percent for voltage fluctuations of ±20 percent of the mains voltage. The PCS100 AVC-20 also removes any imbalances from the supply voltage → 3.

If the voltage fluctuations are even higher, the PCS100 AVC-20 will undertake a partial correction, with a voltage injection of up to 20 percent. For example, with mains voltage drops of 30 percent, it corrects to 90 percent of the nominal voltage – keeping voltage levels inside standard specifications of most electrical equipment.

Common features

The PCS100 AVC has several advantages over competitors' devices:

- Small dimensions: Space is often an issue in industrial environments and the compact dimensions of the PCS100 AVC allow it to be installed in small spaces.
- High reliability: An integrated bypass, and industrial-grade overload and fault capacity contribute to the high reliability.
- Lowest total cost of ownership: The absence of energy storage (batteries), low maintenance and high efficiency mean running costs are low.

The PCS100 AVC-40 and AVC-20 products both feature a large touch-screen LCD, through which the device can be operated and detailed event logs accessed. An integrated Web server allows remote access and emails can be sent to those concerned when a power quality event occurs.

Modern factories with sophisticated equipment face continuous threats from power utility network events such as sags and surges. By installing ABB's PCS100 AVC they are equipping themselves with a sophisticated layer of protection that improves their bottom line by dramatically reducing downtime, scrap material, poor product quality, lost production time and reduced plant maintenance.

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Safe and powerful

Dry transformers for subtransmission

MARTIN CARLEN, MARIANO BERROGAIN – ABB's recent innovative power transformer, the HiDry72, is now in operation in a number of substations around the globe. With HiDry72, ABB has paved the way for dry-type transformer use to move from distribution applications into the subtransmission voltage range. The very capable and very safe oil-free technology behind this power transformer now allows substations to be easily integrated into any building, with full peace of mind. HiDry72 is particularly beneficial for substations located in cities and busy public venues with hefty power requirements.

Title picture
Salvador da Bahia in Brazil, with the Arena Fonte Nova stadium, which contains a 69 kV substation, equipped with 69 kV / 25 MVA dry-type transformers. Photo credit: World Cup Portal.

A number of new stadiums were erected for the 2014 FIFA World Cup in Brazil. One of the stadiums is the Arena Fonte Nova in Salvador da Bahia, a city of 2.7 million, located on the Atlantic coast in central Brazil. The stadium has 55,000 seats and is located in the center of the city ➔ title picture.

Electric power is supplied to this part of the city by a 69 kV subtransmission cable line. With the demolition of the old stadium and construction of the new one, a nearby outdoor substation had to be replaced. The substation site was on a planned recreational space, so the local energy provider came up with the idea of integrating the new substation into the stadium under construction. Fortuitously, this was at the same time that ABB announced the launch of a dry-type power transformer for the 72.5 kV voltage class – HiDry^{72} [1]. HiDry stands for "high-voltage dry"; the superscript "72" indicates the 72.5 kV voltage class.

Those responsible for the project were intrigued by the idea that fire- and explosion-proof dry transformer technology could now be used not only for medium-voltage (MV) applications, but also for high-voltage (HV). It also became clear that dry transformers allowed the most straightforward design and layout, provided the most cost-efficient solution and that their use would remove any safety concerns about integrating the substation into the stadium. Safety is a primary aspect in a venue attended by tens of thousands of spectators.

Dry transformer technology

In contrast to oil-insulated transformers, dry transformers are air-insulated. This has pros and cons: The dielectric strength of oil is about eight times that of air, so the dimensions of an oil-immersed transformer core and coils are smaller than the air-insulated equivalent. On the other hand, dry transformers need no bushings and oil spills cannot occur. Their major advantage, though, is the lack of inflammable oil and other combustible materials. While a typical power transformer contains several thousand liters of inflammable oil, the insulation materials used in fire class F1 dry transformers are self-extinguishing. Dry transformers also provide an alternative to gas-insulated transformers and are safer to handle.

There are a number of different technologies used for dry transformers – like vacuum cast coil (VCC), RESIBLOC® and Open Wound – with each offering different special features. ➔ 1 shows the main components of a VCC transformer.

