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Transformative Role of Photovoltaics in Phasing Out Alternating Current Based Grid by Local DC Power Networks for Sustainable Global Economic Growth

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***Abstract* — for sustainable global economic growth, eradication of global energy poverty and addressing climate challenges, free fuel based solar and wind energy sources are the only viable solution for electricity generation. Due to inherent advantages, photovoltaics has emerged as the major source of electrical power. Local generation of direct current (DC) power by PV and the use of batteries for storing electrical power have the potential of transforming global electricity infrastructure to address the problems faced by alternating current (AC) based centralized power generation and long haul transmission and distribution.**

I. INTRODUCTION

Historical data of crude oil prices of last 50 years show that the maximum and minimum prices as a function of time have been associated with key global geopolitical and economic events [1]. In an earlier publication, we have stressed the importance of free fuel based energy sources for providing sustained global economic growth, solving climate issues and eradication of global energy poverty [2]. Replacing oil based economy by free fuel based economy is the only way to provide energy to every human being in a sustainable and equitable manner [3]. As shown in Fig. 1, for sustainability other than free fuel, abundant raw material and pro-public energy and manufacturing polices are required.

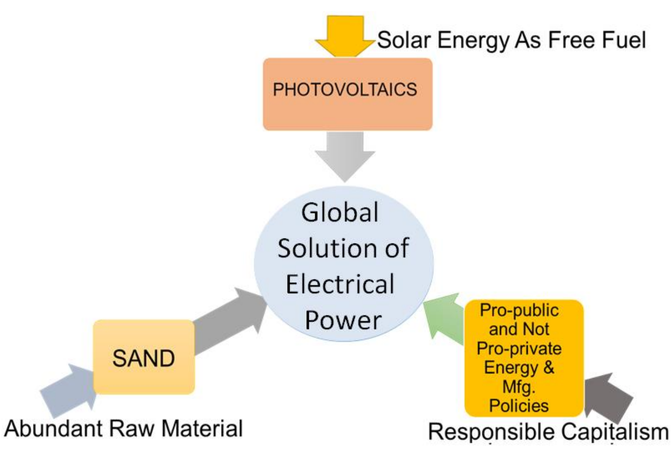

Fig. 1. Proposed solution to the global electricity problems.

For PV module manufacturing, one of us predicted in 1980 that silicon is the ideal base material [3]. Reliability data of silicon solar cells have shown that silicon modules can operate very well beyond the 25 years warranty given by most of the manufacturers. SunPower has published that useful lifetime of their modules is 40 years, which is defined as 99% of PV modules generating at least 70% of their rated power [5]. The amount of energy received on earth's surface from the Sun in an hour is enough to meet all the energy needs of the mankind [6]. Among free fuel based energy sources, only solar and wind are commercially viable for electricity generation. There is no direct competition between PV and wind turbines for generating electricity. PV power generation meets peak power demand during the day. The peak of wind power generation is mostly at night when the electricity demand goes down. Wind energy is also not uniform all over the world and is more susceptible to geographic terrain factors. On the other hand, most of the world population lives in areas that get enough sunlight to generate electricity by PV viably. In addition, wind generates erratic AC power, which is converted to DC power before converting to AC power. Wind electricity cannot be generated locally in every place. [7]. Long haul transmission of wind power is fairly expensive and cost about $5 million per mile [8]. Due to some of these inherent advantages, PV will become the dominant electricity generation technology in the 21st century [7].

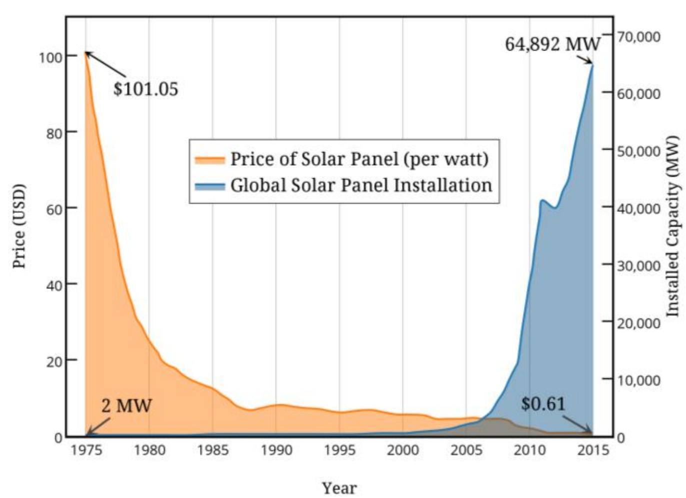

Fig. 2. Near exponential decrease in PV module cost and near exponential growth in PV installation. Data from [9].

