9-5-2014

Emerging Role of Photovoltaics for Sustainably Powering Underdeveloped, Emerging, and Developed Economies

Rajendra Singh
Clemson University, srajend@clemson.edu

Amir A. Asif
Clemson University

Ganesh K. Venayagamoorthy
Clemson University

Akhlesh Lakhtakia
Pennsylvania State University - Main Campus

Mahmoud Abdelhamid
Clemson University

See next page for additional authors

Authors
Rajendra Singh, Amir A. Asif, Ganesh K. Venayagamoorthy, Akhlesh Lakhtakia, Mahmoud Abdelhamid, Githin F. Alapatt, and David A. Ladner

Key Note Paper

2nd International Conference on Green Energy and Technology (ICGET)

5-6 September, 2014, Dhaka, Bangladesh

http://cennser.org/ICGET/

Emerging Role of Photovoltaics for Sustainably Powering Underdeveloped, Emerging, and Developed Economies

Rajendra Singh,[1] Amir A. Asif,[1] Ganesh K. Venayagamoorthy,[1] Akhlesh Lakhtakia,[2] Mahmoud Abdelhamid,[3] Githin F. Alapatt,[1] and David A. Ladner[4]

[1]Holcombe Department of Electrical and Computer Engineering,
Clemson University,
Clemson, SC 29634-0915, USA
E-mail: srajend@clemson.edu

[2]Nanoengineered Metamaterials Group,
Department of Engineering Science and Mechanics,
Pennsylvania State University,
University Park, PA 16802-6812, USA

[3]International Center for Automotive Research
Clemson University
Greenville SC 29607, USA

[4]Environmental Engineering and Earth Sciences,
Clemson University,
Anderson, SC 29625-6510, USA

Abstract— **With the advent of low-cost solar photovoltaic (PV) panels and our ability to generate, store, and use electrical energy locally without the need for long-range transmission, the world is about to witness transformational changes in electricity infrastructures. The use of DC electricity enhances systemwide efficiency. DC microgrids and nanogrids powered by solar PV systems and gigawatt batteries for electricity storage can sustainably power the needs of all human beings equitably and empower every individual. Ultralarge-scale manufacturing of PV systems and batteries, a vertically integrated business model, and a targeted monetary policy of quantitative easing can rapidly power all human activities.**

I. Introduction

With Human needs and demands continue to shift and change. Though poverty has not been eradicated and a large number of people are still struggling to attain a decent standard of living, the vast majority of people enjoy a better quality of life than in the early 19th century. This has become possible due to the emergence and development of new technologies and distribution networks that produce and disperse new wealth. Education and health are major stepping stones towards prosperity, and physical infrastructures create opportunities.

Electricity is a vital resource that enables and empowers individuals and societies. About 1.5 billion people worldwide still lack access to electricity, and 1 billion more have only intermittent access [1]. Another 2.5 billion people rely on wood, charcoal, dung, and coal for cooking and heating [1]. About 780 million people have no access to clean water [2]. Out of 7 million annual premature deaths related to air pollution [3], 4.3 million are attributed to air pollution in homes [4]. Burning of fossil fuels (coal, gas, and oil) for generation of electricity is responsible for 87% carbon-dioxide emissions from human sources [5]. Continued use of fossil fuels to generate electricity and in the transport industry is considered to be responsible for floods, droughts, climate change, and many medical problems [6].

The impact of climate change on global economy is a topic of great importance [7-9]. According to a recent World Bank study, curbing climate change can boost economic growth, create jobs, and save millions of lives [10]. Reduction of emissions of carbon dioxide in Brazil, China, India, Mexico, USA, and the European Union would increase the global gross domestic product by $1.8 trillion per year [10].

National economies can be classified into the three categories of underdeveloped (e.g., Angola, Chad, Ethiopia, Haiti, Liberia, and Zambia), emerging (Brazil, Russia, India, China, and South Africa, collectively known as BRICS), and developed economies (e.g., USA, the European-Union countries, and Japan). The social, political, and economic issues of these three types of economies are different and require different public policies to address national needs. In particular, the lack of technical knowhow, financial resources, and electricity infrastructure in underdeveloped countries is a fundamental barrier in the eradication of poverty.

One hour of incident solar energy is equal to all the energy used in one year on our planet. Electricity generation by photovoltaics (PV), popularly known as solar panels, is going to revolutionize energy production in a manner similar to the role of computer chips in bringing about the information revolution. From both economic and environmental considerations, PV can provide sustained global economic growth [11-16]. The objective of this paper is to argue that PV is ready to transform the electricity infrastructure in all three types of national economies.

II. Technology Readiness

The invention of the semiconductor transistor followed nine years later by its incorporation in semiconductor chips played a vital role in enabling the information revolution that started in the last half of the twentieth-century and is

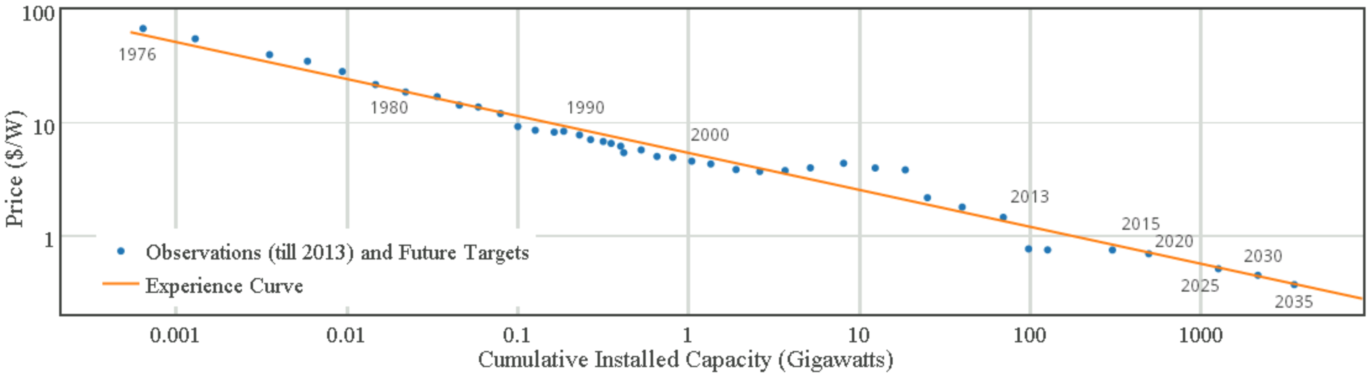

Figure 1. Experience curve of doubling of PV module manufacturing and cost reduction by 20 % and extension to 2035 [17].