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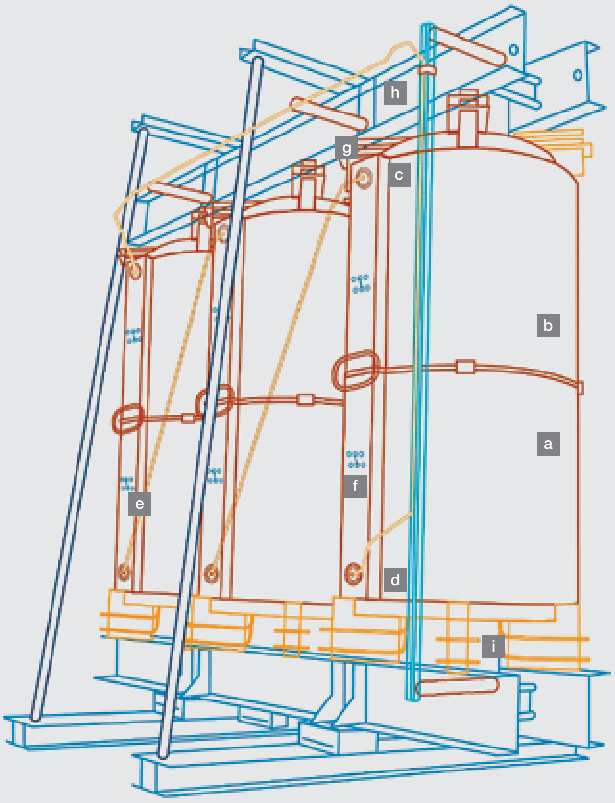
Between the primary and secondary coil of a VCC transformer is an air duct. Since the dielectric constant of the solid insulation material around the winding is higher than that of air, the electric field is mainly taken

1 **Dry transformer**



a – Primary coil (HV)
b – Secondary coil (LV, inside)
c – HV coil terminal (top)
d – HV coil terminal (bottom)
e – Delta connecting bars
f – Taps
g – Transformer core
h – Core clamps
i – Entry of cold cooling air

2 **HiDry[72] characteristics**

Primary voltage	Up to 72.5 kV
Rated power	Up to 63 MVA
Lightning impulse voltage	325 kV for IEC 350 kV for ANSI/IEEE
Short-duration AC withstand voltage	140 kV for IEC 140 kV for ANSI/IEEE
Secondary voltage	Up to 36 kV
Connection group	Y or D
Partial discharge	<10pC
Insulation class	F (155°C) or H (180°C)
Environmental class	E2
Climatic class	C2
Fire class	F1
Cooling	AN, ANAF, AFAF, AFWF A: air W: water N: natural convection F: forced convection
Tapping and OLTC	17 positions (± 8 x 1.25%)
Enclosure	No enclosure, or IP and NEMA (National Electrical Manufacturers Association) indoor or outdoor enclosure according to requirements

up by the air in the duct. The size of the air duct needs to be large enough to withstand lightning impulse testing. Each transformer is tested for partial discharge (a partial discharge level below 10 pC is required). This guarantees that the solid insulation is of high enough quality and is free from voids.

The same air duct also provides a flow of cooling air, which enters at the bottom and creates a self-sustaining flow thanks to the chimney effect. This provides an automatic regeneration of the insulating air. Additional air ducts are located between the low-voltage (LV) coils and core legs. The HV coils are also cooled on their outer surface. For transformers with high power ratings, additional air ducts can be introduced into the LV and HV coils.

The windings can be made from an aluminum or copper conductor, depending on customer preference. Incoming cables or open busbars are directly connected to the HV coils.

Globally, there is a significant trend toward using more dry transformers. The market potential is large: While for LV applications dry transformer technology already strongly dominates, in MV applications oil-immersed units are still the most prominent. For HV applications, besides a few units using SF_6 gas insulation, oil-immersed types predominate as well. HiDry[72] transformers are the first series air-insulated transformers for the 72.5 kV voltage class.

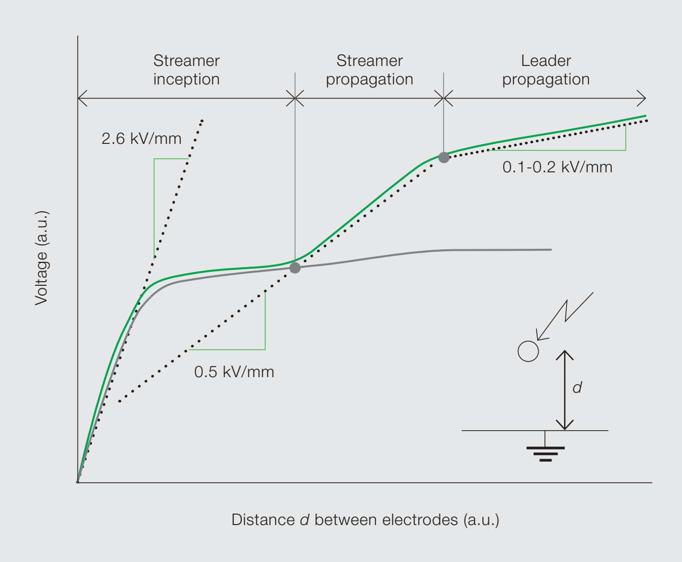
HiDry characteristics and technology

HiDry[72] is available for power ratings up to 63 MVA in either three-phase or single-phase solutions. It offers the same functionality as an oil-immersed power transformer [2, 3] – including on-load voltage regulation using a dry-type on-load tap changer (OLTC). The OLTC offers a regulation range of ±10 percent → 2.

