

Distributed Generation from Renewable Energy Sources: Ending Energy Poverty across the World

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Following an updated outlook of global energy production and utilization, selected examples from both developing and developed countries show how distributed generation from renewable solar energy is the key solution to ending energy poverty across the world. Guidelines aimed at policy makers suggest a systems view of energy that will be instrumental in guiding the transition from fossil fuels to combustion-free renewable energy for all energy uses.

In contrast, energy-saving efforts such as buying highly insulating windows are often hampered by the lack of sufficient financial resources, with the very same lack of money originating from the delay in adopting energy self-generation from RESs, as the available financial resources are used to pay for fossil fuels and energy generated by converting such fuels, including fissile uranium in electronuclear power plants.

1. Introduction

The role played by energy in driving economic growth is generally larger than conventionally assumed.^[1] This would suggest to first focus efforts and resources on improving energy efficiency to promote general economic growth. Yet, as understood by Jevons as early as of 1885, this could well eventually result in higher overall energy consumption in an unwanted economy-wide rebound effect.^[1,2] Indeed, if a fraction $1/n$ of the population starts saving primary energy, then the price of primary energy decreases, enabling the remaining $(n-1)/n$ fraction of the population to purchase higher amounts of primary energy, eventually restoring or even worsening the overall balance of energy consumption.

If, instead, the current and future energy needs of the same, the $1/n$ population fraction are met by energy obtained from renewable energy sources (RESs) such as sunlight, wind, and water, this fraction will not pay for its energy because there is no “fuel” cost to bear, whereas the remaining $(n-1)/n$ fraction will continue to use conventional energy sources. Now, however, the example of the $1/n$ fraction of the population consuming energy at little or no cost while retaining the original wellbeing, will lead the remaining part of the population to progressively follow the same path.

Seen from a global perspective, this process is exactly what is currently taking place across the world following the global solar energy boom started in the early 2000s.^[3]

The latter situation, for which people in developed countries cannot adequately heat, cool, or acquire necessary energy services for their homes defines energy poverty in high-income countries; whereas in developing countries, energy poverty generally often translates into not having access to electricity and to all electricity-enabled technologies including lighting.

Research on energy poverty is flourishing. As put it by Galvin, in developed countries, three main factors determine the domestic energy poverty: low income, energy inefficiency; and high fuel prices.^[4] The condition of the over 1 billion people across the world still missing access to electricity shows evidence that energy poverty is a context-based conceptual construct embedded within the specific social, economic, and cultural conditions which define the energy consumption pattern.^[5]

The path to restoring economic growth in most world's countries, in brief, goes through mass scale adoption of renewable energy in place of oil, whose energy return on investment (EROI) has dramatically decreased from the beginning of the oil era in the early 1900s, and has continued to do so recently going from about 30 in 2000 to 17 in 2013.^[6]

From a global viewpoint, the rapidly declining EROI of oil coupled to rapid global population growth, creates the conditions for energy poverty. We have shown in 2016 that growth in energy demand is driven by the concomitant growth in global population and social and economic activities (i.e., wealth, or gross domestic product).^[7] Yet, whereas relationship between total energy consumption and population is linear, that between global wealth and global population is a power function of the global population.^[7]

According to the latter equation, if global population will keep growing along the current trajectory, the 800 million people that will add to the global population in 2025 will need about 1 700 000 ktoe (kilotonne of oil equivalent) of energy over the 2016 level. Even to keep the oil fraction in the energy mix at the 2016 level (33%), this translates into more than 11 million extra oil barrels per day (b/d).^[7]

The end of energy poverty, we argue in this study, inevitably goes through the mass adoption of distributed energy generation from RESs, and sunlight, wind, and water in particular.

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Following an updated outlook of global energy production and utilization, we show through selected examples how this is currently taking place across the world in both developing and developed countries. Guidelines aimed at policy makers at the end of the study suggest a systems view of energy that will be instrumental in guiding the transition from fossil fuels to combustion-free renewable energy for all energy end uses.

2. Primary Energy Supply

Table 1 shows the global primary energy supply by source in 1990 and in 2017.^[8] Oil is still the dominant energy source, though its increase was limited to 37%, followed by coal (+70%), and natural gas (+87%). The energy obtained burning biofuel and urban waste, grown by 47%, is almost twice higher than nuclear power, which in almost two decades experienced the lowest growth rate (+30%) amid all energy sources.

The amount of hydroelectric energy almost doubled (+91%), whereas that of wind and solar PV energy increased more than sevenfold (+700%).