continuing to shape the world of tomorrow. Simultaneously, since the report of 6%-efficient silicon solar cells in 1954, tremendous progress has been made in reducing the cost of PV modules and the cost of PV-generated electricity [13]. From 1980 onwards, every doubling of the generation capacity of PV modules has been accompanied by a 20% reduction in the selling price, as shown in Fig. 1 [17]. In fact, because integrated circuits, PV modules, and liquid-crystal displays (LCD) have common manufacturing roots, the selling prices of all of these products have declined over the years, as illustrated in Fig. 2 [18-22]. The soft cost (licensing, zoning, environmental impact fees, etc.) of PV generation systems is also being reduced and power-purchasing agreements as low as $0.04/kWh are in place in USA [23].

Although batteries are not considered as solid-state devices, the use of a bank of batteries for desired output power is similar to the use of a large number of solar cells in a PV module to get desired output voltage and current. Batteries are essential to store solar energy harvested when the sun is shining for use when it is not. Therefore, declining battery costs will also assist in the growth of PV-electricity generation.

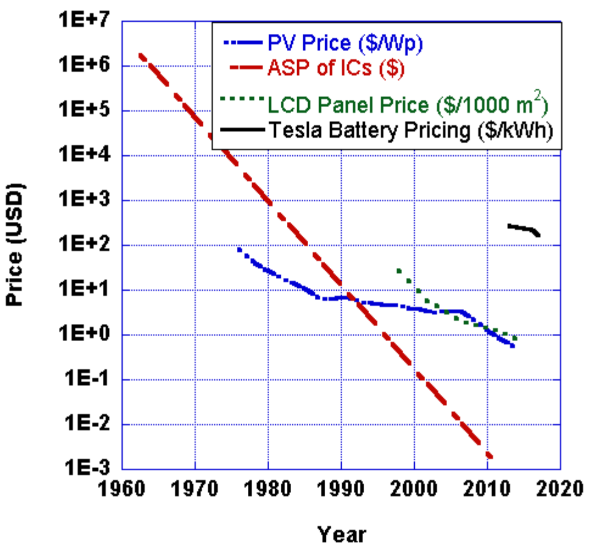

Figure 2. Cost reduction trends for integrated circuits, PV modules, LCDs, and Tesla Motor batteries [18-22, 24].

Fig. 2 also shows the cost reduction in batteries manufactured by Tesla Motors [24]. Furthermore, the replacement of statistical process control (SPC) by advanced process control (APC) in the battery industry can be used to reduce process variations and, consequently, the production costs [25]. The manufacture of GW batteries has the potential to reduce battery costs to less than $150 per kWh in 2017 [24].

In addition to high-volume manufacturing of PV modules [26], an increase in the size of the substrate leads to cost reduction. The LCD industry has already exploited the use of larger glass substrates to reduce the cost of LCD panels. The bulk-silicon industry is currently using mostly 6-inch and 8-inch square substrates, but the future use of 12-inch and even 18-inch square substrates will further reduce the cost of PV modules.

The global cumulative installed capacity of PV modules grew to 140 TW at the end of 2013 [27] and is expected to increase further to 190 TW in 2014 [28]. One barrier to more rapid growth is the variation of PV module prices by as much as 20% from location to location [29]. Trade war between countries producing PV modules is another barrier [30]. However, the experience of the semiconductor industry suggests that these barriers will be surmounted eventually, and the prices of PV modules will continue to fall for many years.

There is no direct competition between PV and wind energy. However, due to the inherent advantages in both cost and reliability, PV is expected to become the dominant source of electricity [31]. For the first time in 2013, both globally and in USA, the total PV installed capacity overtook the installed capacity of wind turbines. A major factor is the decline in the cost of solar panels by 62 % since the beginning of 2011, while the cost of wind turbines has declined by just 12% [32]. Whereas the PV industry employed 2.3 million people globally in 2013, the wind-energy employed just 834,000 [33].

Nuclear energy is not cost-effective [34]. The two-nuclear-plant project of Georgia Power is at least $737 million over budget, and the company has also decided to harvest 535 MW as solar energy [35]. France, one of the world's major proponents of nuclear power and an exporter of nuclear-power plants, recently announced that the share of nuclear plants in France's power generation will drop from 75% to 50%, while