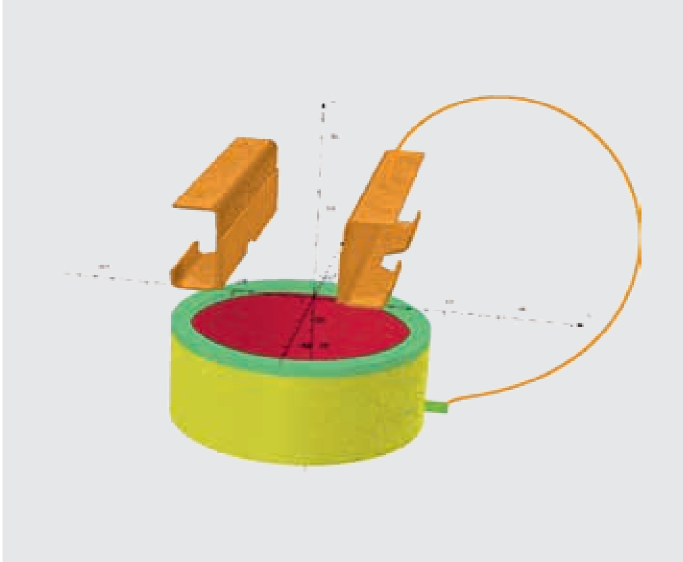
HiDry[72] transformers use the same base technology as is used for MV applications and is available in ABB's VCC and RESIBLOC dry transformer implementations. But the demands placed on transformers for subtransmission voltage levels are much higher than those placed on distribution transformers: The higher voltage, higher rated power and increased range for voltage regulation

While a typical power transformer contains several thousand liters of inflammable oil, fire class F1 dry transformers are self-extinguishing.

3 The dielectric behavior of air is a critical factor in the transformer design.

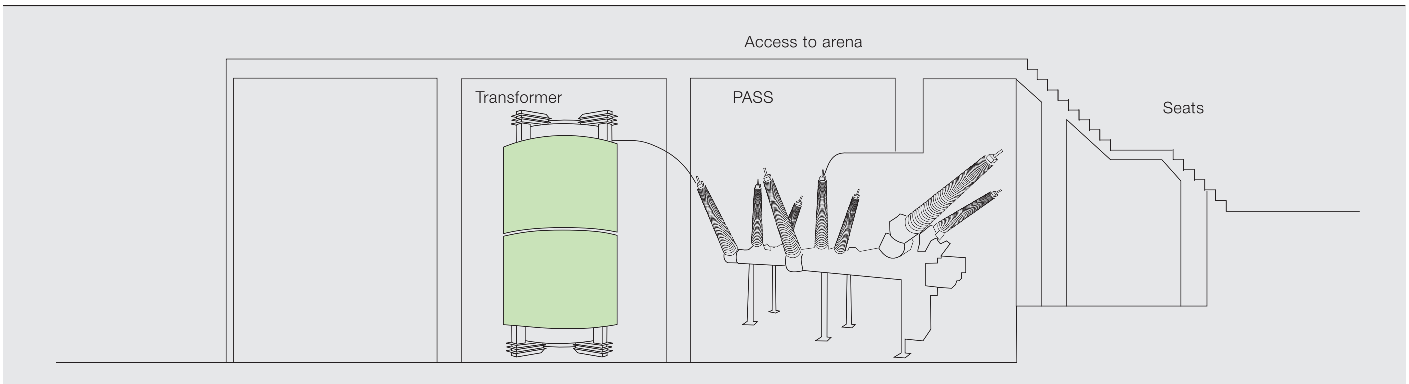


3a The green curve represents the withstand voltage for a sphere-plane arrangement [1].



3b Evaluation of prospective discharge path by dielectric simulations

4 HiDry72 69 kV substation in Arena Fonte Nova, Salvador da Bahia, Brazil, with transformer and GIS installation



Globally, there is a significant trend toward using more dry transformers and the potential market is large.

require complex dielectric, thermal and mechanical problems to be solved.

In particular, when going beyond the 36 kV voltage class a thorough understanding of gas breakdown physics is required in order to minimize dielectric distances in air ➔ 3. Distances are minimized by introducing shielding rings in the windings, shielding core parts, and applying multiple-barrier concepts and barrier arrangements. These techniques influence the local electric field distribution and determine discharge paths.

Fire safety – decisive for indoor and underground substations

HV substations in city centers are mostly located in special buildings, mainly because of transformer fire and explosion risk. However, growing use of HV in inner-city settings and decreasing space availability makes the integration of HV substations into public or private buildings very desirable – a market situation for which HiDry72 is ideally suited due to its excellent fire-safety properties.