Near exponential cost reduction of PV modules and near exponential installation of PV modules shown in Fig. 2 [9] is the origin of PV revolution in power sector [10]. For underdeveloped, emerging, and developed economies, PV will provide sustained economic growth [11]. Intermittent nature of solar energy, and wind energy has been a road block into widespread use of photovoltaics and wind turbines for electricity generation. In the past electrical energy storage has been dominated by pumped hydro storage. However, due to the advancements in technology and volume manufacturing, the cost of batteries is following the price reduction trend of Photovoltaic (PV) modules [12]. Fig. 3 [12], shows the learning curves for Li-ion battery along with that of silicon PV modules.

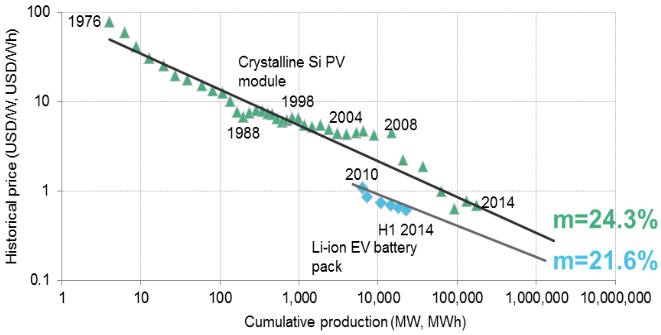

Fig. 3 Similar to PV modules, doubling the volume of manufacturing leads to about 22% cost reduction of batteries [12].

Exponential growth in the sale of electrical vehicles (EVs) is the driver of cost reduction of lithium batteries. Typical cost of pumped hydro storage is about $75-100 /kWh. As shown in Fig 4 [13], in the next 3-4 years, the cost of lithium batteries is expected to be in the range of pumped hydro storage. In addition, due to the absence of inverters and rectifiers in DC power system, the power electronics cost will be further reduced. Some battery manufacturers have predicted 50% cost reduction of battery related power electronics for DC power system. [7].

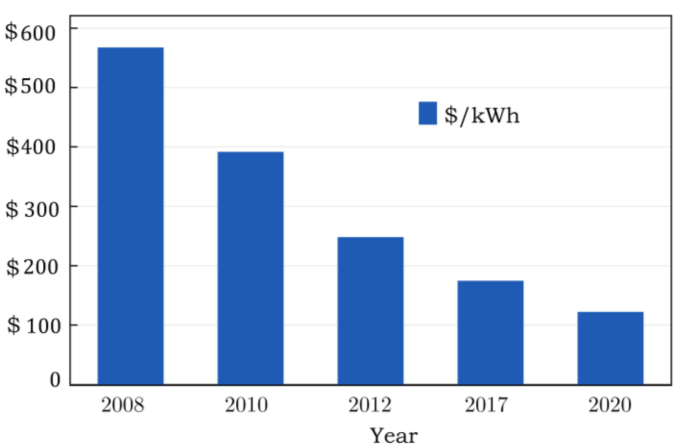

Fig. 4. Li-ion battery cost is declining as the is production ramping up. Data from [13].

The electrical power industry in developed economies is on the cusp of a dramatic transformation driven by a series of changes that includes emergence of rooftop solar and battery storage as the dominant distributed generation source, real time grid monitoring, emergence of microgrid and nanogrid in place of integrated electric grid, improved energy efficiency, advantages of direct current in place of alternating current, cyber and grid security climate control and weather tolerant electric infrastructures. The objective of this paper is to demonstrate that local generation of direct current power by PV and the use of batteries for storing electrical power has the potential of transforming global electricity infrastructure.