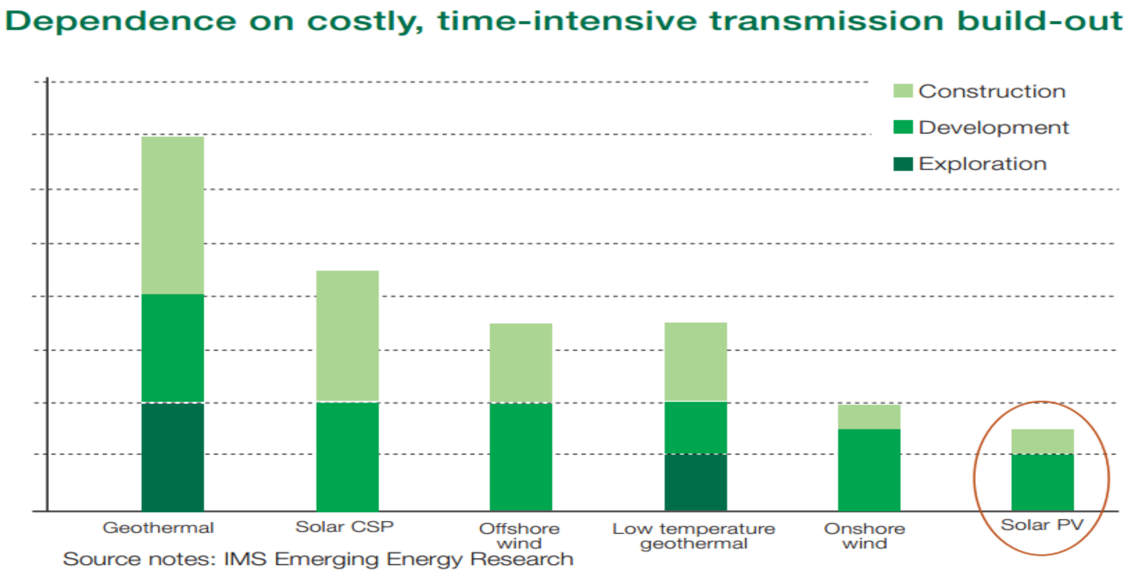

Figure 3. Rapidity of deployment of renewable sources of energy [41]

power generated from renewable sources of energy will rises from 15% to 40% [36].

Apart from environmental issues [37], natural gas is not cost-competitive with PV [38]. With capital investment of about $7/W [39], concentration solar power (CSP) is too expensive to compete with PV and batteries. In China, the cost of solar PV is rapidly catching up to the cost of coal-fired electricity generation, and the cost of building a large-scale solar PV plant could match that of a coal-fired plant by 2016 [40].

Fig. 3 quantifies the rapid-deployment advantage of solar PV generation [41]. Add the high reliability and the low cost, and it is all too apparent that PV is ready to transform the global electricity infrastructure. Manufacturing innovations will continue to increase the performance of PV systems and reduce the cost. Ongoing research will further reduce the cost of storing PV-generated electricity [12,13]

.

III. Modular Nature of PV Leading to Personal Source of Energy

The modular nature of PV makes it possible to generate power from less than a watt (e.g., a solar charger for mobile phones) to several hundred megawatt (solar farm connected to the grid). This flexibility in size is going to transform the century-old electricity infrastructure. Concerns exist regarding the reliability and security of a centralized grid with a high penetration of renewable energy resources, because the sun does not shine on demand. A cloud passing over a PV generation plant reduces the output as seriously as the loss of a conventional generator of the same capacity.

In order to maximize the penetration level and dependence on renewable energy, demand-side management technologies are needed. These technologies could include energy-storage facilities that supply electricity on demand, or a tie to a neighboring power system with excess generation (preferably from clean sources) [42-44].

Furthermore, unlike conventional power plants, PV generation plants usually are connected to the grid through power-electronic converters, which can be turned on or off rapidly. The fluctuations of power and frequency in grids with large PV generation plants raise concerns about dynamic and transient stability**,** because energy harvesting by solar panels shuts off almost instantaneously, in comparison to wind turbines which actually have some kinetic energy available. Real-time monitoring and forecasting of PV generation and dynamic state estimation will be needed [45-47] along with weather forecasting capabilities [48] to overcome the intermittency problems.

As shown in Fig. 4, due the availability of rooftop PV panels on residential and commercial buildings, PV solar farms, as well as local and centralized battery storage, centralized grids will be transformed into and/or replaced by micrograms and nanogrids [49-54]. Whereas a nanogrid can operate independently as it has both generation and storage capabilities, a microgrid can be connected to other microgrids and even a central grid. Microgrids have already begun to emerge in the USA [55].

IV. Importance of PV-Generated DC Power

Due to the availability of inexpensive DC power locally generated using PV systems, aided by storage batteries and power electronics, the global electricity infrastructure will be transformed [56, 57]. The traditional centralized generation of large base-load AC power and its long-haul distribution via high-voltage transmission followed by conversion to lower voltages is expensive because huge losses of energy occur. Based on 2011 data, globally approximately 70% of electricity

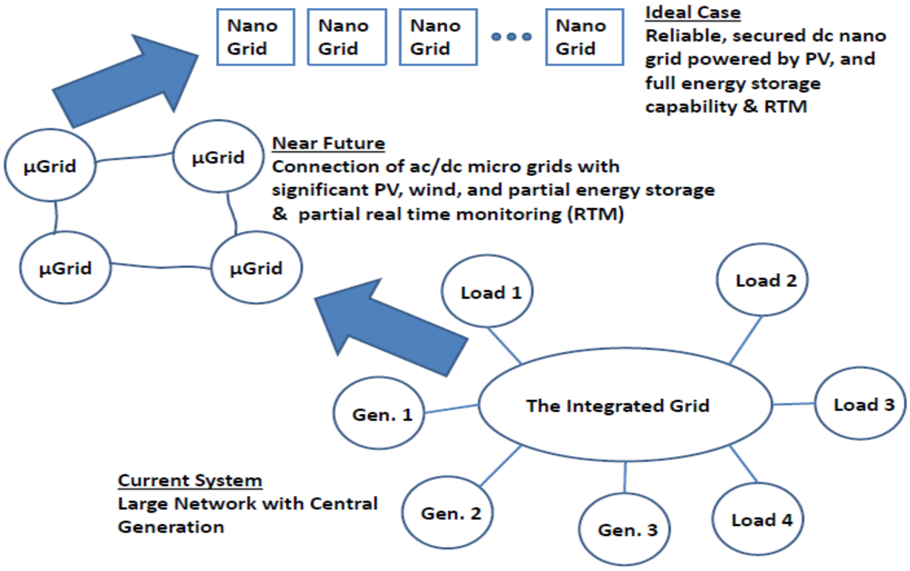

Figure 4. Transformation from centralized grids to microgrids and nanogrids enabled by localized PV generation systems

produced is lost in generation, transmission, and distribution [58]. At the rate of $0.1/kWh, the annual loss of 142 quadrillion BTU (= 41 trillion kWh) of energy amounts to about $4.1 trillion.

