5-2017

Manufacturing of Photovoltaic Devices, Power Electronics and Batteries for Local Direct Current Power Based Nanogrid

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MANUFACTURING OF PHOTOVOLTAIC DEVICES,
POWER ELECTRONICS AND BATTERIES
FOR LOCAL DIRECT CURRENT
POWER BASED NANOGRID

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Electrical Engineering

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by
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May 2017

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ABSTRACT

To meet the current and future demands of electrical power for household, industrial, commercial and transport sectors, the energy infrastructure has to undergo changes in terms of generation, distribution and consumption. Due to the shortcomings of nuclear and fossil fuel based power generation, the emergence of renewable energy has provided a very lucrative option. With the advent of low-cost photovoltaics (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.

For local nano-grids, direct current (DC) -based system has several distinct advantages that are demonstrated through theoretical and experimental results. A PV-powered and local DC power based nano-grids can be more efficient, reliable, cyber secured, and can easily adopt internet of things (IoT) platforms. With DC generation, storage and consumption, significant amount of energy can be saved that are wasted in back and forth conversion between AC and DC. In case of geomagnetic disturbances, such nano-grids will be more resilient compared to centralized distribution network. Free-fuel, i.e. sunlight, based local DC nano-grid can be the sustainable and cost effective solution for underdeveloped, developing and developed economies.

To take advantage of this, the manufacturing of PV, power electronics and batteries have to follow the best practices that aid process control, quality improvement and potential cost reduction. Without proper process control, the variation will result in yield loss, inferior performance and higher cost of production. On many instances, these issues were

not considered, and some technology such as perovskite solar cell, received a lot of attention as a disruptive technology. Through detailed technical and economic assessments, it was shown that the variability and lack of rigorous process control will result in a lower efficiency when perovskite thin film solar cells are connected together to form a module. Due to stability and performance reasons, it was showed the perovskite solar cell is not ideal for 2-terminal or 4-terminal multi-junction/tandem configuration with silicon cells.

Power electronics also play a vital role in PV systems. The challenges and design rules for silicon carbide (SiC) and gallium nitride (GaN) based power device manufacturing were analyzed. Based on it, advanced process control (APC) based single wafer processing (SWP) tools for manufacturing SiC and GaN power devices are proposed. For energy storage, batteries play an important role in PV installation. Li-ion technology will become the preferred storage due to its capabilities. Incorporation of advanced process control, rapid thermal processing, Industrial IoT, etc. can reduce variability, improve performance and reduce quality-check failures and bring down the cost of electrochemical batteries.

The combined approaches in manufacturing of PV, power electronics and batteries will have a very positive impact in the growth of PV powered DC –based nano-grids.

DEDICATION

I dedicate my dissertation to my wife Shamama Afnan, mother Mahmuda Khanam, father Mohammad Shah Alam, sister Mehnaz, mother-in-law, nephew Mahtamim, and very special friends -Tauhid Rahman, Anzila Tonni, and their sons -Reeshan and Rafaan. All of you helped me become who I am today.

ACKNOWLEDGMENTS

TABLE OF CONTENTS

Table of Contents (Continued)

Table of Contents (Continued)

LIST OF TABLES

LIST OF FIGURES

List of Figures (Continued)

List of Figures (Continued)

Figure   Page

CHAPTER ONE

INTRODUCTION

To meet the current and future demands of electrical power for household, industrial, commercial and transport sectors, the energy infrastructure has to undergo changes in terms of generation, distribution and consumption. Due to the shortcomings of nuclear and fossil fuel based power generation, the emergence of renewable energy has provided a very lucrative option. With the advent of low-cost photovoltaics (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 [1]. Ultra-large 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. PV can provide power in a sustainable manner for underdeveloped, emerging and developed countries [1].

The PV market is dominated by mono- and poly-crystalline silicon solar cells. Silicon has accomplished this dominance because of the availability of cheap, abundant raw material (i.e. sand) and by excellence in manufacturing through process control, and low bulk and process induced defect density. In recent years, perovskite solar cell has been touted as the replacement of silicon solar cells. The sudden rise of perovskite solar cells in recent years has been mainly due to its rapid increase is reported efficiency in both scientific publications and mass media. Most of these results were reported for small sized and selected best performing solar cells. Detailed technical and economic assessment of perovskite solar cells for large-scale manufacturing was carried out in reference [2]. In

reference [2] it was shown that the variability and lack of rigorous process control will result in lower efficiency when thin film solar cells are connected together to form a module. Therefore, the key to translating any laboratory prototype's performance in mass manufacturing lies in process control and satisfactory yield, which are lacking in perovskite technology [2]. Additionally, the series resistance was not in effect in very small ($<0.1cm^2$) perovskite cells that are being reported in scientific literature, but efficiency drops when it is fabricated in larger dimension. Based on the PV module manufacturing requirements of no constraint on the supply of raw materials, low variability of every key process and process-induced defects, low cost of manufacturing, prospects for further cost reduction in the future, green manufacturing and long-term reliability, there are absolutely no prospects for commercial manufacturing perovskite solar cells [2].

Apart from its unsuitability in standalone applications, perovskite solar cells are not usable as the top layer in multi-junction solar cells. We compared performance of multi-junction solar cell where perovskite solar cell served as the top layer on a Si cell –in both 2-terminal and 4-terminal configurations. Using spectral data of sun light, absorption data of Si and several perovskite materials, we showed that the available perovskite materials are not ideal for top layer on multi-junction Si solar cell. Thus, the standalone application and multi-junction (or tandem) application of perovskite solar cell is far from being a reality [2]

Power electronics plays a very important role in photovoltaic systems. Wide band gap semiconductor such has SiC and GaN have the potential to provide higher performance and lower cost than current power electronics based on Silicon. In reference [3], we have

analyzed the challenges and design rules for silicon carbide (SiC) and gallium nitride (GaN) based power device manufacturing. We proposed advanced process control (APC) based single wafer processing (SWP) tools for manufacturing SiC and GaN power devices. Due to high defect density in SiC and GaN wafers, manufacturing tools and practices adapted from older generation of silicon manufacturing are not adequate in this case. APC based SWP tools are proposed to realize the true potential of SiC and GaN in manufacturing power semiconductor devices [3].

For storing electrical power, batteries play a crucial role in PV system. As compared to any other type of batteries, Li-ion battery is the most suitable option for PV systems. The large-scale manufacturing is bringing the cost down of Li-ion batteries. In reference [4], it has been shown that further improvements can be made and further cost reduction can happen in battery manufacturing. Advanced process control (APC) can improve the uniformity in all manufactured electrochemical cells. Moreover, rapid thermal processing (RTP) should be employed to reduce thermal stress and surface roughness of electrodes. According to equivalent circuit models of Li-ion battery, these steps would ensure similar electrical performance from each electrochemical cell, and eventually lead to better performance. As compared to current practice, through advanced process control, rapid thermal processing and better supply chain management through industrial internet of things (IoT), the cost of manufacturing and cost of ownership can be significantly reduced [4].

PV powered DC based grid was examined and evaluated for meeting the following requirements: (*i*) ultra-low cost, (*ii*) sustainability and operating cost, (*iii*) efficiency, local

generation and consumption, (*iv*) environmental impact, (*v*) intelligence, monitoring and cyber security, (*vi*) safety and protection, (*vii*) control system and power quality, (*viii*) possibility of reaching uniform global standards, (*ix*) contribution to transportation sector and (*x*) providing accessibility. In all these metrics, PV based DC nano-grid proved itself to be the best option. Moreover, through an extensive discussion, it was pointed out how the PV system and its standalone grid can remain safe from solar storms that can otherwise pose significant damage to existing centralized grids [5]. Except for few inductive loads, virtually all our loads run on DC power. Primary electrical power source of all appliances is DC power. Most appliances include brushless DC permanent magnet motors driven by variable frequency drives (VFDs). In the attempt to use this PV generated DC in our conventional AC installations, a significant portion of the power is wasted. Switching to PV powered DC grid can save significant amount of energy that is wasted in the back and forth conversion between AC and DC. From electronics manufacturer's viewpoint, when DC devices are powered with DC power from DC infrastructure, there is a scope of eliminating rectifier, smoothing filters, etc. from printed circuit board (PCB) of many electronic equipment. This elimination may lead to reduced production cost, increased throughput, reduced assembly time and increased profitability for many electronics manufacturers [6].

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CHAPTER TWO

THE EMERGING ROLE OF PHOTOVOLTAICS FOR SUSTAINABLY POWERING

UNDERDEVELOPED, EMERGING, AND DEVELOPED ECONOMIES

2.1 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 another 1 billion 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 chapter is to argue and establish that PV is ready to transform the electricity infrastructure in all three types of national economies.

2.2 Technological 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 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. 2.1 [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. 2.2 [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].
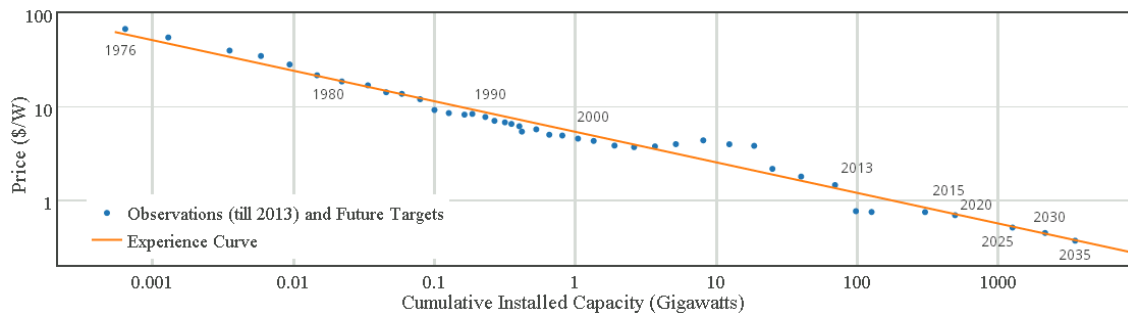
Fig. 2.1. Experience curve of doubling of PV module manufacturing

and cost reduction by 20 % and extension to 2035. Data used

from [17].
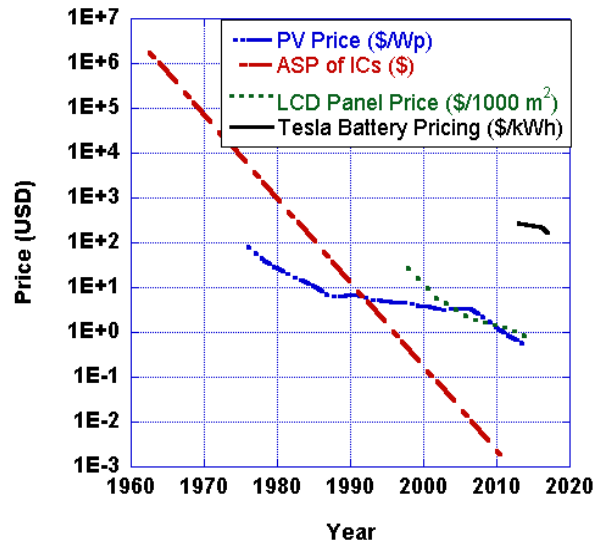
Fig. 2.2. Cost reduction trends for integrated circuits, PV modules,

LCDs, and Tesla Motor batteries [18-22, 24].