HiDry72 transformers use an epoxy resin for the casting of the coils. Epoxy resin is a thermosetting polymer that – in contrast to thermoplastic polymers – does not melt at elevated temperatures. The resin is filled with a large amount of noncombustible silica – either small sand particles or glass fiber – which, in case of fire, takes up heat and reduces the combustion temperature. When subjected to high temperatures, the epoxy does not spontaneously ignite but, rather, degrades and starts to degas and oxidize. Once the external input of heat stops or an external fire extinguishes, this process ceases. Thus, the HiDry72 transformer never poses a flammability risk.

Flammability testing

Transformers of fire class F1 (which is based on the IEC 60076-11:2004 standard) have restricted flammability and the

5 HiDry72 69 kV/25 MVA transformer at the Arena Fonte Nova

5a With dry OLTC (on the left)

5b PASS M00 72.5 kV SF_6/air hybrid switchgear

HiDry72 transformers offer the same functionality as oil-immersed power transformers – including on-load voltage regulation using a dry-type OLTC.

emission of toxic substances and opaque smokes is minimized. The F1 fire behavior test is performed with one complete phase of a transformer – comprising HV and LV coils, the core leg and insulation components. A container filled with ethyl alcohol is placed below the coil and the alcohol is ignited. An electrical heating panel, representing an additional external heat source, is placed along one side of the HV coil, irradiating it with 24 kW. The test is performed in a standardized test chamber and the temperature and optical transmission properties of the exhaust gas are measured.

It is very important that the exhaust gases are not of poisonous or of a highly corrosive nature since they can flow into other parts of the building or be distributed via the ventilation system and may affect a large number of people. High transparency of the smoke allows people to orient themselves and find emergency exits.

ABB's experience of dry transformers with internal failures is that they do not explode or eject parts. Normally the coils crack, local arcing and carbonization occurs, and some smoke is generated. Depending on the fault, the system protection will then disconnect the transformer or the temperature sensor will detect a tripping temperature [4].

Arena Fonte Nova substation, Brazil

The 69 kV substation installation in the Arena Fonte Nova stadium has a redundant configuration of two transformers and two sets of HV switchgear → 4. The transformers are placed below the access area of the stadium, very close to the grandstand. Open busbars fixed to the ceiling of the electric room connect switchgear and transformers. The substation was put into operation in spring 2013, well in time for hosting 2013 FIFA Confederations Cup games.

The 25 MVA transformers connect on the secondary side to the MV switchgear → 5. They have a secondary voltage that is switchable between 11.95 kV and 13.8 kV. The transformer coils are made with VCC technology, which provides robust windings (E2 environmental class) and good protection from environmental

6 HiDry^{72} 31.5 MVA / 66 kV dry power transformer at CESI test lab for short-circuit testing

7 16 MVA / 45 kV dry transformer with OLTC and enclosure for installation in an outdoor substation in Sweden

pollution and humidity. The transformer is cooled by natural convection. It is tested for a lightning impulse voltage of 350 kV.

The dry-type OLTC is installed in front of the transformer, with each phase having its own unit. The OLTC uses vacuum interrupters for switching. It is configured to provide a regulation range of +4/-12 percent in 1.25 percent steps. Both transformer and OLTC are fenced off in order to avoid unintentional personnel contact, but no enclosure is required.

Seville inner-city substation, Spain

There are now many HiDry^{72} transformers installed around the world. In Seville, Spain, for example, Endesa, the largest electrical utility in the country, decided to replace the existing oil-filled power transformers in two substations with HiDry^{72} transformers in order to eliminate any related risk for the neighborhood. Each substation has two transformers. One of the 31.5 MVA, 66/22 kV, OLTC (±8 x 1.25 percent) transformers was successfully short-circuit tested at the CESI independent testing facility in Italy, against the relevant requirements of IEC 60076-5 ➔ 6. The OLTC was mounted on the transformer. This was the largest power rating of a dry transformer ever tested at CESI.

Similarly, the utility in Ulricehamn, Sweden needed to replace an outdoor oil-immersed transformer in a forest. The utility decided to install a 45/11 kV, 16 MVA HiDry transformer and OLTC, thus reducing the environmental risk to zero ➔ 7. The RESIBLOC coils are qualified for temperatures down to -60°C.

Future substations

Combining gas-insulated switchgear with HiDry^{72} transformers allows very compact substations to be constructed and easily integrated into any building. HiDry^{72} transformers can deliver higher voltages and more power to urban areas without the need to build additional substations. The very positive experience achieved so far with the 72.5 kV dry power transformer suggests that the portfolio of dry transformers should be extended to the next-higher voltage class.

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