Overall, the share of water, wind, and sun energies in 2017 amounted to 4.35% of the global energy supply. In 1990, the latter share was 2.52%. However, the uptake of solar and wind powers has been largely nonhomogeneous, with China and Germany hosting a far higher installed renewable power per capita generation capacity.

It is therefore relevant to study the impact of such huge and rapid uptake of RESs on fossil fuel consumption in China (and in India).

3. The Paradigmatic Case of China

By the end of 2018, China had installed 729 gigawatt (GW) of renewable energy capacity out of 1900 GW total installed capacity (**Table 2**).^[9]

In 2018, renewable energy accounted for 26.7% (1868 TWh) of total electricity (6994 TWh) generated during the year.

For comparison, in 2007, 81% of the electricity in China was generated by burning coal, whereas in 2018, coal accounted for only 59% of China's overall energy consumption, regardless of a 8.5% rise in electricity generation.^[9]

Table 1. Total primary energy supply by source, world 1990 and 2017.

Energy source ^{a)}	Energy amount (ktoe) in 1990	Energy amount (ktoe) in 2017
Coal	2 220 466	3 789 934
Natural gas	1 663 608	3 106 799
Nuclear	525 520	687 481
Hydro	184 102	351 029
Wind, solar	36 560	256 830
Biofuels and waste	902 367	1 329 064
Oil	3 232 737	4 449 499
Total	8 765 360	13 970 636

^{a)}Source: International Energy Agency, 2019.

Table 2. Power installed capacity in China and energy generation by source in 2018.

Power source ^{a)}	Total installed capacity [GW] and year on year increase [%]	Electricity generation [TWh] and year on year increase [%]
Thermal	1126 (+2.8%)	4833 (+7.8%)
Nuclear	45 (+24.2%)	294 (+18.6%)
Hydro	352 (+2.5%)	1233 (+3.2%)
Wind	184 (+12.4%)	366 (+20.2%)
Solar	175 (+33.9%)	178 (+50.8%)
Biomass	18 (+20.7%)	91 (+14%)
Total	1900	6994

^{a)}Source: China Electricity Council, 2019.

Discussing the case of China is relevant for all countries in the world because China has achieved goals in new energy technology adoption that other countries will reach in forthcoming years. The Asian country, for example, hosted 401 000 public charging stations for battery electric vehicles (BEVs) as of May 2019,^[10] when the number of charging stations in the USA or in Russia amounted, respectively, to 20 000 and 400. Three major outcomes emerge from the ongoing renewable energy uptake in the Asian country.

The first is that coal-fired thermoelectric plants are increasingly pushed out of the market due to the low number of hours in which they actually operate. In China, renewable electricity is granted priority in grid access. The outcome has been that 47% of China's coal-power companies recorded financial losses in January–August 2018, with the others recording limited (1.1%) profitability.^[11]

The second is that the profitability of all thermal plants will now be eroded by the newly achieved competitiveness of photovoltaic (PV) energy generation. Indeed, the first batch of 250 subsidy-free grid-parity wind and solar projects, with a total capacity of nearly 21 GW (in 16 China's provinces) was approved on May 2019.^[11]

This merit-order effect is not peculiar of China and is regularly observed for all countries with a significant penetration of PV and wind power generation, starting from the world's first in order of time, namely Italy,^[12] Germany,^[13] and Spain.^[14]

The third outcome of the rapid industrial progress with new energy technology occurring in China since about a decade, is that BEVs are starting to impact oil consumption at a significant level. We remind that about 50% of oil consumption in the world is related to transportation, and 40% by road transportation.^[15] Recent estimates point to a lost cumulative demand since 2011 due to the adoption of BEVs of 352 000 b/d (equivalent to the oil consumption of Portugal).^[16]

With Li-ion battery production due to rise more than fourfold between 2018 (when it amounted to 294 GWh) and 2023 (1235 GWh expected^[17]), estimates for which by 2040 electric vehicles could displace 7.3 million b/d of oil demand,^[18] would reveal soon conservative. Indeed, the same consultancy 1 year later almost doubled the estimate of BEV impact on road gasoline and diesel fuel demand at 13.7 million b/d by 2040.^[19]

Important benefits of BEVs extend to renewable energy generation. Quantifying the benefits on the power price formed in

the day-ahead power market, we have quantified, in 2015, the synergistic and beneficial effects on the national energy bill provided by the concomitant expansion of BEV uptake and growth of renewable energy generation, particularly of solar PV.^[20] “Although results are derived taking into consideration Italy’s power market,” we wrote therein, “results are of relevance also to other industrialized countries.”^[20]

This has subsequently been the case of China where in 2018, the country reduced wind power curtailment to 7% (27.7 TWh, from 12% in 2017) and solar power curtailment to 3% (5.49 TWh, from 5.8% in 2017),^[9] also thanks to more several million BEVs absorbing power from the grid at different hours of the day.