A significant part of this energy loss is due to the use of AC power transmission and distribution to service mostly DC loads. DC electricity generated locally by solar panels, and used with a minimum conversion (DC to AC and then back to DC) and minimum transmission can reduce energy losses by as much as 30% [57]. While the cost of generating local DC electricity has fallen, the cost of AC electricity generated by centralized facilities has remained the same [59].

Except for a few applications, most electric loads — cell phones, laptops, light sources, air conditioners, and home appliances, among others — operate on DC electricity. Globally, as the AC electricity infrastructure is decommissioned, its replacement should be designed for DC electricity. Loads that require AC electricity for operation must be equipped to convert DC to AC internally.

The dominant use of DC in place of AC electricity will enhance energy efficiency. Following are the key advantages of PV modules for generating electricity for DC use [12]:

(i) Without the need for inverters to convert from DC to AC, the PV system cost is reduced by about 20% [60]. In addition, system reliability is improved.

(ii) Batteries and capacitors store DC electricity. The cost of a storage device (as much as 50% in some cases) is increased if the input is AC [61].

(iii) The use of DC electricity increases the competitiveness of manufacturing industry and saves jobs worldwide. Energy cost is as much as 33% [62] of the operating cost of a typical aluminum manufacturing plant. As an example, the aluminum industry can save about $10 billion annually [12].

(iv) Worldwide adoption of DC electricity can provide globally uniform electrical and electronics standards, thus providing both economies of scale and seamless compatibility.

(v) In emerging and underdeveloped economies where there is no electricity infrastructure, a DC-electricity infrastructure will help leapfrog a century of electrical progress in developed economies.

Professional interest in local generation of DC electricity has begun to develop, as evidenced by a conference hosted by Clemson University earlier this year [63]. From June 7-10, 2015, the First IEEE International Conference on DC Microgrid will be held in Atlanta, GA [64]. In collaboration with IEEE PES Intelligent Grid Coordinating Committee, the IEEE Standard Association is working to ensure that DC electricity can be safely and conveniently accessed in homes, eliminating the wasteful conversions from AC to DC and, in many cases, from DC to AC, prior to entering a home [65].

V. Role of PV in Transport Sector

The automotive industry is one of the largest sources of greenhouse-gas emissions [66]. The efficiency of the best electric vehicles is about 88%, whereas vehicles powered by internal combustion engines are not more than 35% efficient [67]. Therefore, widespread use of electric vehicles can significantly lower greenhouse-gas emissions.

Photovoltaics can be used to provide energy to electric vehicles at charging stations [68]. Solar panels mounted on an electric vehicle can provide electricity as well [69, 70] to reduce the dependency on the electricity grid. Three wheelers in India and elsewhere can be driven by PV electricity [14]. A three wheeler can go 100 km on less than $1 if run using a battery and onboard solar panels, while the diesel counterpart costs about $4 [71]. The application of PV-generated electricity in the transport sector is not confined only for road transportation but also for flying [72].

In electric vehicles and plug-in hybrid vehicles, batteries supply DC electricity. If charged on a DC electricity grid, batteries will be less expensive to buy and run than if charged on an AC grid.

The cumulative grid efficiency (losses in generation, transmission, and distribution) at the low-voltage levels (< 1 kV) of households in India is around 21% [73]. The cost of these losses is huge. Grids in India and in other less-developed countries depend on hard coal as 65% of the total fuel mix. Lifecycle audits indicate that the household-level of equivalent carbon-dioxide emission from the Indian electricity infrastructure is 1272.2 g/kWh [73]. That figure would drop to just 60 g/kWh, if all electricity was generated using solar PV modules.

Suppose that 0.25 kWh/km energy is needed for an electric vehicle, and that the vehicle lifetime is around 250,000 km. An electric vehicle in India would have a lifetime emission of equivalent carbon dioxide of 79,500 kg if charged using the present Indian electric grid, but only 3750 kg if charged using PV sources. A reduction of 95% is just too good to be ignored, given the urgent need to reduce pollution and resource depletion today. Similar outcomes can be expected in other countries where electricity generation is dominated by fossil fuels.

VI. Role of PV in Solving Global Waters Needs

Almost 800 million people have no access to clean water [2] and global demand for water continues to increase because the global population continues to rise at a rate exceeding 228,000 per day [74]. Limited freshwater supplies mean that droughts will have severe consequences, so that climate change can be expected to have ruinous effects [75].

One way to help meet the increasing water demands is to desalinate seawater and brackish water. Another way is to purify and reuse wastewater. Thermal desalination requires first to heat water in order to vaporize it, leaving behind the salts and impurities, and then to condense the vapor. The alternative process of reverse osmosis uses electrically powered pumps to force water through a semipermeable membrane at high pressure. Whereas thermal desalination entails the consumption of 84 kWh of energy per cubic meter of potable water, large-scale reverse osmosis requires no more than 5.0 kWh of energy per cubic meter [76]. Reverse osmosis is thus the preferred method. Still, it is quite expensive, its energy requirement being the main factor responsible.

As sources of cheap electricity, solar PV systems can play an important role in treating and delivering potable water. This is relevant for large-scale desalination plants that are connected to major electrical grids, but is particularly interesting for small-scale desalination systems that are not connected to any electrical grid. Small-scale systems using currently available reverse-osmosis technology are less efficient than large-scale systems, because the latter remove energy from the concentrate stream and return it to the feed. Also, large desalination plants operate almost continuously, so they do not have start-stop inefficiencies.

But solar power can be used to efficiently operate small-scale reverse-osmosis installations. This requires a redesign of the conventional membranes and modules to tailor them to the intermittency and low power density of solar energy. Pumps requiring less than about one horse power can use DC power generated by PV systems, thus decreasing energy losses from AC/DC conversion. Such simple systems require only PV panels, controllers, and pumps. A key factor that makes these systems feasible is that potable water can be stored for later use. Neither an energy-storage mechanism nor a buffer to even out natural atmospheric and solar fluctuations through the day is needed. This technology is highly attractive to provide clean water in areas that lack water-distribution infrastructure.