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.

Fig. 2.2 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] and many countries are drifting away from this form of energy generation. The two-nuclear-plant project of Georgia Power is at least $737 million over budget, and the company has 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 would drop from 75% to 50%, while 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].
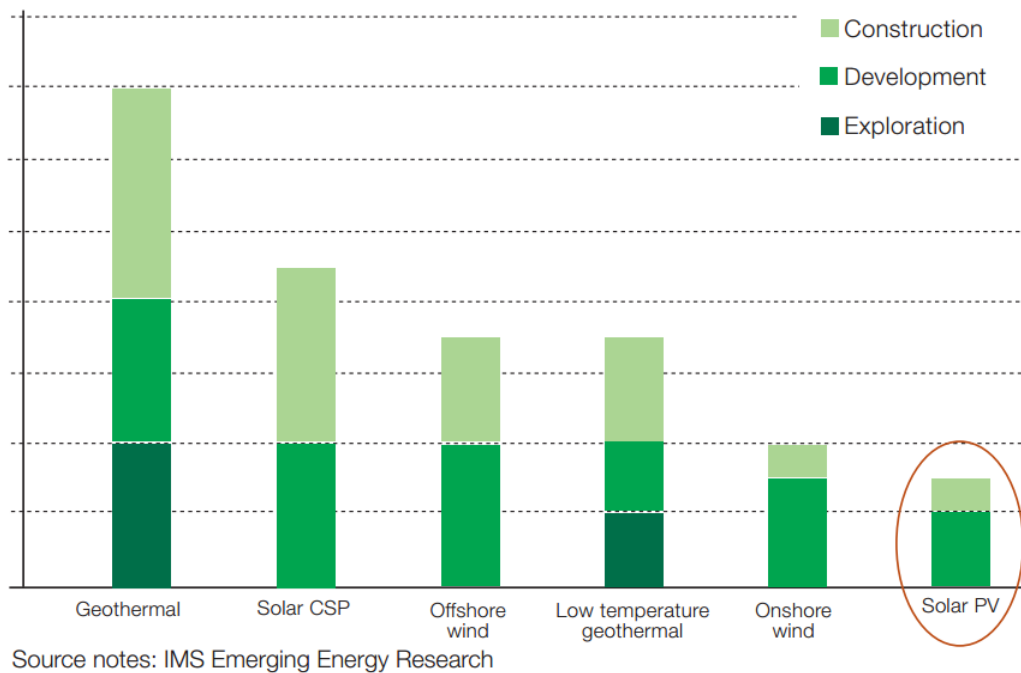
Fig. 2.3. Pace of deployment of different energy generation technologies [41].
 Time is represented in a qualitative way in the y-axis. © ABB Group.

Fig. 2.3 depicts the rapid-deployment advantage of solar PV generation [41]. Adding the high reliability and the low cost, 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].

2.3. 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 that 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.
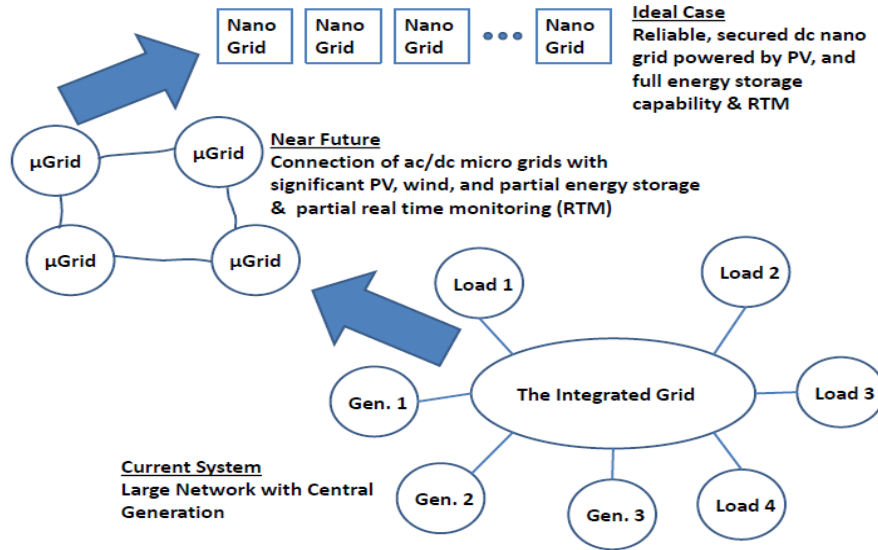
Fig. 2.4. Transformation from centralized grids to microgrids and nanogrids enabled by localized PV generation systems.

As shown in Fig. 2.4, 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 microgrids 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]. While the aging infrastructure i.e. centralized generation and distribution system are not future-proof, we see more and more interest in distributed energy resources (DER).

2.4. 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 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. Replacement of aging technology should be done with a future-ready technology. 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 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].

<u>2. 5 Role of Photovoltaics in Transport Sector</u>

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 were generated using solar PV modules.

A case can be assumed 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.

2.6 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. Moreover, large desalination plants operate almost continuously, so they do not have start-stop inefficiencies.

However, 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 horsepower 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. The exclusion of energy storage and AC/DC conversion can lead to potential cost saving and fewer faults in the system. This technology is highly attractive to provide clean water in areas that lack water-distribution infrastructure.

2.7 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 towards the right direction, it lacks the support required to 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]: (i) the energy source must be very inexpensive and practically impossible to deplete, and (ii) 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.

2.8 Conclusion

In this chapter, we have examined the emerging role of solar photovoltaics to sustainably power all human activities on our planet in 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 ultra-large 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 make this dream a reality at an accelerated pace.

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CHAPTER THREE

LOCAL DC POWER NANOGRID WITH STORAGE FOR COST EFFECTIVE,

SECURED, RESILIENT AND EFFICIENT ENERGY INFRASTRUCTURES

3.1 Introduction

With the promises of sustainability, clean energy and cost effectiveness, Photovoltaics (PV) has ushered us to the new age of power generation. The renewable sources, especially solar, are experiencing astronomical growth, when compared with the fossil fuel based electricity generation. If we compare the new installations of energy generation in the USA for 2015 and 2016, the dominance of solar energy is evident [1]. In the USA, renewable sources accounted for about 99% of the installed capacity in first quarter of 2016, and PV alone has contributed two thirds of it [1]. The first 1-million PV installation in USA happened over 40 years, but next 1-million installations are expected to take place within next 2 years [2]. The declining cost of PV modules have proven to be a great boost that has drawn attention from industries, businesses, individual home-owners, utility companies, etc. Irrespective of the nature or size of the economy –developed, developing and under-developed, PV can be the sustainable source of energy [3]. All over the world, households and businesses install solar PV to reduce carbon footprint and to offset the utility bill, but PV has potential of contributing more than this by becoming the primary power source. Besides generation, the storage is also a crucial part of PV system. Energy storage in batteries, especially lithium ion (Li-ion) type, has shown a rapid decrease in cost. As the centralized generation and storing are moving towards distributed energy

resources (DER), further down the road, DC power can gradually take over from legacy AC powered network [4]

Local DC network can bring a paradigm shift by offering many benefits compared to the AC counterpart [5]. Lower cost, security, resiliency and energy efficiency –all play a decisive role in bolstering the argument in favor of DC based nanogrid systems. This revolution in renewable energy is going to make a tremendous impact on the industries as well. To remain cost effective and competitive, the industries will also need to identify and avail of the opportunities. In this article, we would examine the PV based DC nanogrids, and present its benefits over conventional centralized grids. This PV based DC nanogrid architecture has the potential bringing about a paradigm shift in power, utility, and industrial sector.

3.2 Requirements of Future Energy Network

The United States' and other developed economies aging electricity infrastructure including generation, transmission and distribution facilities were built over the course of a century. The electricity industry 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 local DC in place of AC, cyber and grid security, intelligent loads and climate control, and weather tolerant electric infrastructure [6]. In addition to the changes in electricity infrastructure, the emergence of electric vehicles (EV) is also changing the landscape of

transport sector. Faster and low cost charging of EV's requires local DC power [6]. With continuous cost reduction of PV systems, and forthcoming cost reduction in battery technology via the electrical vehicle industry, now onsite energy generation and storage is an option available to individuals, communities and industries, etc. AC power increase the cost of batteries (as much as 50% in some cases) [7]. As compared to AC power, local DC power on board of a ship (20 MW operating at 1,000 V) increases the energy efficiency by 20% and reduces the electrical footprint and weight up to 30% [8]. Long haul transmission of AC power is quite expensive (~ $5 million/mile) [9]. Local DC power generated by PV, batteries, electric vehicles (EVs), intelligent loads and real-time monitoring of standalone cyber secured DC nano- and microgrids are the enabler of a forthcoming energy efficiency revolution.

The key drivers of projected changes in electricity infrastructure are presented in Fig. 3.1. Driven by the constituents of Fig. 1, the market forces will define the requirements for the future power networks. The power network of the future has to evolve. The future power network has to position itself in such a way that it can address the changes in nature of loads, consumer behavior, new regulation, etc.
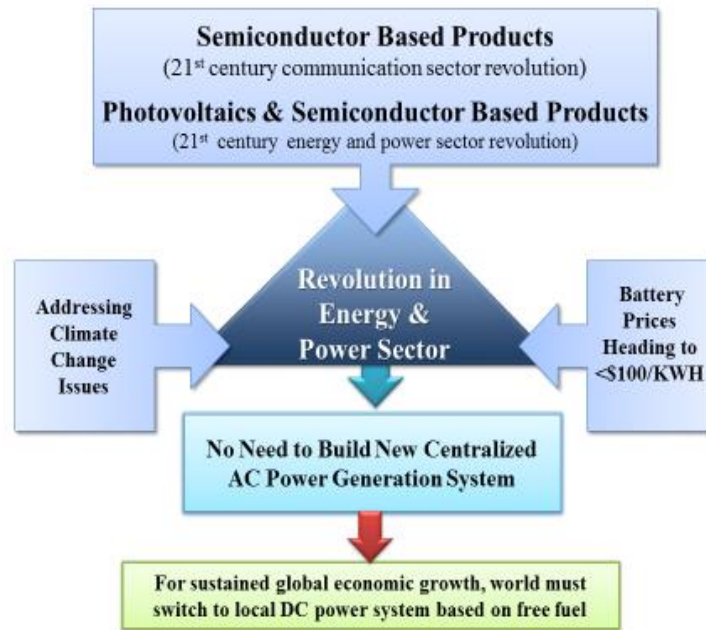
Fig 3.1. Key drivers of projected changes in electricity infrastructure.