II. PV as a Source of Local DC Power

Currently the generation, transmission and distribution of power is dominated by AC power. This is mostly due the fact that the outcome of the famous 'war of currents' was favoring AC [14]. The existence of low cost semiconductor products for building intelligent control systems, low cost PV and low cost batteries means that we can generate, store and use electricity locally as shown in Fig. 5. It is worth mentioning here that PV based local DC power does not mean roof top PV. Except few inductive loads, virtually all our loads need DC power as the input power. Primary electrical power source of all appliances is DC power. Air conditioners, washers, dryers, heavy duty food processors and refrigerators all appliances include brushless DC permanent magnet motors driven by variable frequency drives (VFD). A VFD initially rectifies the AC input to DC, then applies pulse width modulation to create the desired output frequency and phase. DC powered VFDs can bypass the losses associated with power rectification. About 25 % of direct current (DC) power generated by photovoltaics (PV) is wasted in converting to alternating current (AC) before transmission and distribution. This is also true for off grid applications of PV involving AC power. In addition, another 7-10 % power is lost when AC power is converted back to DC power to feed DC loads. More than 30 % energy can be saved by the use of local DC power [15], which translates to 30 % capital cost reduction of PV system. The energy management system (EMS) of local DC power based power network is much cheaper than the corresponding AC counterpart, since there is no frequency

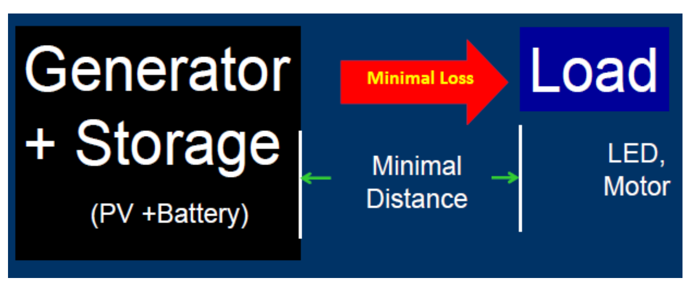

Fig. 5. Concept of local DC power with minimum distance between generation, storage and intelligent loads.

control. The availability of low-cost batteries, is the driver of potential transformation of fossil fuel based surface transport to transport dominated by electrical power. In addition to electrical vehicles, a new wave of electric powered rides such as scooters, longboards, and unicycles are ready to play an important role in mass-transit system [16] As compared to AC, fast charging of EVs is provided by DC charging [17]. In the United States, the gasoline bill per year is about $400 billion. Almost equal amount is spent on electrical power. Even 25 % change of transport sector from gasoline based transport to electrical power based transport will provide an additional $100 billion market of electrical power. The use of PV generated DC power in transport sector will provide major growth opportunity of PV systems.

The future energy grid has to evolve as power network, since the nature of the loads and consumer behavior is changing. The consumers are using more electronics, requiring electric vehicle charging and gradually will move towards intelligent appliances with more computational processing power and internet connectivity. Due to small attack surface area, DC power provides better cyber security solution than AC system . In Table 1, we have listed the key requirements of the future power network. All of these requirements can be addressed with PV based DC micro- and nanogrids [18]. In addition to meeting low-cost and climate challenges, PV based local DC power network (example shown in Fig. 6) also addresses the challenges of reliability, resiliency, access to all, electromagnetic protection and solar storm problems faced by AC power grid [18].

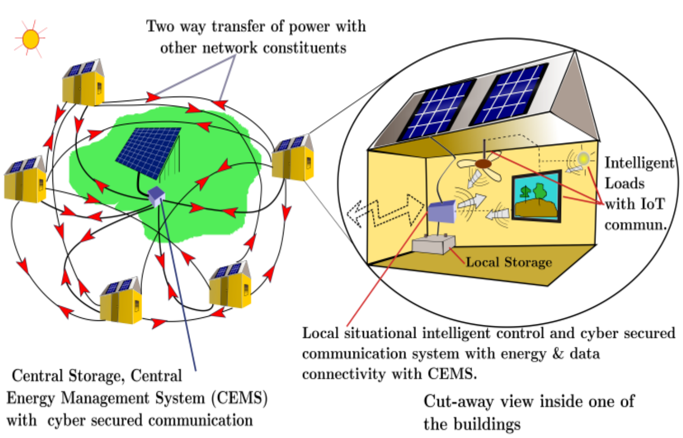

Fig. 6. DC microgrid operations with several DC nanogrids showing PV generation and energy storage at the nanogrid and microgrid levels. The components in the nanogrid and microgrid are empowered with advanced communication, computing and security capabilities.