VII. Solar PV Electricity for People Who Have No Access to Electricity

The Less than a hundred persons together are as rich as the poorest half of the world [77, 78]. In a world where income inequality and poverty are the norm, a paradigm shift in thought and action is required to address the electricity needs of more than 20% of the world's population.

The United Nation's Advisory Group on Energy and Climate Change called for an initiative to achieve universal access to modern energy services by 2030 [1]. While the initiative is a step in the right direction, it lacks the support required to truly overcome the unmet energy needs worldwide. The distribution of free or inexpensive solar lanterns and similar devices helps, but does not contribute to the alleviation of poverty at the scale necessary.

While non-governmental and non-profit organizations have often viewed the electricity-lacking 1.5 billion people as underprivileged, the paradigm shift requires viewing this portion of the population as an untapped market of potential consumers. Similar to the unconventional, yet successful, monetary policy of quantitative easing [79], economists at the International Monetary Fund, the World Bank, and other multinational institutions need to view the 1.5 billion people as consumers needed to stimulate struggling economies. Metcalfe has recently suggested that the strategy used to ward off a global depression might now be deployed to sustain progress toward extreme poverty around the world [80]. World Future Council has argued along the same lines [81].

If about 20% of the world's population is considered as a single market, then the only solution to provide electricity to most economically disadvantaged populations must have two attributes [15]: (1) The energy source must be very inexpensive and practically impossible to deplete. (2) The distribution infrastructure must be composed of microgrids and nanogrids. Both attributes require the massive use of solar PV systems, supported by the exploitation of other green sources of energy.

The solar PV generation infrastructure will require ultrahigh volume manufacturing of standardized PV modules in a single location; real or virtual vertical integration of PV manufacturers, financiers, and utility companies; and low-interest financing of all major transactions. The deployment of exactly similar solar PV equipment at multiple locations worldwide would keep manufacturing, transportation, and installation costs low. With DC rather than AC adopted, variations in the frequency of electricity would vanish, and the mutual compatibility of electrical appliances and machinery would be enhanced.

VIII. Conclusion

In this paper, we have examined the emerging role of solar photovoltaics to sustainably power all human activities on our planet this century. Technology assessment shows that PV and batteries are ready to transform the global electricity infrastructure. Microgrids and nanogrids of PV-generated DC electricity will enable this transformation, enhance the availability of potable water, reduce the emission of greenhouse gases, and empower every human being. Political effort must be brought to promote ultralarge-scale manufacturing of PV generating systems and gigawatt storage batteries, to adopt a vertically integrated business model, and embrace the monetary policy of quantitative easing to rapidly make this dream a reality.

References

[1] "Achieving Universal Energy Access", United Nations Foundation. [Online]. Available: http://www.unfoundation.org/what-we-do/issues/energy-and-climate/clean-energy-development.html (Accessed 12 July 2014)

[2] "Billions Daily Affected by Water Crisis", Water.org. [Online]. Available: http://water.org/water-crisis/one-billion-affected/ (Accessed 12 July 2014)

[3] "7 Million Premature Deaths Annually Linked to Air Pollution", World Health Organization, 25 March, 2014. [Online]. Available: http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/ (Accessed 12 July 2014).

[4] "Household air pollution and health", Fact Sheet No. 292, World Health Organization, March 2014. [Online]. Available: http://www.who.int/mediacentre/factsheets/fs292/en/ (Accessed 12 July 2014)

[5] What's Your Impact, "What are the main sources of carbon dioxide emissions?" [Online]. Available: http://whatsyourimpact.org/greenhouse-gases/carbon-dioxide-sources. (Accessed 5 July 2014).

[6] "Climate Change 2014: Impacts, Adaptation, and Vulnerability: Summary for Policy Makers", Intergovernmental Panel on Climate Change, March 31, 2014. [Online]. Available: https://ipcc-wg2.gov/AR5/images/uploads/IPCC_WG2AR5_SPM_Approved.pdf (Accessed 12 July 2014)

[7] B. C. Howard, "5 Dire Warnings From Bipartisan Report on Climate Change's Economic Impact", National Geographic Daily News, June 24, 2014. [Online]. Available: http://news.nationalgeographic.com/news/2014/06/140624-bipartisan-report-risky-business-climate-change-science/ (Accessed 12 July 2014).

[8] "The Cost of Doing Nothing", The Economist, June 28, 2014. [Online]. Available: http://www.economist.com/news/united-states/21605936-scorched-farms-flooded-homes-and-lower-productivity-cost-doing-nothing (Accessed 12 July 2014)

[9] J. Spross, "Right Now We 'Grossly Underestimate' Economic Damage From Climate Change, New Paper Says", Climate Progress, June 16, 2014. [Online]. Available: http://thinkprogress.org/climate/2014/06/16/3449645/stern-updated-climate-model-economic/ (Accessed 12 July 2014)

[10] N. Glinski, "World Bank Says 'Climate Smart' Policies Boost Growth", Renewable Energy World, June 26, 2014. [Online]. Available: http://www.renewableenergyworld.com/rea/news/article/2014/06/world-bank-says-climate-smart-policies-boost-growth?cmpid=SolarNL-Saturday-June28-2014 (Accessed 12 July 2014)

[11] R. Singh, "Solar Can Transform the Grid", SPIE Professional, July 2014, [Online]. Available: http://spie.org/x108820.xml (Accessed 12 July 2014)

[12] R. Singh, G. F. Alapatt, and G. Bedi, "Why and How PV Will Provide the Cheapest Energy in the 21st Century", Facta Universitatis Series: Electronics and Energetics, vol.7, No. 2, pp. 275-298, 2014.

[13] R. Singh, G. F. Alapatt, and A. Lakhtakia, "Making Solar Cells a Reality in Every Home: Opportunities and Challenges for Photovoltaic Device Design", IEEE J. Electron Device Soc., Vol. 1, No. 6, pp. 129-144, 2013.

