Microgrids as drivers in the global energy transition towards renewables

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1. Climate change and the need to intervene

Mitigation and adaptation to climate change are key challenges of the 21st century. The global climate is changing and this is leading to increasingly serious risks for ecosystems, human health and the economy. The trend in long-term global warming is going on, or rather it is accelerating. According to the World Meteorological Organization (WMO, 2018) the 20 warmest years on record have all occurred in the past 22 years and the top 4 were in the past 4 years alone. The IPCC special report on the impacts of global warming of 1.5°C (IPCC, 2018) claims that for the decade 2006-2015 the average global temperature was 0.86°C above the pre-industrial baseline. This digit, however, has increased to 0.93°C in the most recent decade (2009-2018), and to 1.04°C in the last five years (2014-2018). The impacts of climate change, in the form of sea level rise, more extreme weather events, floods, droughts and storms are already evident in many countries worldwide.

These changes occur because large amounts of greenhouse gases are released into the atmosphere as a result of many human activities carried out all over the world, including, among the most important, the combustion of fossil fuels for energy production, heating and transport. The use of fossil fuels also causes the release of atmospheric pollutants harmful to the environment and human health. Energy use is by far the main source of greenhouse gas emissions due to human activity. About two-thirds of global greenhouse gas emissions are related to the use of fossil fuels for energy purposes. To be able to limit global warming, the world urgently needs to use energy efficiently, making use of the clean energy sources.

The efforts made so far globally to mitigate climate change culminated in 2015 with the Paris agreement, the first universal legally binding global climate agreement adopted by 195 countries. The goal (limiting the average global temperature increase well below 2°C, while trying to reduce it to 1.5°C, compared to pre-industrial levels) is ambitious and cannot be achieved without making a major overhaul of global energy production and consumption.

In support of the global climate agenda, the EU has adopted climate and energy targets that are binding for 2020 and proposed targets for 2030 as part of its overall efforts to move to a low-carbon economy and reduce greenhouse gas emissions of 80-95% by 2050. The first set of climate and energy targets for 2020 includes a 20% reduction in emissions (compared to 1990 levels), an energy consumption of 20% coming from renewable sources and a 20% increase in energy efficiency. The next goal of 2030 will provide for an update of these objectives: the emissions must be reduced by 40%, 27% of the energy must come from renewable sources and energy efficiency will have to increase by 27% (or 30%, according to the recent proposal of the European Commission) with respect to the reference objectives.

Renewable power and electrification technologies, therefore, have been identified as the key enablers for energy-related CO_2 emissions reductions.

Weather-related effects, as the unusually large number of hot and cold days, cause a fast increase in energy demand in the form of electricity. The latter has grown two thirds faster than energy consumption as a whole since 2000. The uptake of electric vehicles also contributed to this high use of electricity. Electricity in 2016 accounted for 19% of total final energy consumption, but its share is expected to grow. By 2050 electricity could become the central energy carrier, growing from a 20% share of final consumption to an almost 50% share – and, as a result, gross electricity consumption would more than double. But the shift towards greater electrification can play an important part in the energy transition only if it is accompanied by a decarbonization of the power sector. Renewables have emerged as the fastest growing energy source in the last decade, outpacing the growth of any other energy source, including fossil fuels (oil, coal and natural gas). Renewable power could therefore provide the greater part of global power demand (estimated in 86%).

Looking at the contribution of the main sources to the global energy balance, and identifying different energy ages over time, we observe that at the age of biomass first followed the coal age, then the oil age, then that of gas and finally the nuclear age. Even though nuclear energy is a low-carbon technology, the growth prospects for nuclear energy seem limited. After rapid expansion in the 1970s and 1980s, the growth of nuclear power has slowed in the last three decades. The share of nuclear in electricity generation declined from 17% in 2000 to 10% in 2017. Around two thirds of today's nuclear power plants in advanced economies are more than 30 years old and will be shut down in the foreseeable future unless their lifetimes are extended. Some countries are building new nuclear power plants, notably China, India, Russia, and the UAE. In others, governments are planning to phase out nuclear power, as in Germany, Switzerland, Spain and South Korea. Overall, nuclear era seems today aborted. Each of these energy transitions was different, but all required at least 30 to 50 years. The last and current trend is instead characterized by an extraordinary and above all fast growth in renewables[1]. Since 2012, renewables have added more new power generation capacity than conventional sources of energy. Solar power added more new capacity in 2017 than did coal, gas, and nuclear plants combined. Wind and solar now provide 6% of electricity generation worldwide, up from 0.2% in 2000. In the aggregate, renewables account for around a quarter of global electricity generation. Countries such as Denmark already generate more than half their electricity from variable renewable energy sources. In 2017, Costa Rica's electricity was generated entirely from renewable energy for 300 days. For several days in the past year, the power systems of Germany, Portugal and Denmark were able to run entirely on renewables. The trend is estimated to continue in the coming years (Scorrano and Danielis, 2018).