TABLE I
REQUIREMENTS OF FUTURE POWER NETWORK

Characteristics of Power Network	Driving Force
Electromagnetic Protection	National Security
Solar Storms	National Security
Ultra-low Cost	Economic Growth
Free Fuel	Free Solar Energy : Sustainable Economic Growth
Local Direct Current Power Generation	Highest Energy Efficiency of Grid
Source of Local power	Photovoltaics: Ultra Low Cost
Local Energy Storage	Batteries: Proven Energy Storage Device
Climate Change Challenges	National and Global Economic Growth
Cyber Security	National and Economic Security
Internet of Things	Cyber, EMP , and Solar Storms Secured & Energy Efficient
Reliability	Need for More Than 99.99 % Reliability
Resiliency	Increased Natural Disasters
Situational Intelligence	Intelligent Control System
Real Time Monitoring	Intermittency of Solar Power
Nanogrid/Microgrid	Physical Security: User Has Control
Low Voltage Direct Current Power	No Environmental, Health and Safety Issues
Accessible to all	Global new middle class, Social Justice

III. FUTURE ENERGY DEMANDS AND REDUCING ENERGY WASTAGE

As projected by Energy Information Administration (EIA), there will be a 48% increase in world energy consumption by 2040, and more than half of this increase will come from Asia. [19]. Renewables are named as the fastest growing energy source with average 2.6% per year growth through 2040 [19]. In short term projection for USA, electricity generation from renewables (excluding hydropower) is forecasted to grow by 13.3% and by 8.6% in 2016 and 2017, respectively [20]. It can be inferred that there is going to be a steep increase in energy demand and there is a momentum in renewable energy generation.

As compared to AC power, we have discussed the virtues of DC power in section II, In this section, we are going to focus on the role of DC power in improving energy efficiency.

Providing enough electricity to the entire population of this earth is a mammoth task. Therefore, every possible avenue that can lead to most efficient use of energy and generated electricity has to be explored. Therefore, we cannot afford to waste electricity in conversions from DC-to-AC and vice versa.

With this in mind, a paradigm shift is needed in the way we think about the electricity infrastructure. A significant part of this renewable energy is coming from PV, and PV generates DC. In the attempt to use this DC in our conventional AC installations, a significant portion is wasted. Commercially available inverters are marketed as "efficient devices" with best DC-to-AC conversion efficiency up to 97% [21]. However, it should be always noted that this apparent high number is true only under optimum condition i.e. best loading point and 25°C as the operating temperature. Any departure from this best point, increase or decrease in load, will result in lower efficiency. Obviously, the inverters do not operate under the optimum loading all the time. In particular, when working with PV generated DC, the inverters are more likely to have various input powers that are significantly different than the highest performance operating point. Performance under different load condition can be ascertained by the California Energy Commissions (CEC) efficiency and Euro efficiency [22], [23]. These two efficiencies can, at best, "partially" address the efficiency variation with loads but these are not free from limitations. These efficiencies consider the inverter will have variable load for a fixed percentage of times. The testing is done at 25°C, while the inverter may operate at higher temperature most of the times. The temperature de-rates the performance of inverter drastically [24]-[26].