Table 3.1 offers a quick summary about the requirements of future power network. It lists various new dimensions of future infrastructure such as free fuel based ultra-low cost local power generation, cyber security, higher reliability of power network and internet of things (IoT), etc.

TABLE 3.1: 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

Many of the requirements noted in Table 1 cannot be met by today's integrated central grid architecture. Therefore, it is essential to take a different approach to address these issues and ensure readiness for future. A single house, powered by PV with storage, can be a DC nanogrid. When several of these come together, it forms a DC microgrid. Typical example of a DC microgrid is shown in Fig. 3.2.
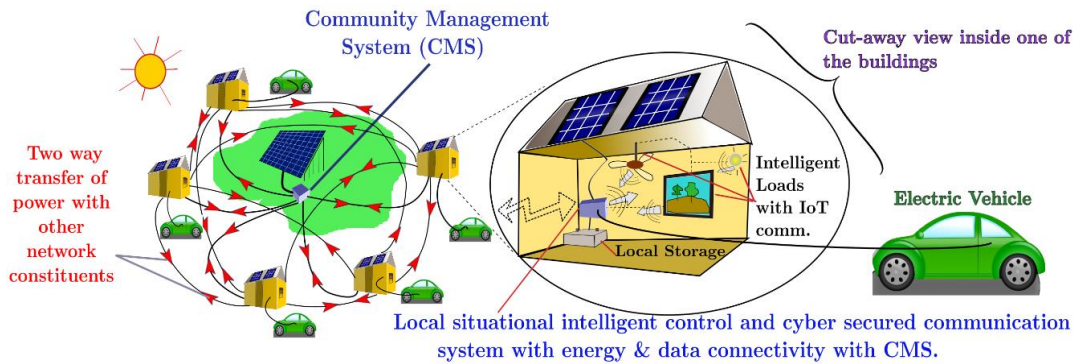
Fig. 3.2. DC microgrid operations with several DC nanogrids showing

PV generation and energy storage at the nanogrid and microgrid

levels.Community management system handles the power

transfer between the households

The DC microgrid, powered by PV and batteries as storage device, emerges as an excellent choice, when benchmarked against those characteristics pointed out in Table 1. Some of the key strengths of PV based DC nanogrid and microgrid are discussed in this section.

3.2.1 Ultra-low cost:

In many parts of the world, PV generated electricity has already proven to be cheaper than other energy sources. Our prediction is that by 2024, the cost of PV generated cost of electricity with storage will be $0.02 per KWh [10]. From the learning curve shown in Fig. 2, the cost of the battery is also decreasing with technological advancements and volume production [11].
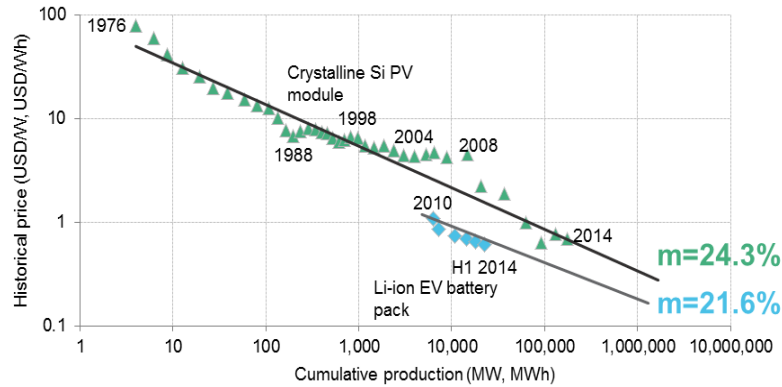
Fig. 3.3. Cost reduction trends of photovoltaic modules and Lithium

batteries. From [11]. © Bloomberg New Energy Finance.

For data center applications, 380V DC was found to be the most efficient operating voltage [12]. For protection of such data centers, DC mode uninterrupted power supply (UPS) can be deployed at 10-20% less cost than their AC counterparts [12]. A study investigated the converters (AC-AC, DC-AC, AC-DC and DC-DC) in terms of cost

per kilowatt, and concluded that the DC-DC converter is the cheapest among these when voltage level switching is desired [13]. Due to the absence of inverters, rectifiers and frequency control devices, the capital cost of a local DC power system will be lower than a comparable local AC power system.

3.2.2 Sustainability and operating cost:

PV based DC nano- and microgrid are powered by free fuel. Therefore, it will remain sustainable in any economy regardless of other variables, and it is immune to changes in policy, tariff, geo-politics or price of coal, gas, crude oil, etc. Due to higher reliability lesser equipment, the operating cost of DC power system will be lower than the corresponding AC power system. The PV panels require much less maintenance due to absence of rotary machinery. The dust cleanup, connection check, etc. are simple tasks in PV maintenance and does not require highly specialized personnel as in the case of AC power plant. Li-ion battery also does not require a lot of maintenance. Thus, the overall operating cost of PV based DC system is expected to be much less.

3.2.3 Efficiency, IoT, local generation and consumption

As reported in a study [14], 33% of electrical power could be saved by converting all appliances running currently on AC to high-efficiency and DC-internal technology. Direct current power sources (e.g. PV) can save additional 14% energy by avoiding DC-AC and AC-DC losses [14]. In addition to the 47% energy savings, energy will be saved further by using intelligent loads based on the use internet of things (IoT) and it is going to open many doors to new possibilities [15]. With proper standards and protocols in place, it will be convenient to integrate IoT connected smart loads to the intelligent controllers of

DC nanogrid. Local generation, storage and utilization do not require massive transmission network and its associated investment. This reduces the energy loss during transmission and distribution.

3.2.4 Environmental Impact

As compared to current centralized AC power generation, transmission and distribution system, free fuel (solar and wind energy) based local DC power system will be far superior in terms of carbon emission related environmental impacts. Even compared to local AC power systems, the local DC power will be better due to higher energy efficiency and use of fewer components.

3.2.5 Intelligence, Monitoring and Cyber Security

PV based DC nano- and microgrids are less vulnerable to cyber-attacks [16]. It is difficult for a remote attacker to access an isolated and self-contained PV based DC nano- and microgrid. Situational intelligence, real time monitoring, physical security and user control –all can be incorporated in PV based DC nano- and microgrid. Large grids and distributions require a lot of nodes where monitoring data are generated and collected, and commands are sent to be executed. This transmission and reception of data creates opening for malicious intruders who might gain access to systems or data through sophisticated attacks [16]. In the age of internet of things (IoT) and remotely connected servers, a possible attack may come from any point, even from far ends of the internet. PV based DC nano- and microgrids will employ intelligent control systems that are local and can remain secured from cyber-attacks.

3.2.6 Safety and Protection

The DC nanogrids and microgrids can operate at a lower voltage, and thus eliminate the environmental, health and safety issues associated with high voltage AC transmission and distribution. There is no issue of safety for 48V DC applications. For the data center and other general purpose applications, several companies supply DC power distribution hardware operating at 380 V including circuit breakers with rated currents ranging from 15A to 2,500A [19].

3.2.7 Control System and Power Quality

DC grids can have fast and uniform transient response, and it makes it less sensitive to faults. Eventually, it results in simpler and universal design. Due to its isolation from larger grids, a DC nano- and microgrids are immune to external transients and faults in AC network. For internal faults, DC nanogrid has the potential to improve power quality and reduce transients [21].

3.2.8 Possibility of Reaching Uniform Global Standards

The AC voltage standards are fragmented, and compatibility of equipment can be an issue due to different voltage levels that persist across the globe. The adoption of DC electricity can pave the way for a uniform voltage standard and move towards seamless compatibility [1].

3.2.9 Contribution to transportation sector

Transportation sector will also benefit immensely from the PV based DC systems. Electric vehicles (EV) and hybrid plug-in vehicles employ store energy in batteries in DC

form, but they are charged from AC via conversions. If the batteries are charged from DC networks, it can open a path for higher overall efficiency for the transportation and can result in cost reduction [1].

3.2.10 Providing Accessibility

PV based DC nanogrid and DC microgrid hold the key to open the door of energy accessibility to the people living in underdeveloped economies [1]. This will stimulate economic growth, create a global middle class and establish social justice.

Thus, PV powered DC nanogrids and microgrids not only satisfy all the desired criteria but also provide some added benefits. All these virtues establish PV powered DC based nanogrid as the most suitable candidate for future energy infrastructure.

In the late part of 19th century, the outcome of 'War of Currents' between AC and DC favored AC [17]. At that time that seemed to be the right track. However, the innovations, the consumer usage patterns, improvements in PV, storage, etc. is sufficient reason for us to revisit the preferred format (i.e. DC vs. AC) of electricity again to meet the demands in future. Now, we have the capability of generating, storing and distributing electricity locally. Compared to this, late 19th century DC electricity generation could not run efficiently in such distributed manner. These new capabilities, thanks to advancements in PV and storage technology, warrant that we need to revisit the decision between AC and DC.

In early days of commercial usage of electricity, both DC and AC were trying to become the standard method of generation, distribution and usage. DC was championed by

Thomas Edison and General Electric. On the other camp, Nikola Tesla and Westinghouse pushed for adoption of AC.

In the late 18th century and early 19th century, the use of electricity was mostly for lighting needs. The power loss in transmission line was a big concern at that time. As the load (incandescent lights) moved further away from the generation source (dynamo), the line loss would result a significant voltage drop. This required the generating stations to be located in closer proximity. It was quite challenging to establish so many generating stations and ensuring other logistics support such as fuel, maintenance, etc. The cost of the thicker wires was a big concern for DC distribution. Edison tried to mitigate the thick wire and cost issue by introducing 3-wire DC system, but it was not enough to keep DC transmission competitive at that era [18]. AC won the war of currents due to its stepping up/down capability using transformers and allowing the generators to be placed far away from the loads. After 'War of Currents', world mostly leaned towards the AC [17].