Many enabling trends are driving the rapid deployment of renewables.

First of all, the **widespread and rising concern about the climate crisis** caused by fossil fuels have led governments, businesses, investors and the public to recognize the need to decarbonize the global economy. **Pollution**, mainly caused by the burning of oil and coal, is making the air dangerous to breathe in many

[1] The main renewable energy sources are bioenergy, geothermal, hydropower, ocean, solar and wind. Among these, solar energy and wind power are undergoing very rapid growth, while the others are growing more gradually. Solar and wind, in particular, are variable renewable energy sources, since the amount of power they generate varies with the weather and the time of day.

cities. The World Health Organization estimates that nine out of every ten people in the world breathe polluted air that is hazardous to health and wellbeing, and that air pollution kills 7 million people every year, making it the fourth largest cause of death. Climate change poses an existential threat to humanity and the Earth's eco-systems.

Moreover, **energy sources are limited.** Global fossil fuel consumption is rising, and new reserves are becoming harder to find. Those that are discovered are significantly smaller than the ones that have been found in the past. Globally, we currently consume the equivalent of over 11 billion tonnes of oil from fossil fuels every year. Crude oil reserves are vanishing at a rate of more than 4 billion tonnes a year, and if the trend does not change, our known oil deposits would run out in just over 53 years. If we will use gas to fill the energy gap left by oil, our known gas reserves will run out too, in just 52 years. Although we have enough coal, if we increase its production as a consequence of the depletion of oil and gas, our known coal deposits could be gone in 150 years. Unlike fossil fuels, green energy made from wind and solar power is sustainable, because it is generated by resources that won't run out. For example, the energy payback for solar power technology is just two years. That means it only takes two years for a solar park to make the same amount of energy used in its manufacture and installation. And after that, it can provide decades of clean energy.

Moreover, many countries are shifting to renewables because they lack oil and gas reserves and wish to be less dependent on energy imports. Many major oil-producing countries are also setting targets for increasing the proportion of renewables in their energy mix. The United Arab Emirates' energy strategy, for example, sets an objective of 44% of renewables in its power supply and a 70% reduction in its carbon emissions by 2050. Russia auctioned 2 GW of renewables in 2017 and another 1 GW in 2018. Also local governments and municipalities have played a role in establishing renewable energy targets. California, for example, has adopted a 60% renewable electricity target by 2030, and several cities, from Mexico City to Madrid, have announced plans to ban diesel cars.

The **cost of renewable energy** has significantly **dropped** over the past years, to the point where almost every source of green energy can now compete on cost with oil, coal and gas-fired power plants. Hydroelectric power is the cheapest source of renewable energy, at an average of $0.05 per kilowatt hour (kWh), but the average cost of developing new power plants based on onshore wind, solar photovoltaic (PV), biomass or geothermal energy is far below $ 0.10/kWh. Not far behind is offshore wind, which costs close to $0.13/kWh. All these fuel types are now able to compete with the cost of developing new power plants based on fossil fuels such as oil and gas, which typically range from $0.05/kWh to over $0.15/kWh.

Technological advances and increased investment, allowing a steep decline in costs of renewable energy and energy storage, made possible a competitive cost advantage of technologies such as solar and wind, even without subsidies. Since 2010, the average cost of electricity from solar PV and wind energy has fallen by 73% and 22% respectively. Auction prices suggest that by 2020 the average cost of electricity that is generated by solar and wind sources will be at the lower end of fossil fuel electricity costs. The cost of lithium-ion batteries, which are used in electric vehicles, has fallen by 80% since 2010. As a result of these cost declines, investments in renewable technologies are increasingly driven by competitive business models and the profit motive. Significant cost declines are expected to continue over the course of the next decade. IRENA estimates that by 2025 the global weighted average cost of electricity could fall by 26% from onshore wind, by 35% from offshore wind, by at least 37% from concentrated solar power (CSP) technologies, and by 59% from solar photovoltaics (PV). The cost of stationary battery storage could fall by up to 60%, and there is growing confidence that electric and conventional vehicles will be sold at comparable prices by the mid-2020s.