4. India and Developing Countries

Now that PV modules sell at less than \$0.3/W and lithium battery packs at \$125/kWh in 2019 from \$280/kWh in 2014^[21], numerous countries, both those industrially developed and those in course of industrial development, are following China’s path in adopting renewable energy generation and electric vehicles on mass scale. Producing energy from water, wind, and sun, and then using said electricity to power electric vehicles, indeed, dramatically reduces oil and natural gas imports vastly improving national security and the foreign trade balance.

Accordingly, power generation from RES is finally being uptaken on multi GW scale by countries such as Egypt, Algeria, Morocco, Jordan, United Arab Emirates, Mexico, Chile, Saudi Arabia where the large-scale uptake of solar energy had lagged behind.^[22]

The case of India is of particular global relevance due to the fact that India is the world’s second most populated country. Chiefly installed in the course of 5 years only (2015–2019), India hosted 33.8 GW of installed PV power by September 30, 2019 (4 GW of which were from rooftop solar systems).^[23] Out of 356 GW total installed power capacity by March 2019 (Table 3), RESs in India already accounted for 21.8% (77.64 GW).^[24]

Table 3. Power installed capacity in India as of March 2019.

Power source ^{a)}	Total installed capacity [GW] and year on year increase [%]
Coal	200.7 (+1.9%)
Gas	24.93 (+0.1%)
Diesel	0.63 (–24%)
Nuclear	6.78 (0%)
Hydro	45.39 (–0.02%)
Solar	28.18 (+30.15%)
Wind	35.625 (+4.6%)
Biomass	9.104 (+4.64%)
Small hydro	4.593 (+2.4%)
Waste-to-energy	0.138 (0%)
Total	356.07 (+3.55%)

^{a)}Source: India Ministry of Power, 2019.

Almost all India’s installed PV power was deployed thanks to public tenders for large-scale solar projects with ever decreasing price for the solar electricity purchased by the government through power purchase agreements. Indeed, the government’s initial target of 20 GW capacity for 2022, was achieved already in January 2018.

With 36.625 GW of wind power, India is the fourth-largest wind power producer in the world, and hosts in Rajasthan the Bhadla Solar Park, shortly to become with a final capacity of 2.255 GW, the world’s largest solar power plant.

The case of the latter solar park is relevant because it shows evidence of today’s ultralow cost PV power generated by utility-scale solar parks. Construction of the solar park took place in four separate auctions. In late 2017, the Bhadla Phase III 500 MW auction ended with record low tariffs of INR 2.44 (\$0.037) per kWh to develop 200 MW, and another company winning a bid to develop another 300 MW of grid-connected solar power with a tariff of INR 2.45 (\$0.038).^[25]

Figure 1 shows that the tariff paid by India’s government through its Solar Energy Corporation of India has gone in a few years from 8 to 2.44 INR/kWh.^[25] India is the world’s second country in terms of overall agricultural output (first world’s fruit and milk producer), and agriculture is the primary source of livelihood for about 58% of its population.^[26]

Loss of arable land to huge PV systems needs to be carefully avoided so as not to interfere with the growth of its agrarian sector. In its place, the government is rightly favoring the installation of multi GW PV stations in the country’s desert areas of the country, mostly located in the north, such as that hosting the Bhadla Solar Park, and to its northwest (the Thar desert) in areas such as Thar (Rajasthan), Rann of Kutch (Gujarat), Ladakh (Jammu and Kashmir), and Lahul and Spiti Valley (Himachal Pradesh) with a total geographical area of 330 000 km². This, in its turn, requires the deployment of long-distance transmission lines and substations connecting the power stations where energy is produced with cities and rural areas where it is consumed, adding cost to the shift to renewable energy. The 2013 “vision” of India’s power utility for which by 2050, 300 GW of India’s 485 GW renewable electricity capacity (adding to 180 GW of hydropower) would be produced by a combination of 271 GW of solar PV and 29 GW of wind power installed in the four deserts of India’s north and northwest,^[27] today is technically and economically feasible.