However, now the modularity of PV can solve this problem of distribution of generation and essentially be in the same building/house where the energy will be consumed. PV installations also allow very easy scale up in future whenever more energy is required. In remote places where the number of consumers are relatively small, it is quite challenging to draw transmission lines or to a operate generator that require fuel delivery. On such instances, the PV based DC system can provide optimum solution by eliminating the transmission challenges and by almost hassle free operation. It is worth mentioning that once DC was considered unfit for transmission, but now high voltage DC (HVDC) transmission is successfully operating and growing for long distance power transmission.

The tough challenge such as having high voltage DC breaker has already been addressed by equipment manufacturer [19].

In early days of electricity, the usage of electric lightbulb brought about significant change in the lifestyle of people. Now, PV based DC power can change the game by providing efficient and self-sustained systems that are capable of addressing future challenges. A large number of world population lack the access to electricity or have intermittent access. If they are empowered with the PV based DC energy infrastructure, it can trigger significant economic activity. Now there are compelling reasons for us to rethink our future mode of power, local generation, distribution and consumption. Many technologies e.g. LED lighting, semiconductor electronics, many consumer appliances, advanced power electronics and control, etc. were not available in the past when AC was picked as the mode of power. The list of advantages of DC has grown [20] : (i) PV generates DC, batteries store DC and converting it to AC causes loss, (ii) greater energy efficiency, (iii) higher power quality, (iv) smaller equipment,(v) less complexity and lower cost, etc. Therefore In the light of recent innovations and advancements, we need to revisit this chapter.

In other words, in the early days of electricity, DC was not ultimately favored, because it had to be located near the load. Now, DC should be favored since it can be very easily placed near loads utilizing PV as energy generator and battery as the storage.

3.3 Cost Effectiveness of PV and Storage for Local DC Power

In early days, PV was considered to be an electricity generation method that was suitable for special cases and niche application. Due to relentless research efforts from academia and industry, and improvements in manufacturing practices (advanced process control, novel technologies, etc.), the cost of PV has went down and the efficiency has went up. Now, PV is not only reliable but also cost effective. On many instances, solar farms have offered a very low price to utility companies [21]. Many wrongly assumed that PV business model was mostly driven by government subsidy. However, it has been proven that even without subsidy the PV is still cheaper than many other conventional energy sources [22, 23]. There are many examples like where at the end of subsidy, the market kept growing .Without subsidy, an 800MW solar power contract was awarded to a bidder with only $0.03/kWh [24]. Another 120MW solar plant is selling power for $0.0291/kWh or $29.1/MWh [25]. From the first part of the year 2016 (H1-2016) to the second half of 2016 (H2-2016), the installer system pricing for residential, commercial and utility (fixed-tilt) dropped by 8.6%, 12.5% and 17.4%, respectively [26]. The prices are shown in Fig. 3.4:
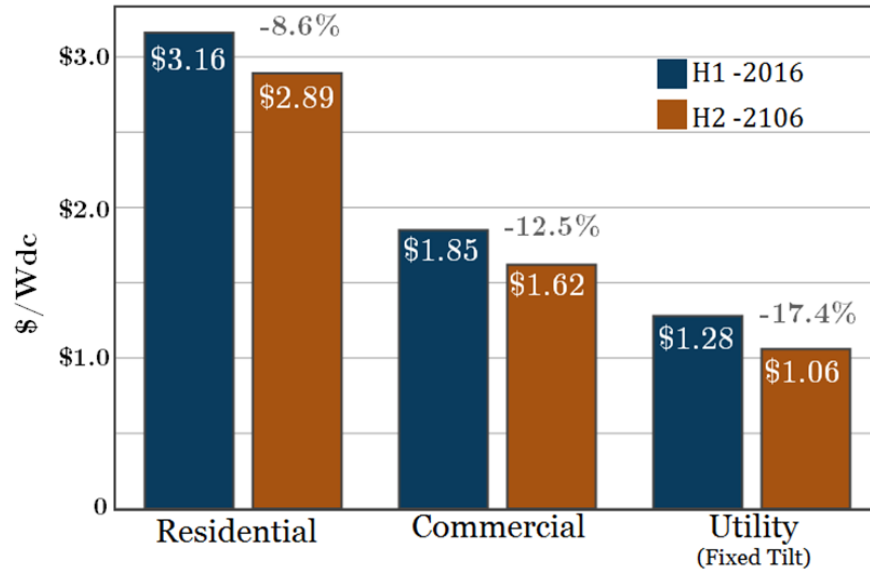
Fig. 3.4. Installer System Pricing by Market Segment for first and

second half of year 2016. Data from [26].

The United States' Department of Energy (DOE) through their project 'SunShot' aimed to reach system pricing of $1.00 per watt by 2020. However, due to rapid price decrease, this target was achieved three years early [27]. When this SunShot pilot project was initiated in USA in 2011, the installed per watt cost was $4.08 [28].

3.4 Efficiency in PV Powered DC Nano-Grid

By using fewer equipment and less number of conversion, DC is capable of generating, storing and delivering energy locally and efficiently. A test case reported approximately 30% loss of power from generation from PV, through DC-AC-DC conversions and storage, to the final internally rectified use as DC in a load [4].

To study the power loss in the DC-DC conversion, DC-AC conversion, and a combination of DC-DC and DC-AC conversion, the following experiments were conducted. The measurement results are summarized at the end of this section.

3.5.1 Measurement of Power Loss from DC-DC Conversion

In this experiment, power from a solar panel was used to charge a battery. The devices used for the experiment included a solar panel, a charge controller, a battery, and two power meters. The experiment setup is shown in Fig. 3.5:
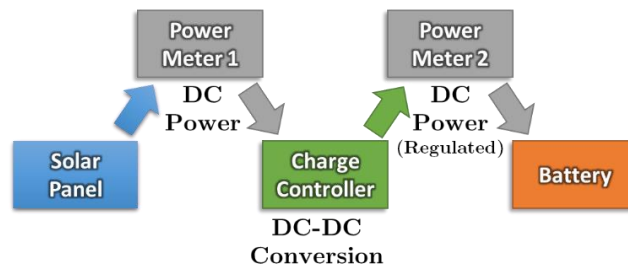
Fig. 3.5. Arrangement for DC-DC Conversion experiment

In this experiment, DC power obtained from a solar panel flows through a charge controller, which produces a regulated DC power output (DC-DC conversion). This regulated DC power was fed to a battery to charge it. The power outputs were measured after each step using power meters. Table 3.2 shows the summary.

Table 3.2. Power measurements and power loss calculations for DC-DC Conversion

Power Meter 1 Average Power Reading approx. (Watts)	Power Meter 2 approx. (Watts)	% Power Loss Due to DC-DC Conversion
2.33	2.06	**11.6**

3.5.2 Measurement of Power Loss from DC-AC Conversion

In this experiment, power from a battery was used to drive an AC lamp. The devices used for the experiment included a battery, an inverter, a lamp, and two power meters. The experiment setup is shown in Fig. 3.6:
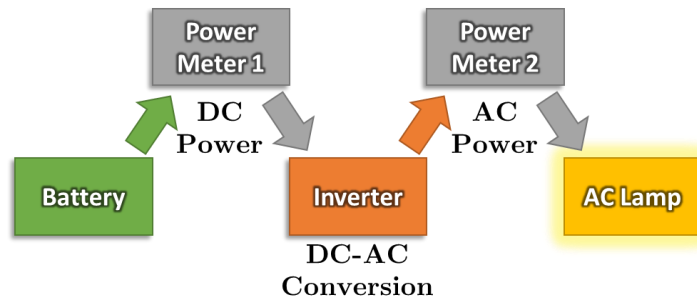
Fig. 3.6. Arrangement for DC-AC Conversion experiment.

In this experiment, DC power was obtained from a battery. The next step was to convert this DC power to AC power in order to drive the AC lamp. This DC-AC power conversion was carried out using an inverter. The AC power output from the inverter was fed to an AC lamp to turn it on. The power outputs were measured after each step using power meters.

Table 3.3. Power measurements and power loss calculations for DC-AC Conversion experiment

Power Meter 1 approx. (Watts)	Power Meter 2 approx. (Watts)	% Power Loss Due to DC-AC Conversion
42.98	34.25	**20.31**

3.5.3 Measurement of Power Loss from DC-DC and DC-AC Conversion

In this experiment, power from a solar panel was used to drive an AC lamp. The devices used for the experiment included a solar panel, a charge controller, an inverter, a lamp, and three power meters. The experiment setup is shown in Fig. 3.7:
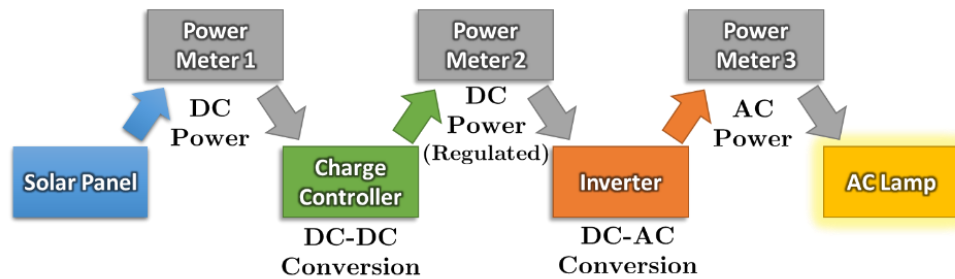
Fig. 3.7. Arrangement for DC-DC and DC-AC Conversion

In this experiment, DC power obtained from a solar panel flows through a charge controller, which produces a regulated DC power output (DC-DC conversion). The next step was to convert this regulated DC power to AC power in order to drive the AC lamp. This DC-AC power conversion was carried out using an inverter. The AC power output from the inverter was fed to an AC lamp to turn it on. The power outputs were measured after each step using power meters.

Table 3.3. Power measurements and power loss calculations for experiment 3

Power Meter 1 APR (Watts)	Power Meter 2 APR (Watts)	Power Meter 3 APR (Watts)	% Power Loss Due to DC-DC Conversion	% Power Loss Due to DC-AC Conversion	% Net Power Conversion Loss
50.59	45.91	36.25	9.25	21.04	**28.35**

From these, we can see that the conversion can cause loss of power and efficiency. Therefore, the best practice would be reduce the number of steps. DC generation (in PV) followed by DC storage (in battery) and using DC in load –such systems are the ultimate path to the efficient energy generation, storage and consumption.

3.5 Resilience of PV Powered DC System in Case of Geomagnetic Storm

Industries and manufacturing plants require uncompromised assurance of electrical power delivery from the grid. Any interruption in power supply can cause delay in production, loss of productivity, even wastage of materials in process. That is why industries place paramount importance on their energy source and infrastructure.