These falling costs cause the time lag between the financing of a project and its completion to be very low, below 2.3 years for all renewable sources. Solar PV projects are the quickest to construct and can be built in less than a year after financing is completed. Onshore wind **construction times** are also comparatively short, again averaging less than one year. Construction of offshore wind projects averages close to two years after financing is agreed, so a project financed in 2018 may not become operational until 2020 or beyond (IRENA and CPI, 2018). These numbers are not comparable with those typical of other energy sources. Nuclear energy, for example, requires 6 to 12.5 years to become operational.

Technological innovations, including higher solar photovoltaic (PV) module efficiencies and taller wind turbines, have played an important role in accelerating the deployment of renewables in the electricity sector, as also suggested by the increasing number of patents in clean energy fields. In the long term, next generation biofuels and renewable hydrogen generated from electrolysis may permit renewables to extend into a growing range of hard-to-electrify sectors, such as aviation, shipping and heavy industry. Innovations in digitalization and energy storage are also opening up new frontiers. New digital technologies, such as smart grids, the internet of things, big data, and artificial intelligence, are being applied in the energy industry, helping to raise its efficiency and accelerate the use of renewable energy within emerging smart generation and distribution systems.

Among renewables sources, solar energy, and solar photovoltaic in particular, is experiencing the highest growth. Considering that in an hour, the sun radiates solar energy enough to cover for human energy consumption for a year, then favoring the development of solar PV modules could be essential to capture this naturally free vast amount of energy provided by nature. With respect to other renewable energy systems (e.g. wind turbines) PV modules have lower (almost negligible) operating and maintenance costs, since they have no mechanically moving parts, except in cases of sun-tracking mechanical bases. They are totally silent, consequently, they are suitable for urban areas and for residential applications. The latter, in particular, are easy to install on rooftops or on the ground without any interference to residential lifestyle. These advantages resulted in huge investments absorbed by this sector which have led to a growth that has gone from 25 GW in 2010 to 663 GW expected by the end of 2019. Solar also beats coal in new installed capacity even if the latter continues to be one of the predominant fossil sources (about 529 GW compared to 638 GW of photovoltaic).

The consequence has been a drastic reduction in solar energy modules' prices in the past years, which are expected to continue to decline in the coming years. Nonetheless, solar photovoltaic modules are one of major renewable energy systems that have been promoted through government subsidy funding, encouraging the installation of a large number of plants. This has favored the start-up of the photovoltaic market both at a global level (as regards the production of photovoltaic modules), and at a national level (as regards the construction of the plants). In turn, the increase in the number of installations and the production of modules has enabled the chain companies to achieve economies of scale and therefore a drastic drop in prices at all levels, triggering a virtuous circle and allowing the progressive reduction and finally, the cancellation of the incentive. The result has been a significant reduction in the price of installations, more than halved in the five-year period 2011-2015. This has led many countries to the so-called **grid parity** regime, which occurs when the cost of electricity produced by photovoltaics is lower than the price the user pays for buying it from the grid. This means that the final consumer (end user) will find more convenient (from the economic point of view) installing a photovoltaic system that satisfies its electricity consumption on average rather than buying electricity from the grid, even in the absence of incentives. Consumers, however, seem not fully aware of this fact. The wrong perception that photovoltaics is no longer economically viable since the era of incentives ended is confirmed by the stagnation of the growth of installations precisely at the end of the incentives. On the contrary, the convenience of photovoltaics has never been so marked, not even during the era of incentives (Massi Pavan and Lughi, 2012), also considering the payback time and the internal rate of return. Solar modules cost is still on a fast reducing track and is expected to continue reducing for the next years – consequently solar PV modules has indeed a highly promising future both for economic viability and environmental sustainability. Considering the point of view of the energy system as a whole, instead, it is important to compare the costs of producing electricity with photovoltaics or traditional plants. When these costs are comparable, we can say that we are in a fuel parity regime; entering the fuel parity regime means that it becomes economically convenient to produce electricity through a photovoltaic system rather than a traditional plant. Italy, in particular some areas such as Sicily, represents an important example where fuel parity conditions are consolidating, mainly due to the high solar irradiation and the consequent high producibility of the plants (Massi Pavan et al., 2016). It has been calculated that the cost of the energy produced by large photovoltaic plants (so-called utility-stairs, generally dedicated only to the sale of energy and not to serve a specific user) is less than 70 euros per megawatt-hour, in line with the cost of production in plants powered by traditional sources.