It is also relevant to learn that to save arable land and water since 2012, India has pioneered the construction of large, grid-connected PV systems on top of canals and on their banks (Figure 2). Due the shadow during the warmest days and hours of the solar year, the PV modules significantly reduce water evaporation from the channels underneath making more water would be available for irrigation, whereas the electricity generated by the PV array meets the large and increasing demand from irrigation pumping stations. Alone, the Gujarat state-owned Sardar Sarovar Narmada Nigam (SSNNL) company which built the huge (1.5 billion cubic meter water capacity) Sardar Sarovar Dam and operates a canals network 75 000 km long, already operates 35 MW of grid-connected solar capacity on Narmada’s Vadodara branch canals (20 MW canal-top and 15 MW canal bank).^[28] The outcomes in terms of energy produced and water saved were so successful, that the same company started in 2019,

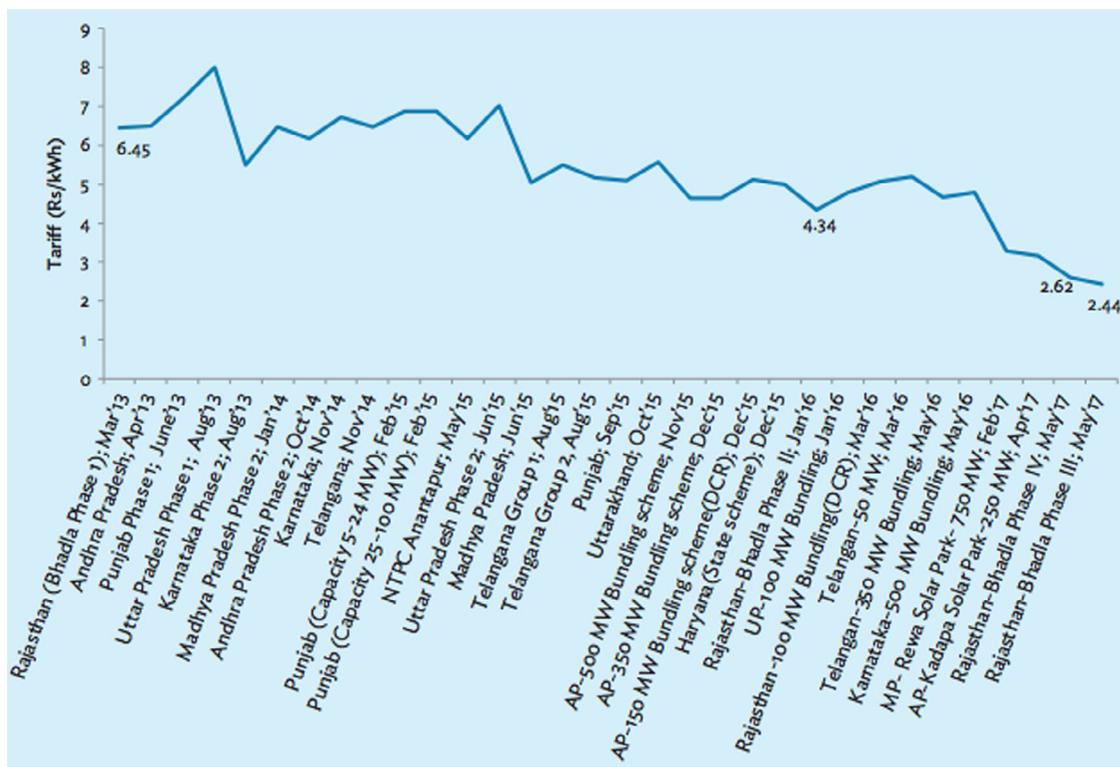


Figure 1. PV electricity tariffs in power purchase agreements signed with India's government since the Bhadla Solar Park Phase I bidding. Rs = Indian rupees. Reproduced with permission.^[25] Copyright 2018, Asian Development Bank.