Though it is not encountered frequently, the threat from solar flare, the threat from solar disturbances cannot be ruled out [6]. Usually, CME's occur due to some complicated interactions between plasma and magnetic fields on the Sun. A reliable prediction mechanism for CME is still an ongoing research, and is beyond the scope of this manuscript. Usually, a limited number of particles hit earth's atmosphere and create aurora. The ejected particles and plasma bombard on the magnetosphere leading to variation in magnetic field lines of the earth. This event is termed as geomagnetic storm (GMS). At a larger magnitude, the interactions of these radiated high-energy particles and plasmas with Earth's magnetosphere can be potentially harmful to modern technology, especially to communication and electric grids. We should design and build our energy infrastructure in such a way that disaster may be avoided and damages from such events can be kept at minimum level.

The Sun's activity cycle spans over ~11.11 years, which is known as the 'Sunspot Cycle', and there are peaks in the cycle when more sunspots and flares occur [29]. Few events are noteworthy because of their magnitude and impact. Among the documented observations of geomagnetic storms, the largest one dates back to 1859 [30]. This landmark event was named 'Carrington event' after astronomer R.C. Carrington. At that time, the

use of electricity was very limited and there was not much technology in existence. Therefore, the impact from a storm of such a big magnitude was mostly limited to the disruption to telegraph systems [31]. In 2003, the 'Halloween Solar Storm' caused disruptions in power grid and communication systems in different corners of the world [32]. In 1989, the collapse of Quebec Hydropower (Canada) grid was triggered by geomagnetic storm [33].

The transformers are the major victims of GMS [6]. A fluctuating external magnetic field or additional current can play havoc on transformers own cycles. A detailed analysis on distortion of transformer excitation current can be found in [34].

United States' Department of Energy (DoE) and Department of Homeland Security (DHS) sponsored studies concluded that there are vulnerabilities in US grid from such events and it needs to be addressed [34] [35]. The worst-case scenario depicted by [34] estimated a loss of 1-2 trillion USD. Insurance companies also consider solar storm as one of the risks to electricity infrastructures. According a 2012 estimate, more than 300 extra high voltage (EHV) transformers in the USA are at risk as shown in Fig. 3.8 [36]. According to risk assessment by a major insurance syndicate, if a storm of very high magnitude (as Carrington event) takes place, 20-40 million people will be affected for 16 days to 1-2 years, and the financial loss will range from $0.6-2.6 trillion [37]. Severe space weather is listed as one of the 'National Risks' that can cause civil emergency in the UK [38].
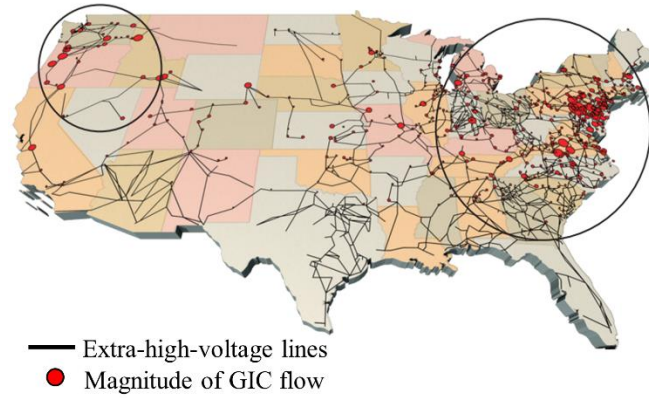
Fig 3.8. Effect of simulated geomagnetic storm on extra-high-voltage

In the USA. The size of the red circle indicates relative magnitude.

From [36]. © IEEE

The higher voltage transmission lines have longer spans and smaller resistance (at per unit length). The overhead lines and the return path through the ground act as a loop for the changing magnetic field. The high ground clearances of the high voltage lines offer a very large cross sectional loop area for the magnetic field. The geomagnetic induced current (GIC) can be expresses using the simple equation [35] below:

$$i_{GIC} = \frac{dB}{dt} \frac{A_{loop}}{\Omega} \qquad \qquad \text{...... (3.1)}$$

In equation (3.1), B is the magnetic field from GMS, A_{loop} is the area of the loop created by overhead line and return path, Ω is the total resistance of the loop and t is time. The lower resistance of the high voltage line aids GIC flow through the AC grid.

DC nano- and microgrids do not offer any significant cross sectional area (or loop) to the changing magnetic field from GMS. Smaller geographic expanse of each DC nanogrid or DC microgrid makes it very unlikely to be affected by GMS. Owing to

nanogrids isolated state, it is not subjected to cascaded failure. Having no transformer also gets rid of the neutral to ground connection in PV based DC nanogrids.

The magnetic field has very limited effect on semiconductor-based solar cells. Some early studies of magnetic field on PV and photo-magnetoelectric effect (PME, also PEM) can be found in [39] and [40]. Any rise in current density is an operating solar cell can result from either i) increased carrier generation, or ii) increased carrier collection. If a charge is moving in a space where both electric field and magnetic field are present, the charge will experience a force in a direction perpendicular to both the fields. In real life applications, the PV cells have very small thickness compared to its surface area, and thus very little GMS magnetic flux will intersect PV cells from the sides due to smaller cross section. To collect the photo-generated carriers, most of the commercial solar cells deploy thin metal fingers in the front and metal contacts on the rear. When PV cell is illuminated and the circuit is closed, the net current flow is across the junction. If magnetic field $(\vec{B})$ is perpendicular the PV cell surface, it will be in the same direction as the current $(\vec{J})$ and electric field $(\vec{E})$ across the junction. Then, their cross product $(\vec{J} \times \vec{B})$ will yield zero. The GMS and its corresponding magnetic field will come from random direction. No one has ever reported generation of charge carrier in semiconductor by nano-Tesla magnetic field only (in dark). Therefore, based on the above discussion, it can be stated that the semiconductor based solar cells will have no significant change in its operation and it will not be damaged by hundreds of nano-Tesla magnetic field changes, whether it happens during day or night.

However, magnetic field can affect or increase the photocurrent density in experimental solar cells such as perovskite [41] and dye-sensitized [42] cells. The magnetic fields used in both cases were several orders larger than the fluctuations that take place from the GMS corresponding to solar eruption. It may be noted that these solar cells are not commercially available and not used in any terrestrial applications. Moreover, the possible usages of these types of cell as top-layer of a multi-junction cell cannot be commercialized [43]. Therefore, the interaction between these type of cells and solar storms are not any concern for PV based DC nanogrids and microgrids. Though it might sound far-fetched, the adoption of PV based system can safeguard against a potential disaster from geo-magnetic storm.

The storage system has to be ready for the space weather threats. The presence of magnetic field can affect the electrochemical reactions [44]. The movement of charge carriers under magnetic field in electrochemical reactions are studied under magnetoelectrolysis and magneto hydrodynamic (MHD). However, the magnetic field has to be extremely strong (around 1Tesla) to exert significant Lorentz force on charge carrying ions [45]. In solar related disturbances, the magnitude is smaller (in 1000s of nano-Tesla). Therefore, we can assume the batteries to remain safe in the usual range of geo-magnetic storms caused by solar disturbances or CME. It might be noted that in 1989, 2003 or even from the telegraph era 1859 event, no battery/electrochemical cell damage was reported.

3.6 Industrial Transformations due to Local DC Power

It may be noted that in industrial environment, may heating and rotary machines utilize DC internally i.e. they convert the incoming AC feed into DC before executing their tasks. In an all DC-powered scenario, the equipment is built without the rectifier as it can draw directly from the DC bus. Excluding rectifiers may lead to reduced price and capital cost, and may even result less failure and maintenance. At the beginning of such transitions, the number of equipment vendor might be limited. However, with continued transformation towards DC and rising demand of such equipment, the production will ramp up and the lower cost will benefit all stakeholders.

The manufacturing industries spend a good amount of its operating costs for paying utility bills. As more and more manufacturing steps are being automated i.e. being performed by machines, the use of electricity is increasing. Though the manufacturing industries are taking steps to reduce the electricity consumption by switching to LED based lighting, improved architectural design to use natural light, motion activated lighting, etc. However, the biggest consumption of energy takes place in machines (motors, heating, assembly lines, etc.). Aluminum industry can be taken as an example where significant loss occurs when the total energy (AC) is converted to process energy (DC). Table 3.4 shows the amount of KWh required for smelting one ton (1000 kilograms) of aluminium based on the data gathered from International Aluminium Institute [46].

Table 3.4. 2015 Data of Energy Consumed in Producing One Ton of Aluminium [46]

Region	DC Energy	AC Energy	% Loss in Current Plants
North America	13,772	15,130	8.98%
South America	14,607	15,751	7.26%
Europe	14,444	15,522	6.94%
Africa	13,714	14,550	5.75%
Gulf Region	13,618	14,497	6.06%
Asia (excl. China)	13,928	14,891	6.47%
China	12,875	13,562	5.07%

Weather related grid outage is also a big concern [47]. In connected grids, the bad weather events can cause service disruption over a very large area, The PV based DC nano-grids, due to its confined nature and smaller footprint, can remain safe from disruptions that originate hundreds of mile away in the AC grids.