[14] R. Singh, G. F. Alapatt, and M. Abdelhamid, "Green Energy Conversion & Storage for Solving India's Energy Problem through Innovation in Ultra Large Scale Manufacturing and Advanced Research of Solid State Devices and Systems", *Proc. Int. Conf. on Emerging Electronics*, IIT, Bombay, December 15-17, 2012, pp. 1-8, 2013. doi: 10.1109/ICEmElec.2012.6636220

[15] R. Singh and G. F. Alapatt, "Innovative Paths for Providing Green Energy for Sustainable Global Economic Growth", Proc. SPIE 8482, art. no. 848205, 2012.

[16] R. Singh, G. F. Alapatt, and K. F. Poole, "Photovoltaics: Emerging Role as a Dominant Electricity Generation Technology in the 21st Century", *Proc. 28th Int. Conf. on Microelectronics*, Nis, Serbia, May 13-16, 2012, pp. 53-63, 2012. doi: 10.1109/MIEL.2012.6222796

[17] W. Rickerson, *et al.* "Residential Prosumers - Drivers and Policy Options", IEA-Renewable Energy Technology Deployment, June 2014. [Online]. Available:http://iea-retd.org/wp-content/uploads/2014/06/RE-PROSUMERS_IEA-RETD_2014.pdf (Accessed 13 July 2014)

[18] S. W. Jones, "Exponential Trends in the Integrated Circuit Industry", www.icknowledge.com, Feb 12, 2008. [Online]. Available: ftp://217.219.170.14/Computer%20Group/Faani/vaset%20fani/second/imani/source/Exponential3.pdf (Accessed 12 July 2014)

[19] J. G. Dorn, "Solar Cell Production Jumps 50 Percent in 2007", Eco-Economy Indicators, Earth Policy Institute, Dec 27, 2007. [Online]. Available: http://www.earth-policy.org/indicators/C47/solar_power_2007 (Accessed 12 July 2014)

[20] J. Jones, "Huge Regional Price Variations in Chinese-Produced Solar Modules", Greentech, May 2, 2014. [Online]. Available:http://www.greentechmedia.com/articles/read/Huge-Regional-Price-Variations-in-Chinese-Produced-Solar-Modules (Accessed 12 July 2014)

[21] D. Barnes, "TFT LCD Business Cycles and Trends", Display Economics Report, www.DisplaySearch.com, Sept. 21, 2005.

[22] R. Larsen, "Samsung's 2014 TV Line-up - with Prices," Flat Panels HD, March 21, 2014. [Online]. Available: http://www.flatpanelshd.com/article.php?subaction=showfull&id=1395392640 (Accessed 12 July 2014)

[23] E. Wesoff, "Anatomy of a Deal: 4-Cent-per-Kilowatt-Hour Solar in Palo Alto", Genentech, March 20, 2014. [Online]. Available: http://www.greentechmedia.com/articles/read/Anatomy-of-a-PPA-4-Cent-Per-Kilowatt-Hour-Solar-in-Palo-Alto-CA (Accessed 13 July 2014)

[24] "Better Power-packs will Open the Road for Electric Vehicles", The Economist, June 12, 2014. [Online]. Available: http://www.economist.com/news/business/21604174-better-power-packs-will-open-road-electric-vehicles-assault-batteries (Accessed 12 July 2014)

[25] A. A. Asif, G. F. Alapatt, and R. Singh (unpublished).

[26] R. Singh, "Can the US Return to Manufacturing Glory?", Photovoltaics World, pp. 40-43, March/April 2012.

[27] J. M. Roney, “China Leads World to Solar Power Record in 2013”, SustainaBlog, June 2014. [Online]. Available: http://sustainablog.org/2014/06/china-solar-power-record-2013/ (Accessed 13 July 2014)

[28] “Solar PV Module Shipments to Grow 30% in 2014”, SolarBuzz, May 20, 2014. [Online]. Available: http://www.solarbuzz.com/news/recent-findings/solar-pv-module-shipments-grow-30-2014-according-npd-solarbuzz (Accessed 13 July 2014)

[29] J. Jones, “Regional PV Module Pricing Dynamics: What You Need to Know”, Genentech, November 22, 2013. [Online]. Available: http://www.greentechmedia.com/articles/read/regional-pv-module-pricing-dynamics-what-you-need-to-know (Accessed 13 July 2014)

[30] M. Barker, “Solar PV Trade Investigations Lag PV Market Dynamics”, SolarBuzz, May 16, 2014. [Online]. Available: http://www.solarbuzz.com/resources/blog/2014/05/solar-pv-trade-investigations-lag-pv-market-dynamics (Accessed 13 July 2014)

[31] “Champions of Photovoltaics Technology,” Photovoltaics World, October 1, 2010. [Online]. Available: http://www.renewableenergyworld.com/rea/news/article/2010/10/champions-of_photovoltaics (Accessed 13 July 2014)

[32] W. Wade, “Utilities Threatened by Competitive Renewable Energy Growth,” Bloomberg, April 9, 2014. [Online]. Available: http://www.renewableenergyworld.com/rea/news/article/2014/04/utilities-threatened-by-competitive-renewable-energy-growth?cmpid=SolarNL-Saturday-April12-2014 (Accessed 13 July 2014)

[33] “Solar Energy Jobs Increase, Wind Power Decrease”, Worldwatch, July 2, 2014. [Online]. Available: http://www.agprofessional.com/news/Solar-energy-jobs-increase-wind-power-decrease-265401441.html (Accessed 13 July 2014)

[34] R. Singh, N. Gupta, and K. F. Poole, “Global Green Energy Conversion Revolution in 21st Century Through Solid State Devices”, Proc. 26th Int. Conf. on Microelectronics, Nis, Serbia, May 11-14, 2008, vol. 1, pp. 45-54, 2008. doi: 10.1109/ICMEL.2008.4559221

[35] J. Shah, “Solar More Viable as Georgia’s New Nuclear Power Plants Face Overruns”, Saportareport, September 15, 2013. [Online]. Available: http://saportareport.com/blog/2013/09/solar-more-viable-as-georgias-new-nuclear-plants-face-overruns/ (Accessed 13 July 2014)