Figure 2. Part of the 10 MW canal atop and 15 MW canal bank solar PV arrays at Vadodara Branch Canal commissioned in September 2017 by SNNL. Reproduced with permission.^[28] Copyright 2015, Sardar Sarovar Narmada Nigam.

the construction of another 100 MW solar PV project atop branch canals of river Narmada in four locations.^[29]

Compared with 2013 state-of-the-art 250 W PV modules in monocrystalline silicon, however, today's bifacial PV modules mass manufactured in China in 2020 use passivated emitter and rear cell (PERC)-type, half-cut solar cells exceed 500 W nominal power (with extrapolated trend predicting that in 2020 PERC cell efficiencies will approach 24% efficiency).^[30] Similarly,

improved protective coatings such as photocatalytic coatings based on titania nanoparticles ensure 5–6% higher yearly production (thanks to the self-cleaning property of nanostructured TiO₂) when compared in real-life tests to older modules with no photocatalytic nanocoating.^[31]

5. Ending Energy Poverty across the World

After decades of limited progress, distributed generation via domestic PV on mass scale has finally started to improve livelihoods and to drive social development and economic growth across the world. Selected recent examples illustrate how this is happening in both developing and developed countries.

In Bangladesh, 5.5 million solar home systems installed between 2003 and 2018 provide electricity to 20 million people, namely more than 12% of the population, with the country aiming to install another 500 000 systems by 2021.^[32] Similarly, in slightly more than 3 years starting in 2016, India's government has installed 135 079 solar light-emitting diode (LED) street lights in various parts of the immense country.^[33] According to phase III of the same plan (Atal Jyoti Yojna) to illuminate dark regions through solar street lights, a total of 300 000 solar street lights will be installed across India, starting from north eastern area and from islands devoid of grid connectivity.^[34]

In sub-Saharan Africa, where close to 700 million people do not have access to electricity, today's low-cost PV solar modules coupled to low-cost LED lights and Li-ion batteries is bringing

electricity to thousands of people each day. For example, a Nairobi-based company after acquiring 600 000 customers across Kenya, Tanzania, and Uganda in 7 years only (2012–2019), in early 2019, was found to affordably sell different off-grid domestic solar power kits to 500 new homes everyday.^[35]

Showing evidence of how today's ultralow cost of solar energy and energy storage technologies allow low-income families in Africa's rural areas to access electric lighting, mobile phone recharging, radio listening (and now even TV watching), one such kit consisting 2 small PV modules (8 W), a 6.4 Ah Li-ion battery, two LED lights (one bulb and one strip), 2 mobile phone charge cables, one rechargeable radio, one rechargeable torch, and their charge cable in early 2020 was sold in change of an initial deposit of 2499 Kenyan Shelling (ksh, equivalent of \$24.90), with a daily payment of 50 ksh (\$0.5) for 410 days.^[36] The payment system makes use of the customer mobile phones.

Similar findings hold true for developing and developed regions of the world, with results now being routinely reported in the scholarly literature.

In metropolitan Seoul, in 2016, the South Korea's government entirely covered the installation cost (\$450 of a simple PV system comprised a single 260 W module equipped with a microinverter and a meter installed in the veranda of several low-income households living in public rental apartments.^[37]

The electricity bill of one representative user for 1 year (April 2018–March 2019) shows that real energy production (264.7 kWh) was higher than the average production expected (243.4 kWh/year), with a reduction in the energy bill of about 20% (from 247 810 to 200 120 KRW).^[37] The latter achievement was possible with a single solar module with a rated power of 260 W. Today's 60 cell, 21.4% efficient PV modules in monocrystalline silicon manufactured in South Korea by one of the two country's leading electronics manufacturer have a nominal power of 370 W.^[38]

Getting back to developing regions, today's solar PV coupled to today's Li-ion battery technology has become capable to supply high-quality electricity (stable voltage, for prolonged duration up to 24 h/day) in most Indian villages still not reached by the national grid (305 million people).^[39]

For instance, in addition to being completely lit by solar-powered road LED lights, the village Mandironwala Bhuddi in the Uttar Pradesh's district of Amroha since early 2019 meets all its primary electricity needs including home lighting thanks to modern PV modules that have been installed on the rooftops of every house in the village, thanks to India's government.^[40] Installation of both modules, batteries, LED lamps, and cables is quick, and the cost affordable with children starting to read and study using solar lights the day subsequent the installation.