3.7 DC Power Network in Household Application

Availability and options for DC equipment are a major concern among the consumers as well as policy makers. Right now, the appliances are mostly sold with AC standard (110V or 220V). Though many appliances use DC internally, the connection to the wall outlet is still AC. Since, DC based nanogrids, at this stage, are capable of adopting standards for voltage level. With suitable policy, the market for DC appliances can grow and many manufacturing industry will find potential, even untapped, markets. In our experiment, we used a refrigerator that has both AC and DC power input. Such appliances are used in recreational vehicle (RV). It was found that, in AC mode, there is 'leakage' or wastage of electrical energy when the refrigerator's compressor is not running. This is due

to idle-losses in the rectifying transformer. In DC, such phenomena do not exist. Fig. 3.9 shows the comparison of power consumed during 12 hours of operation in DC and AC mode.
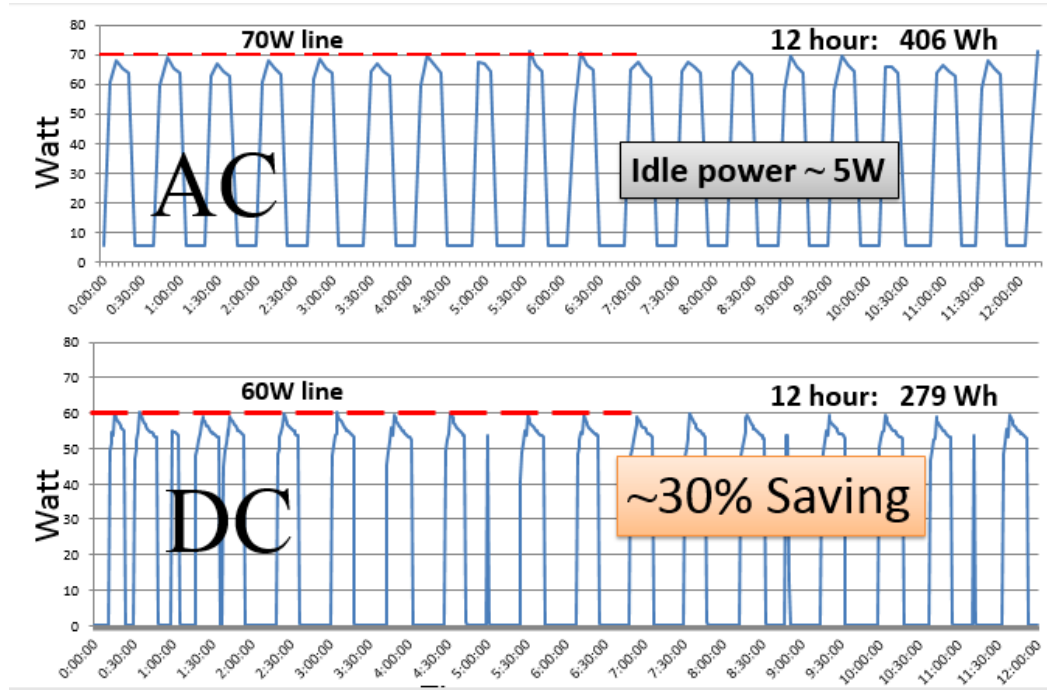
Fig. 3.9. Comparison of energy usage by the same appliance

in DC and AC mode.

In AC, the consumption was 406 Wh. In a similar 12-hour time, the DC consumption was 279 Wh. In our experiment, we found about ~30% saving in energy usage for this refrigerator between AC and DC modes. It is noteworthy that during the period when refrigerator is idle (the compressor is turned off by internal thermostat), the AC mode still consume some power around 5 watt. This loss may be incurred by the zero-load current in step-down transformer used in rectification. Whereas during the idling in DC mode operation, the power consumption is extremely small (~0.01W). Though the number of

manufacturers/vendors is comparatively small for DC based appliances, the gradual increase in DC appliance market can lure in major manufacturers and this can reduce the price for such appliances.

3.8 Readiness of PV Technology

Since the 6% efficient solar cell from 1954, the PV technology has demonstrated tremendous progress [48]. After decades of research and development, now we have single-junction, non-concentrated cell efficiency of 25.6% [49] and module efficiency of 24.1% [50]. PV technology is on the track of achieving manufacturing excellence by intensive R&D, incorporation of advanced process control and scaled up production. As a result, the cost of PV module is low enough to compete with and grab market share from other electricity generation technologies. Currently, a stable network of PV cell and module manufacturers, distributors and installers are operating in different corners, and are actively adding PV capacity to customers of all sizes. Many utility-scale turnkey projects are also underway all over the world. If this success of PV is accompanied by other supporting and auxiliary technologies (batteries, power electronics, appliances, etc.) and suitable policies, the world will experience faster growth in PV-based DC nano-grids.

3.9 Conclusion

In this chapter, it was demonstrated 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. Significant amount of energy can be saved if the new expansion and construction of electricity infrastructure is built using PV-based DC nano-grid.

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CHAPTER FOUR

TECHNICAL AND ECONOMIC ASSESSMENT OF PEROVSKITE

SOLAR CELLS FOR LARGE SCALE MANUFACTURING

4.1 Introduction

For sustainable global economic growth, electricity is a vital resource that enables and empowers individuals and societies. Free incident solar power per year on earth is 23,000 TWy [1], and can be a sustainable energy source to humanity [2]. One hour of incident solar energy is equal to all the energy used in one year on our planet. Commercially, solar energy can be converted into electricity by following two approaches: (i) use of photovoltaic (PV) devices without concentration, and (ii) use of concentrated solar power (CSP). The limitations of CSP were explained at length to compete with PV devices [3]. Very recent economic data further support the limitations of CSP to compete with PV devices for generating electricity [4]. The global cumulative installed photovoltaic (PV) capacity has reached the 180 -gigawatt (GW) milestone at the end of year 2014, and is expected to increase by 177% from 2014 levels to reach almost 500 GW (498 GW) mark by the end of 2019 [5]. Over 90 % of PV market share consists of non-concentrator bulk silicon solar cells [3]. Thus, the future direction of research in photovoltaic devices must take into consideration the current manufacturing trends of the PV devices in the global context of electricity generation

In recent years, perovskite solar cells or organo-metal halide Perovskite (OHP) have received lot of attention [6-8]. The general field of photovoltaics is 60 years old (started in 1954 with the report of 6% efficient silicon solar cell), and the terrestrial

photovoltaics is 42 years old (a lot of research started just after oil embargo of 1973). Future research direction of PV must follow the path that will lead to the capability of providing the cheapest electricity in the 21st century [9]. Based on the existence of a wide variety of fundamental technical and economical knowledge base, the purpose of this chapter is to examine the potential of perovskite solar cells for large-scale manufacturing.

4.2 Potential of Perovskite Solar Cell

The perovskite materials, mostly composed of organic, metal and halogen, are easy to synthesize. The common formula includes $CH_3NH_3(Pb,Sn)X_3$ where X = halogen (mostly I, Br or Cl). It is also common to use MAPbI3 to indicate $CH_3NH_3PbI_3$ where M= CH_3(methyl) and A= NH_3 (amino). One of the early works in 2009, Ref. [10], demonstrated the efficiency of 3.81% (with $CH_3NH_3PbI_3/TiO_2$) and open circuit voltage of 0.96 V (with $CH_3NH_3PbBr_3/TiO_2$) was reported. The work of Ref. [10], sparked interest among chemist, material scientists and engineering community. As shown in Fig. 4.1, the efficiency of perovskite solar cells has made steady progress, and is now higher than organic solar cells and it competes with other thin film solar cells. The pace of perovskite's efficiency growth has drawn a significant attention and more research groups are getting involved in perovskite related research that is evidenced by large number of publications related to perovskite in recent years.
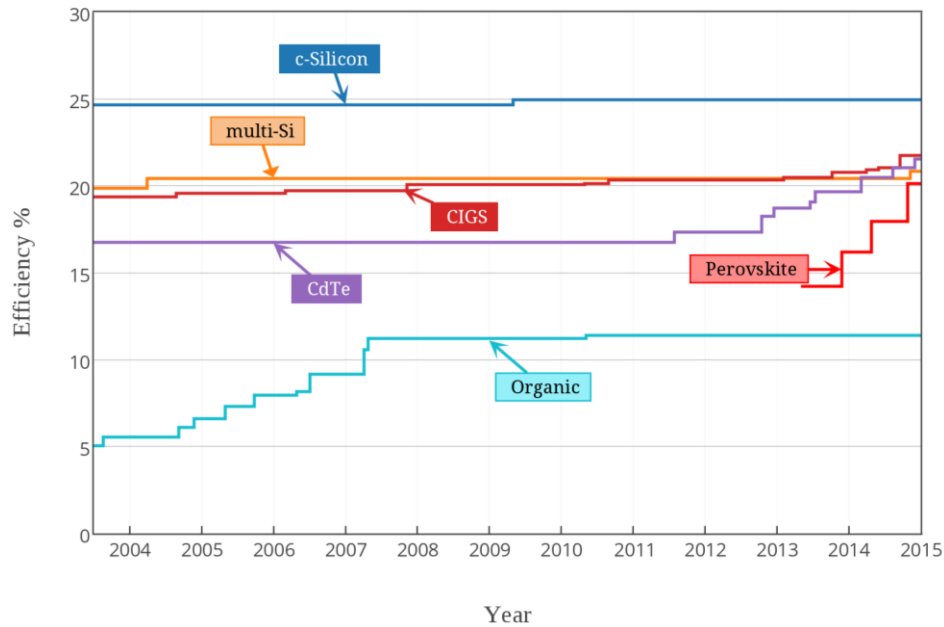
Fig. 4.1: Perovskite cells have demonstrated a very rapid rise in

efficiency in few years. Data from [11].

Progress in reported efficiency of small area devices and the increase in the number of publications are the key reasons for media attention [12-14]. However, it should be noted that the exponential growth in publications and increase in efficiency does not necessarily translate into real world success, and it does not guarantee that the product will be manufactured. There are many such examples in the semiconductor world. As an example, the names of "nano material", and "nano technology", and carbon nano tubes (CNTs) have received tremendous attentions from academic and industrial researchers. CNT based transistors were proposed for replacing silicon CMOS. As early as 2002, it was stated [15-17] that due to manufacturing related fundamental limitations, CNT based transistors cannot replace silicon CMOS. The fundamental reason is that there is a need for a higher level of control of the process variation which is far beyond than what is currently

achievable through conventional methods [17]. Thus, without inventing a fundamentally new process control, CNT cannot be used in semiconductor devices where the performance of integrated system depends on acceptable manufacturing variation of each CNT [18]. Attempt to start a commercial process of manufacturing CNT based flash memory by a startup company called 'Nantero' failed miserably to launch the proposed new product [19]. Thus, it is very important to examine the fundamental manufacturing requirement of a solar cell. In the following section, we have examined key manufacturing considerations.

4.3. Manufacturing Considerations for Perovskite Solar Cells

The key considerations for large scale manufacturing of any new solar cell (including perovskite solar cells) are following:

4.3.1 Efficiency Considerations and Variability

In case of non-concentrated silicon solar cells, the highest efficiency reported to date is ~25% [25]. With huge investment already on bulk silicon solar cells, perovskite solar cells will need to demonstrate more than 30% efficiency as a large area single junction cell [3]. In addition, the manufacturing cost of PV modules based on perovskite solar cells must be lower than the cost of bulk silicon PV modules. As shown in Figure 4.2 [20], the cost of PV modules based on bulk silicon is reduced by about 24% when the cumulative manufacturing production is doubled. In any manufacturing, controlling the process variability is very crucial [21]. The issue of process variability and its effect on the performance of photovoltaic module has been discussed at length in our previous publication [3].
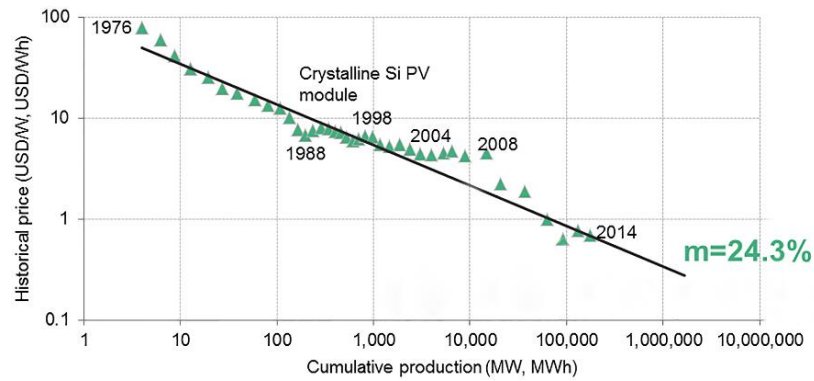
Fig. 4.2. Learning experience curve of bulk silicon PV module manufacturing.