[36] P. Fairley, “Renewables Up, Nuclear Flat in French Energy Plan”, IEEE Spectrum, June 24, 2014. [Online]. Available: http://spectrum.ieee.org/energywise/energy/nuclear/renewables-up-nuclear-down-in-french-energy-plan (Accessed 13 July 2014)

[37] J. Farrell, “Natural Gas Isn’t a Bridge Fuel, It’s a Gateway Drug”, Renewable Energy World, February 03, 2014. [Online]. Available: http://www.renewableenergyworld.com/rea/blog/post/2014/02/natural-gas-isnt-a-bridge-fuel-its-a-gateway-drug (Accessed 13 July 2014)

[38] “Minnesota Regulators Choose 100 MW-AC Solar PV Project over Natural Gas”, SolarServer, March 28, 2014. [Online]. Available: http://www.solarserver.com/solar-magazine/solar-news/current/2014/kw13/minnesota-regulators-choose-100-mw-ac-solar-pv-project-over-natural-gas.html (Accessed 13 July 2014)

[39] J. Doom, “Megalim Solar Gets $820 Million for 121-Megawatt Plant in Israel”, June 16, 2014. [Online]. Available: http://www.businessweek.com/news/2014-06-26/megalim-solar-gets-820-million-for-121-megawatt-plant-in-israel (Accessed 13 July 2014)

[40] G. Parkinson, “Suntech Says Solar PV Costs to Match Coal in China 2016”, Genentech, May 30, 2014. [Online]. Available: http://www.greentechmedia.com/articles/read/suntech-says-solar-pv-costs-to-match-coal-in-china-by-2016 (Accessed 13 July 2014)

[41] “Six Stages of Solar Bankability”, ABB. [Online]. Available: http://www05.abb.com/global/scot/scot299.nsf/veritydisplay/2fa374aa511be1558525792e005e47fb/$file/ABB_%20solar_whitepaper_final.pdf (Accessed 13 July 2014)

[42] R. L. Welch and G. K. Venayagamoorthy, “Energy Dispatch Fuzzy Controller for a Grid-Independent Photovoltaic System”, *Energy Convers. Management*, Vol. 51, No. 5, pp. 928-937, 2010.

[43] G. K. Venayagamoorthy and R. Welch, “Energy Dispatch Controllers for a Photovoltaic System”, *Eng. Applicat. Artific. Intell.*, Vol. 23, No. 2, pp. 249-261, 2010.

[44] G. K. Venayagamoorthy, “Tie-Line Bias Control of a Power System with Large PV Plants Using PMU Information”, Foz do Iguassu, Brazil, *XIII Symp. Specialists in Electric Operational and Expansion Planning*, May 18-21, 2014.

[45] P. H. Nguyen, G. K. Venayagamoorthy, W. L. Kling, and P. F. Ribeiro, “Dynamic State Estimation for Distribution Networks with Renewable Energy Integration”, *Int. J. Smart Grid and Clean Energy*, Vol. 2, No. 3, pp. 307-315, 2013.

[46] S. M. Ruffing and G. K. Venayagamoorthy, “Short to Medium Range Time Series Prediction of Solar Irradiance Using an Echo State Network”, *Proc. 15th Int. Conf. Intelligent Syst. Applicat. Power Syst.*, Curitiba, Brazil, November 8-12, 2009. doi: 10.1109/ISAP.2009.5352922

[47] G. K. Venayagamoorthy, “Dynamic, Stochastic, Computational and Scalable Technologies for Smart Grid”, *IEEE Computational Intell. Mag.*, Vol. 6, No. 3, pp. 22-35, 2011.

[48] M. Wright, “Solar + Battery Hybrid Inverters That Read Weather Forecasts”, CleanTechnica, July 4, 2014. [Online]. Available: http://cleantechnica.com/2014/07/04/solar-battery-hybrid-inverters-weather-forecast/ (Accessed 13 July 2014)

[49] G. Parkinson, “Consumers Are the Big Winners in Solar-Plus-Storage Revolution”, RenewEconomy, May 6, 2014. [Online]. Available: http://www.greentechmedia.com/articles/read/Consumers-Are-the-Big-Winners-in-Solar-Plus-Storage-Revolution (Accessed 13 July 2014)

[50] C. Martin, “SolarCity Says Batteries Reduce Risk of Utility Backlash”, Bloomberg, June 26, 2014. [Online]. Available: http://www.bloomberg.com/news/2013-06-26/solarcity-says-batteries-reduce-risk-of-utility-backlash.html (Accessed 13 July 2014)

[51] G. Parkinson, “Rooftop Solar: Does It Really Need the Grid?”, RenewEconomy, April 25, 2014. [Online]. Available: http://www.greentechmedia.com/articles/read/rooftop-solar-does-it-really-need-the-grid (Accessed 13 July 2014)

[52] G. Parkinson, “Ergon says Renewables and Batteries may be Cheaper than Grid”, RenewEconomy, October 1, 2013. [Online]. Available: http://reneweconomy.com.au/2013/ergon-says-renewables-and-batteries-may-be-cheaper-than-grid-21838 (Accessed 13 July 2014)

[53] S. Vorrath, “Could a 500-house Community go Off-grid?”, RenewEconomy, March 25, 2014. [Online]. Available: http://reneweconomy.com.au/2014/could-a-500-house-community-go-off-grid-31978 (Accessed 13 July 2014)

[54] L. Guccione and P. Bronski, “Will the Electricity Grid Become Optional?”, RMI Outlet, February 25, 2014. [Online]. Available: http://blog.rmi.org/blog_2014_02_25_will_the_electricity_grid_become_optional (Accessed 13 July 2014)

[55] S. Lacey, “Here’s Where Solar, Storage and Microgrids Are Starting to Take Hold in the US”, GreenTech Media, July 1, 2014. [Online]. Available: http://www.greentechmedia.com/articles/read/heres-where-solar-storage-and-microgrids-are-starting-to-take-hold (Accessed 13 July 2014)