4. The microgrid system

Solar energy, as all the other renewable energy sources, has an intermittent nature. No shining at night, but also cloudy or rainy weather during daytime makes solar energy modules less reliable a solution. Moreover, the amount of energy generated by the PV does not usually match the consumption profiles, forcing a demand response to reduce operating costs. However, to overcome these issues and to assure a continuous and reliable supply of electric power, especially for on-grid connections, microgrid systems are becoming promising alternatives to the central distribution paradigm (Yan et al., 2017). Microgrids are the building box of the present and future smart grids. In general, the microgrid consists of the power conditioning system, the energy storage, the loads and energy management and control system. Microgrids can operate independently (off-grid modes) or in synchronization with the electricity grid (grid-connected) ensuring the supply with local and reliable energy at all times. This means that depending on the solar adoption ratio of a microgrid and on the hour of the day, the microgrid can either import power from the grid or export power to the grid.

Microgrids keep the power flowing by disconnecting – or islanding – from the central grid when it begins to fail. The microgrid’s batteries then serve customers until power is restored on the central grid. Other ancillary services to the central grid refer to support functions, such as frequency control and spinning reserve.

A benefit closely related to electric reliability is the energy resilience. While reliability is about keeping the power on, resilience describes the ability to avoid power outages in the first place or to recover quickly if they do occur. Microgrids are hence able to coordinate the match between the supply side and the demand side, increasing the renewable energy penetration. The electricity produced by PV plants can be directly consumed or, in case of excess of production, fed into the grid or stored in an energy storage. Microgrids, therefore, contribute to integrate these renewables into the energy mix. Moreover, the efficient management of energy supply guarantee cost savings, by selling energy and services back to the grid. This gives consumers a new kind of control in energy markets. They no longer just consume energy, but also can produce and control it through their microgrids. Such customers are called prosumers. Advanced microgrids are also able to leverage the daily energy prices fluctuation on its customers' behalf. When demand for grid energy is high and grid prices increase, the microgrid controller may signal to use more of its own resources to avoid paying the higher prices.

An empirical evidence (Massi Pavan et al., 2019) is the microgrid financed by "MUSE – Cross-border collaboration for a sustainable and energetically efficient university mobility", a project cofinanced by the European Regional Development Fund via the cross-border cooperation program Interreg Italy-Slovenia. It is a grid-connected microgrid consisting of a PV system installed on the rooftop of a university building (University of Trieste, Italy), an energy storage system, and a charging station for electric vehicles. More specifically, the microgrid consists of a 3.9 kW_p photovoltaic generator, a 4.6 kVA inverter, a 10 kWh lithium iron phosphate battery, an interface board performing the connection with the low voltage 230 V grid, and a 22 plus 22 kW charging station. An Energy Management System is used to monitor, control, and optimize the performance of the different components of the microgrid, though inputs given by some external references (meteorological forecasts, electricity price, etc.). Finally, an outdoor 55'' display shows in real time the main parameters of the plant. When considering a storage battery and simulating the electric vehicle load profile, hence detecting both the time and the amount of energy needed for the charging, Massi Pavan et al. (2019) find that 72% of the requested energy comes from the solar generation (60% of the energy flows from the storage to the electric vehicle, and 12% from PV plant to the electric vehicle) and thus renewable.

Conclusions

The transformation of the global energy system that we are already witnessing in the power sector needs to accelerate substantially to meet the objectives of the Paris Agreement. These require to limit the rise in average global temperatures "well below" 2°C and ideally to limit warming to 1.5°C, compared to pre-industrial levels. To this aim, the focus should be paid on energy-related carbon dioxide (CO_2) emissions, which make up around two-thirds of global greenhouse gas emissions. Electrification, in particular, is emerging as a key solution for reducing emissions but only if paired with clean electricity, which increasingly can be sourced at the lowest cost from renewable energy. The renewables' boom is leading the current energy transition, with the photovoltaics as the standard bearer. Grid-parity and fuel-parity represent a fundamental step in the growth path (globally at record rates) of this solar technology. The abatement margins linked to economies of scale, the reduction of BOS (balance of the system) and third-generation technologies guarantee enormous potential for the global growth. Microgrids are able to overcome the downside of solar energy of generating power only when sun shines. Hence, they balance the variable output of renewable energy with traditional generation assets with no human intervention. A microgrid benefits its customers and society in many ways. It provides efficient, low-cost, clean energy, enhances local resiliency, and improves the operation and stability of the regional electric grid. Through sophisticated, automated energy management, a microgrid can bolster clean energy use and can create economic value for customers — as well as the broader grid. Finally using a microgrid promotes local control, leading to the so called democratization of energy and the rise of the prosumer.

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