Adopted from [20]. © Bloomberg New Energy Finance.

The worst performing cell will dominate the power output, and pull down the overall power output and performance of the entire module. Fig. 4.3 shows the percentage difference of laboratory scale reported cell efficiency and manufactured module efficiency [22-29]. The variation of voltage, current and resistance contribute to this decrease in efficiency of the manufactured modules.
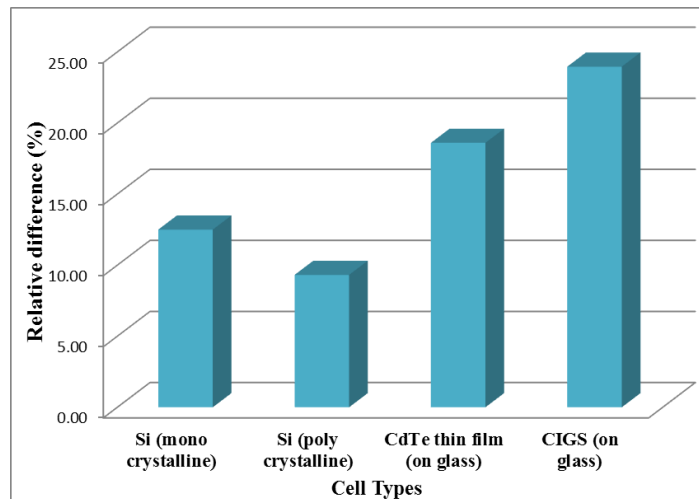
Fig. 4.3. Relative difference in module efficiency and cell efficiency

of some single junction solar cells. Data from [22-29]

75

In a news article, the best perovskite solar cell efficiency of 20.1% has been reported.[8] The authors referenced in news article of Ref. 7 have also published a recent article in open literature and claimed efficiency of 18.4% [30]. A careful study of Ref 30 (specifically the figure 3(a) inside Ref. 30) shows that the 18.4% efficiency of solar cell with an area of 0.096 cm^2 is the average of forward and reverse bias sweep of 17.8% and 19%, respectively. Such practice of averaging forward and reverse bias sweep is not in line with real world application of solar cells for generating power. In addition, the hysteresis curve obtained in reverse and forward bias indicates inherent reliability problem of the devices reported [30]. When a module with 10 perovskite solar cells (each cell is postage stamp size) is fabricated, the module efficiency is only 12% [31]. A statistical analysis showed that increase in standard deviation of solar cell parameters has direct impact on power output, and power loss is a function of parametric variation [3]. In the worst case scenario, a severe fault in one or few cells may even render a module completely unusable.

To provide controlled process variability, semiconductor industry uses advanced process control in place of statistical process control [32]. this adds to the capital cost of manufacturing equipment and operating cost of particular process equipment. In addition to that, for a new type of solar cells, the cost of custom built processing equipment is much higher than "off the shelf" equipment used by silicon solar cell manufacturers. This issue of process control has been one of the fundamental reasons for failure of over 200 companies that started in 2008 with the goals of inventing and commercializing disruptive PV technologies, most of these companies have either gone bankrupt or do not exist anymore [3].

4.3.2 Large Area Device Performance and Series Resistance

Besides the scaling up issues mentioned above, there are series resistance issues that get masked when cells of smaller size are tested and reported. As shown in Ref. [33], if a solar cell is smaller than a certain size, the measurements will not reflect the effects of series resistance. This is due to the fact that the resistance of the solar cell is a non-linear function of current as the current-voltage relation is given by:

$$I - \frac{V - IR_S(I)}{R_{sh}} = I_0 \left[e^{\frac{V - IR_S(I)}{V_{th}}} - 1 \right] - I_L \qquad \ldots \ldots \ldots (4.1)$$

where,

$$R_s(I) = R_1 + R_2 + R_3 + \frac{I_L R_3}{I} \qquad \ldots \ldots \ldots (4.2)$$

Here, I_0 is the reverse saturation current, I_L is photo-generated current, V_{th} is thermal voltage, R_{sh} is shunt resistance, V is external voltage and I is external current. R_1, R_2 and R_3 are linear contact resistance, lumped value for front layer sheet resistance and base resistance, respectively. Based on the methodology of ref. [33] and using AM 1.5G spectrum, the minimum area to demonstrate series resistance effects for a solar cell of band gap of 1.5 eV (under ideal condition when all photo generated carriers are collected) should to be at least 0.35 cm^2 in size [9]. However, many studies on perovskite cells are done on much smaller cells. For 0.09cm^2 perovskite solar cell, the reported efficiency was 12.04%, but for 0.98cm^2 size, it dropped to 8.27% [34]. In contrast, 25.6% efficiency was reported for 143.7 cm^2 Si solar cells [35]. In another investigation [36], a 5cm x 5cm perovskite module with 12 cells was reported, and the resulting efficiency was only 9.9%. The lower efficiency of less than 10% on an area as small as 25 cm^2 is one of the fundamental

reason that the hype of perovskite solar cells has no relevance of manufacturing these devices for commercialization.

4.3.3 Lead-free Manufacturing

When selecting the candidate material for solar cell, the material should be nontoxic and lead-free [3]. Most of the perovskite research has been conducted with Pb based materials. In Ref. [37], news on lead free perovskite is reported. However, no data has been reported about the efficiency and electrical properties of Pb-free perovskite solar cells. Comparison of performances of halides of Pb, Sn and Pb-Sn alloys revealed that the complete elimination of Pb from the perovskite compound causes a significant drop in photo conversion efficiency [38]. Another investigation reported Pb-free perovskite cells with several halogen combinations of $CH_3NH_3SnI_{3-x}Br_x$ (x=0,1,2,3), but the efficiency was below 10%.[39] Lead based perovskite solar cells do not meet the environment , health and safety criterion of manufacturing solar cells [3].

4.3.4 Stability and Reliability

The stability issues will be a major roadblock for commercialization of perovskite solar cells. For increasing stability, the use of mixed halide $CH_3NH_3PbI_{3-x}Cl_x$ had been proposed, and its use also makes the diffusion paths longer [40]. In Ref. [41], it was reported that the higher Br content $(> 20\,\%)$ provides better stability, but lower Br content $(< 10\%)$ leads to better efficiency. These two conditions are contradictory to each other. In another study, the authors reported that even after encapsulation, perovskite cells lost 20% of initial photo conversion efficiency after 500 hours of exposure [42]. Another investigation pointed out that the instability in cells with TiO_2 may arise from light-induced

78

desorption of surface-adsorbed oxygen and proposed the use of Al_2O_3 [43]. Moreover, Al_2O_3 has also been reported to aid power conversion efficiency [44]. However, encapsulation or the use of Al_2O_3 could not prevent the degradations, which were identifiable in 5-hour exposure of light [43]. It is worth mentioning that for competing current commercial PV modules, the perovskite PV modules must have a lifetime of at least 30 years. A report prepared by the US National Renewable Energy Laboratory revealed that c-Si modules have an average degradation rate of only 0.47% per year (installed before year 2000) to 0.36% per year (installed after year 2000) [45]. In another study, Si solar modules that were exposed to sunlight for 25 years, lost only 3.8% in between measurements in 1985 and 2006 [46]. Si based solar cell manufacturers provide warranties that state the modules would keep operating within a small and defined degradation[47]. The best warranty in the market promises 95% and 87% of their peak performance in first 5 years and at the end of 25 years, respectively [48]. The reliability data of silicon solar cells have shown that silicon solar cells can operate very well beyond the 25 years warranty given by the manufacturers. Sun Power has published [49] that useful life of their modules is more than 40 years, which is defined as 99% of modules producing at least 70% of their power.

4.3.5 Cost of Ownership Issues

Before establishing the technology of any new type of solar cell, there are many established capital cost and operating cost issue that need to be dealt carefully. Among those, the cost of ownership (COO) of any equipment is very crucial [50]. Detailed cost analysis of perovskite solar cell is not available except some comments about expected

79

prices [37]. However, it should be noted that this is just a projection, and no mathematical details or supply chain data are available for perovskite solar cells.

4.4 Future Growth of Thin Film Solar Cells in the Context of Global PV Market

Falling prices of PV modules [51] are largely responsible for exponential growth of PV industry in recent years [52]. As shown in Fig. 3.1, there has been no major improvement in the efficiency of silicon solar cells since 1999. The thin film market share has been decreasing every year, and is expected to decrease in the future [53]. The thin-film PV module share is expected to decline from 8% in 2014 to 7% in 2015, compared to 15% market share in 2010 [5].

We do not wish to convey the message that there is no future of thin film PV module manufacturing. We have shown in previous section that thin film PV modules have limited success in competing directly with bulk silicon PV modules. The most successful thin film company, First Solar, is not only a PV module manufacturer, but also project developer, and eventually involved directly or indirectly in selling electricity to the customers [54]. There are niche markets where thin film PV modules have the potential of playing a very important role. Building integrated photovoltaics (BIPV), and throwaway products are two markets where thin films PV may make a very important contribution [3]. To date, there is no thin film technology that can penetrate the above mentioned markets.

4.5 Performance Evaluation of Perovskite PV as Top Layer in Two-Junction and Four-Terminal Architecture

Due to lattice matching and ultra-low interface defects features, conventional tandem cells have been successful only in the case of III-V compound semiconductor solar cells. For other structures, no significant progress has been made in the last sixty years. In a previous publication [4], we have demonstrated that the only way to increase the efficiency of bulk silicon solar cells is to use the multi-junction multi-terminal architecture.