[56] R. Singh, “DC Microgrid and Nanogrid: The Next Big Thing in the Energy Sector”, GreenTech Leadership Group, January 24, 2014. [Online]. Available: http://greentechleadership.org/dc-microgrid-nanogrid-next-big-thing-energy-sector/ (Accessed 13 July 2014)

[57] R. Singh and K. Shenai, “DC Microgrids and the Virtues of Local Electricity”, *IEEE Spectrum*, February 6, 2014. [Online]. Available: http://spectrum.ieee.org/green-tech/buildings/dc-microgrids-and-the-virtues-of-local-electricity (Accessed 13 July 2014)

[58] “How Much Energy is Consumed in the World by Each Sector?”, US Energy Information Administration, May 19, 2014. [Online]. Available: http://www.eia.gov/tools/faqs/faq.cfm?id=447&t=1 (Accessed 13 July 2014)

[59] Solar Cell Central, “Solar Electricity Cost?”, Four Peaks Technologies. [Online]. Available: http://solarcellcentral.com/cost_page.html

[60] T. Enzendorfer, “A Lifecycle Approach to Inverter Management”, *Solar Industry Mag.*, Vol. 7, No. 1, January 2014. http://www.solarindustrymag.com/issues/SI1401/FEAT_02_A-Lifecycle-Approach-To-Inverter-Management.html (Accessed 14 July 2014)

[61] G. Parkinson, "EOS: Utility Scale Battery Storage Competitive with Gas", RenewEconomy, December 17, 2013. [Online]. Available: http://reneweconomy.com.au/2013/eosutilityscalebatterystoragecompetitivewithgas36444 (Accessed 14 July 2014)

[62] S. Burns, "Power Costs in the Production of Primary Aluminum", MetalMiner, February 26, 2009. [Online]. Available: http://agmetalminer.com/2009/02/26/power-costs-the-production-primary-aluminum/

[63] First Conference on Local DC Electricity, Clemson University, Clemson, SC, USA, March 30–April 1, 2014. http://clemsonenergy.com/local-dc-conference-general-information/ (Accessed 14 July 2014).

[64] Sheraton Atlanta Hotel, http://www.sheratonatlantahotel.com/, Starwood Hotels & Resorts Worldwide, Inc.

[65] IEEE Standards Association, http://standards.ieee.org/email/2013_10_cfp_dchome_web.html (Accessed 14 July 2014)

[66] B. Bilgin and A. Emadi, "Electric Motors in Electrified Transportation", IEEE Power Electronics Mag., Vol. 1, No. 2, pp. 10-17, June 2014. doi: 10.1109/MPEL.2014.2312275

[67] "Using Energy Efficiently", Tesla Motors. [Online]. Available: http://www.teslamotors.com/goelectric/efficiency (Accessed 14 July 2014)

[68] "EV ARCTM " Envison Solar. [Online]. Available: http://envisionsolar.com/ev-arc/ (Accessed 14 July 2014)

[69] "Let the Sun In", Ford Motor Company, January 2, 2014. [Online]. Available: https://media.ford.com/content/fordmedia/fna/us/en/news/2014/01/02/let-the-sun-in--ford-c-max-solar-energi-concept-goes-off-the-gri.html (Accessed 14 July 2014)

[70] J. Cobb, "VIA SolTRUX Is One Bright Idea," HybridCars. [Online]. Available: November 26, 2013. http://www.hybridcars.com/via-soltrux-is-one-bright-idea/ (Accessed 14 July 2014)

[71] S. Gopinath, "Indian Engineer Prepares Solar Tuk-tuk for London Odyssey", Reuters, July 14, 2014. [Online]. Available: http://www.reuters.com/article/2014/07/14/india-tuktuk-idUSL6N0PN0CE20140714 (Accessed 14 July 2014)

[72] M. G. Richard, "Google Buys Titan Aerospace, Maker of Solar Planes That Can Stay in the Sky for Years", TreeHugger, April 16, 2014. [Online]. Available: http://www.treehugger.com/aviation/google-buys-titan-aerospace-maker-solar-planes-can-stay-sky-years.html (Accessed 14 July 2014)

[73] R. Itten, R. Frischknecht, and M. Stucki, Life Cycle Inventories of Electricity Mixes and Grid. ESU-services Ltd., Uster, CH. 2012, (available in ecoinvent v3.01) [http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf], updated [June 2014]

[74] "2010 World Population Data Sheet", Population Bureau, 2010. [Online]. Available: http://www.prb.org/pdf10/10wpds_eng.pdf (Accessed 14 July 2014)

[75] "IPCC Fourth Assessment Report: Climate Change 2007", Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability, Intergovernmental Panel on Climate Change. [Online]. Available: http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch3.html (Accessed 14 July 2014)

[76] "Water Desalination Using Renewable Energy", International Renewable Energy Agency, March 2012. [Online]. Available:http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20I12%20Water-Desalination.pdf (Accessed 13 July 2014)

[77] C. Larson, "The World's 85 Richest Are Now Worth as Much as 3.5 Billion Poorest", Bloomberg BusinessWeek, January 20, 2014. [Online]. Available: http://www.businessweek.com/articles/2014-01-20/the-worlds-85-richest-now-worth-as-much-as-3-dot-5-billion-poorest (Accessed 13 July 2014)

[78] K. Moreno, "The 67 People As Wealthy As The World's Poorest 3.5 Billion," Forbes Insight, March 25, 2014. [Online]. Available: http://www.forbes.com/sites/forbesinsights/2014/03/25/the-67-people-as-wealthy-as-the-worlds-poorest-3-5-billion/ (Accessed 13 July 2014)

[79] "What is Quantitative Easing?", The Economist, January 14, 2014. [Online]. Available: http://www.economist.com/blogs/economist-explains/2014/01/economist-explains-7 (Accessed 14 July 2014)

[80] M. Metcalfe, "Printing Money to Help the Poor", Businessweek, May 08, 2014. [Online]. Available: http://www.businessweek.com/articles/2014-05-08/could-central-banks-print-money-to-help-developing-nations (Accessed 13 July 2014)

[81] F. Bywaters (World Future Council), personal communication to R. Singh, June 27, 2014.