As a case study, we did an analysis on a specific location: Charleston, SC of USA. The irradiation and climate data for every hour for the month of June, 2003 were taken from National Solar Irradiation Data Base [27]. We considered a 5 KW PV installation with 21.5% efficient PV panels [28] and a 5KW commercially available inverter [15]. The generated DC from the PV was converted to AC, and for consumption of the power, we considered the AC was again converted back to DC in various electronic equipment and consumer electronics. We considered various rectification losses at the end devices (e.g. rectifiers in LED light bulbs, chargers for cell phones and laptops, power supply units inside desktop computers, etc.). The PV provided various input powers to the inverter and at these different loading conditions, the efficiencies of the inverter were extracted and calculated from the efficiency curve furnished by manufacturers [21]. The temperature effect on the inverter was also factored in by adjusting the output efficiencies for any temperature higher than 25°C. Considering all these, it will have about ~30% loss from the point of electricity generation (PV) and to the final use (device), and we will lose about 276KWh out of about 933KWh generated in one month. Inclusion of batteries in the AC power network will provide additional losses in the power network.

Many PV installers and vendors recommend having some excess generation capacity on the DC (PV side) [29], [30]. This so called 'oversizing' or DC-to-AC capacity ratio between PV and inverter can range from 1.10 to 1.35 [29]-[31]. This variation depends on vendor, planner, planning software and geographic location. Other factors include: the market price of PV, cost of electricity and payback period of the extra investment [29]. The key arguments that are made in favor of this excess capacity in PV side are: (a) the cheaper cost of PV, and (b) to drive the inverter in more favorable higher load condition.

Moreover, the life times of inverters are usually shorter than that of PV panels. Even excluding early failures, the inverter needs to be replaced at least once during the life time of the PV system [32]. This adds to capital cost and causes unwanted service interruption. Getting rid of inverter can result in reduced capital cost, less maintenance, less failures and more reliable infrastructure.

Inside most electronic equipment, a portion of the printed circuit board (PCB) is dedicated for converting AC into DC, and DC is used in most areas of the PCB. If these device can be powered with DC power from DC infrastructure, there is a scope of eliminating these rectifier, smoothing filters, etc. from PCB [33]. If the PCB becomes smaller while performing the same tasks (except AC/DC conversion), it will allow us to fit more units per square area. Usually in industrial production lines, the components are placed on repeated patterns in identical blocks on a large PCB which is later cut into individual PCBs that go inside the final product. If the final PCB can be of smaller size, we would die out more PCBs from the production line. Moreover, time will be saved when we do not need to solder the AC/DC conversion rectifier, filters, etc. on the PCB. In short, we will be able to reduce production cost, increase throughput, reduce production time and increase profitability of many electronics manufacturing facilities. It might also be possible to eliminate the discrete chargers used for charging Li-ion batteries in laptops and cell phones.

Overall, PV and battery based local DC power network has the potential of transforming global electricity infrastructure [15, 34]. The major barrier is the lack of regional, national and international public polices. As shown in Fig. 7, at all levels public policies must be introduced so that new global electricity infrastructure should be based on local DC power. Typical examples of this scenario are incandescent light bulb and light emitting diodes as the sources of light.

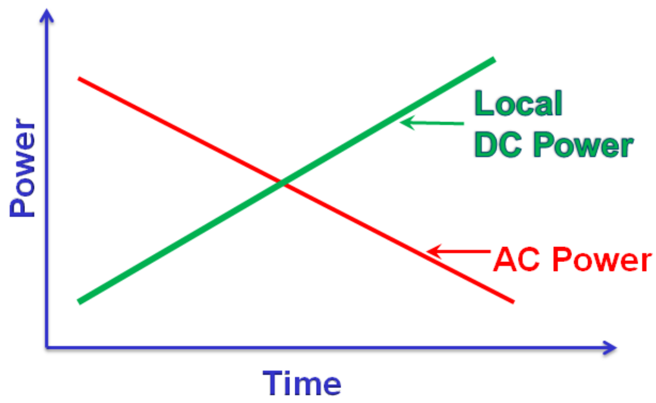

Fig. 7. Expected outcome of proposed policy changes.

IV. Conclusion

In this paper, we have shown that the electrical networks based local DC power generated by PV and stored in batteries have the potential of meeting the challenges of low cost, climate issues, cyber security, reliability, resiliency, electromagnetic protection, solar storms, and access to all faced by electricity infrastructure based on AC power.

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