Actually, the technology has evolved so rapidly along with prices decline that sales of solar lanterns and solar fans recorded by a trade association representing about 25% of India's companies selling off-grid solar lighting products declined 20% (year-on-year) in the first half of 2019, whereas the sales of multilight and complete solar home systems, which can run appliances such as television sets, recorded a dramatic increase (multilight system sales doubling to 92 000 units, and solar home system sales crossing the 50 000-unit mark for the first time).^[41] Still, India represents by far the world's largest market for solar

lanterns with sales in only the first 6 months of 2019 approaching 1 million units and exceeding \$28 million in value.^[41]

Similar rapid progress in rural electrification using solar PV technology is being reported virtually from all world's areas still not reached by the electric grid. In China's rural Qinghai-Tibet region, the highest plateau in the world with an altitude between 3000 and 5000 m, it was enough to install two solar air collectors and an electricity-driven heat pump to heat water at the low temperatures (25–30 °C) required for floor radiation heating to entirely replace wood, animal dung, and coal traditionally burned by Tibet's residents for heating, vastly improving the livelihood conditions.^[42]

China's scholars directed the renovation works and field measured the energy consumption and indoor air temperature of the home prior and after renovation. The energy demand of the renovated house was 153.3 kWh/day lower than that of the original home, whereas the average air temperature of the living room and two bedrooms reached 12.8, 11.0, and 10.2 °C, namely 8.78, 7.61, and 6.82 °C higher than temperatures of the rooms in the old building.^[42]

According to calculations carried out in June 2016 by an energy scholar in South Africa, the combined unit energy cost of a real solar energy home system including a 200 W PV module (at \$0.7987/W rate), a solar water purifier (5 L/day capacity), two batteries (105 Ah each), 12 LED bulbs (11 W each), and a solar water heater (2 m² collector) capable to provide electricity and purified water over the system 25 year lifespan for a rural home in Uganda was roughly \$0.03.^[43] "Solar energy usage by rural households in lighting, hygiene water heating and family drinking water" he concluded, "should be strongly advocated to reduce energy poverty."^[43]

6. Guidelines and Conclusions

Four major guidelines stem from the analysis conducted in this study on how to alleviate and eventually terminate energy poverty across the world via distributed generation from RESs. They concern both policy makers in rural regions of developing countries where the electric grid is absent or insufficient, as well as European countries impoverished by over two decades of financial austerity^[44] and increasing energy prices due to privatization of energy utilities.

First, ending energy poverty should always translate into alleviating poverty in general. This, following the studies of Israel and Jehling,^[45] requires policy makers and urban energy managers to adopt a systems view of energy, fully integrated in its local socioeconomic context so as to avoid, for instance, top-down energy policy approaches marginalizing local manufacturers of renewable energy systems. This was indeed the case of Peru's town of Arequipa where some 55 000 of 200 000 households are equipped with solar water heaters manufactured in the city since the 1930s, whose local manufacturers were indeed marginalized by the introduction of quality certifications and efficiency thresholds.^[45]

Second, aware that energy ecosystems are plural and heterogeneous, new energy policy should be designed and implemented based on specific renewable energy resource endowment, local resource base, as well as consumption patterns.

Third, policy makers following the advice of energy managers trained to the aforementioned systems view of energy via education going beyond technology, to include key social, economic, and management aspects,^[46] are recommended to establish public renewable energy institutes able to provide enhanced education including updated best practices and lessons learned from across the world,^[47] and to articulate clear and effective transitions plans with targets, financial resources, and indicators necessary to achieve realistic targets for distributed generation from RESs.

Fourth, policy makers more aware of the key social dimension of the energy transition should develop effective, cultural-driven, communication activities built around what matters most to the community to be engaged.

It may not be surprising, in this respect, to learn that adopters of solar energy in Wisconsin share “an interest in technical innovation and enjoyment of the technical aspects of energy systems,”^[48] whereas those in Ghana citizens seek “autonomy in electricity supply via domestic solar systems” chiefly due to poor (inefficient and costly) centralized electricity provision.^[49]

From international^[50] and national^[51] energy agencies through energy research institutes^[52,53] and consultancies,^[54] several organizations have lately devised energy scenarios considering the largely unexpected impact of energy generation from RES.

Here, it suffices to notice that after emphasizing the “unbearable high cost” of renewable energy for over two decades critics of renewable energy—now that the cost of generating electricity via PV modules and wind turbines has literally collapsed—point to the “unbearable cost” and lack of reliability posed by the intrinsic intermittency of energy obtained from sunlight, wind, and water.

However, we have lately shown in other studies how, thanks to solar energy coupled to the now affordable Li-ion battery,^[55] and solar hydrogen storage technologies, not only families and companies but also entire regions and islands can now safely rely on renewable energy to meet all their energy needs.^[56] In doing so, replacing polluting and unevenly distributed fossil fuels with RESs of no marginal cost, human communities from rural villages to cities and nations will save those financial resources whose lack of, as Jevons first understood as early as 1885, creates the conditions for energy poverty.

Conflict of Interest

The authors declare no conflict of interest.

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