(a)   (b)
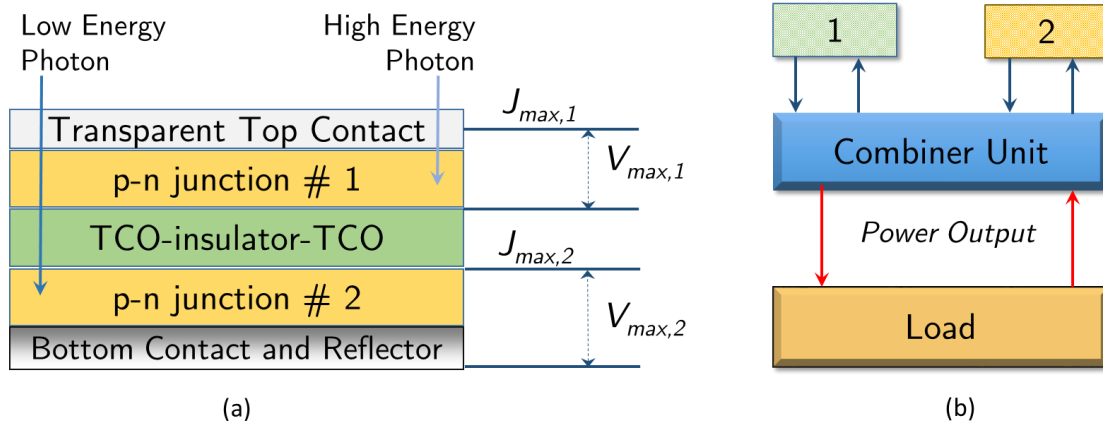
Fig. 3.4. (a) Schematic of the proposed two-junction four terminal

solar cell. (b) External circuitry to combine electricity from

two junctions. From [3].

In Fig. 3.4, we have shown the use of thin film as top junction material in the fabrication of two- junction and four-terminal (TJFT) device architecture. In this section, we have examined the role of perovskite solar cells in the development of architecture shown in Fig. 4. The absorption coefficients of Si [55], along with another perovskite materials [56] are shown Fig. 4.5.
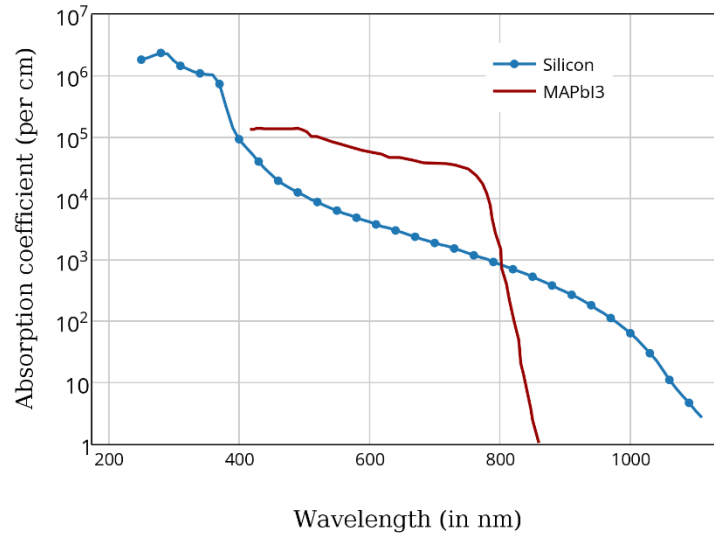
Fig. 4.5. Absorption coefficient of silicon and a perovskite material
(MAPbI3) at different wavelengths. Data from [55, 56].

We have used ideal conditions to calculate the efficiency of TJFT structure. Following are the key assumptions: a) the thickness of silicon solar cells is 180 μm, b) each absorbed photon contribute to one electron-hole pair and only one minority carrier contribute to photocurrent, c) all generated minority carriers are collected at electrodes and no bulk or surface recombination takes place, d) no photons are reflected and, e) the presence of electrodes, hole transport layer, glass, etc. are ignored, and only perovskite material ($CH_3NH_3PbI_3$) and Si absorb the photons. These assumptions do not represent the real world situation, but allow us to visualize the highest possible performance that can be achieved by the combination of perovskite material and Si.
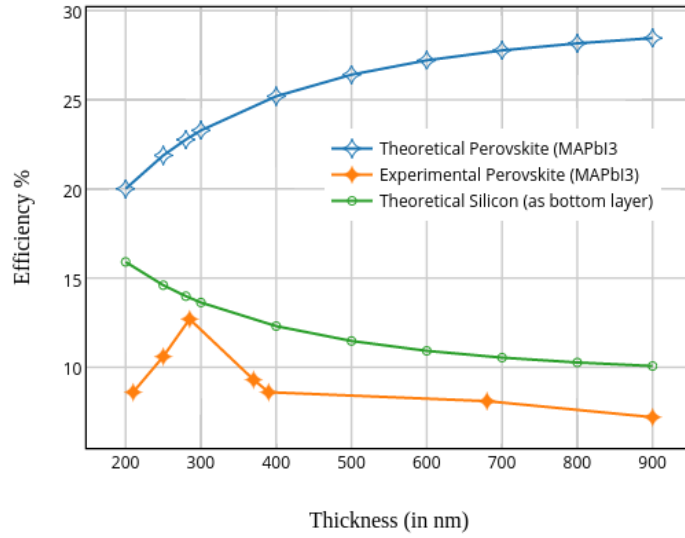
Fig 4.6. Efficiency of perovskite (top layer) and Si (bottom layer)

as individual cells as parts of TJFT structure.

Experimental perovskite data from [57].

In Fig. 4.6 we have calculated theoretical efficiency of individual cells (individual layers) in TJFT structure as a function of thickness of the top $CH3NH_3PbI_3$ perovskite solar cell. The absorption coefficient data of Fig. 4.5, are used to calculate the efficiency of top and bottom cells. For different values of thickness, the theoretical efficiencies of Si cell and MAPbI3 cell are compared against the experimental values of efficiency of MAPbI3 solar cells from Ref. 57. Due to the absence of bulk and surface recombination in theoretical calculations, the efficiency of perovskite solar cells keeps increasing with thicker solar cells. However, as the experimental data [57] of Fig. 4.6 shows, after certain thickness the efficiency start decreasing for perovskite cells with the increase in thickness.

Fig. 4.7 shows a comparison of internal photon conversion efficiency (IPCE) of Si, $CH_3NH_3PbI_3$, $CH3NH_3PbI_2Br$ ($\approx$MAPbI2Br) and $CH_3NH_3SnI_2Br$ ($\approx$MASnI2Br) solar cells [34, 39, 57,58]. If we compare $CH3NH_3PbI_2Br$ and $CH_3NH_3SnI_2Br$, it is evident that the substitution of Pb by Sn causes drop in IPCE.
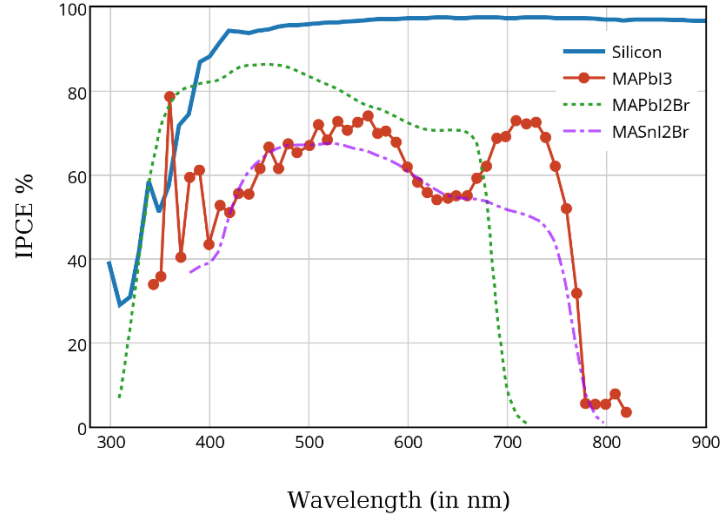
Fig. 4.7. IPCE of Si, $CH_3NH_3PbI_3$, $CH_3NH_3PbI_2Br$ and $CH_3NH_3SnI_2Br$

solar cells. Data from [34, 39, 57, 58].

In legend, M =CH_3 and A= NH_3.

The data clearly shows that except at certain wavelengths, the IPCE's of perovskite solar cells is far below than that of Si solar cell. Due to high absorption coefficient (Fig. 4.5), the top layer perovskite cell will absorb more photons, yet produce less photocurrent due to lower values of IPCE.

In Fig. 4.8, we have compared the theoretical performances of 2-terminal and 4-terminal devices where the top layer is perovskite solar cell and the bottom layer is silicon solar cell. As can be seen from Fig. 4.8, the efficiency of 2-terminal solar cell is lower than

the efficiency of 4-terminal device. In 2-terminal arrangement, both layers have different

photocurrent but the smaller current becomes the current for the whole arrangement.
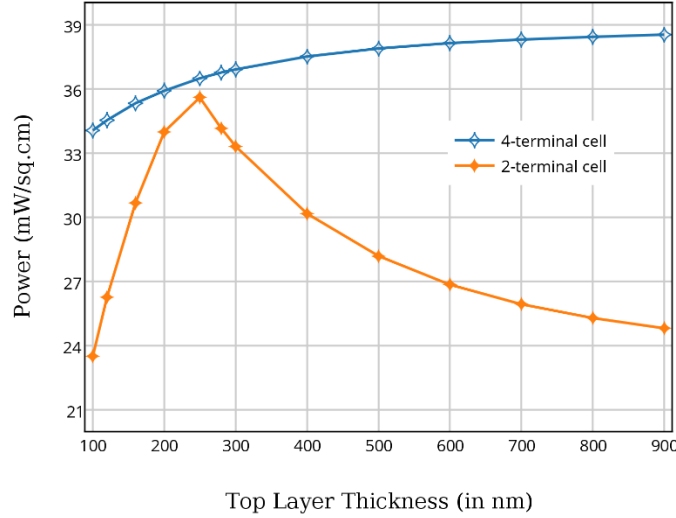
Fig. 4.8. Theoretical maximum power that can be harvested by

2-terminal and 4-terminal tandem cell (with Si and MAPbI$_3$).

Si thickness is 180μm.

These results demonstrate that only for ultra-thick and ultra-high performance

materials (not invented yet), under ideal conditions, it is possible to achieve efficiency of

perovskite/silicon solar cells of the order of about 35%. However, in real world, due to

limited diffusion length of perovskite solar cells, such high efficiency values cannot be

achieved. Experiments performed on 2-terminal perovskite/silicon solar cells support our

prediction. The efficiency of perovskite/silicon solar cell is only 13.7% [59]. One can argue

that the cost of 4-terminal perovskite/silicon soar cell will be significantly higher than the

cost of silicon solar cells. This will not be true, since the major cost contributor of silicon

solar cells is glass. As compared to 25% efficiency of silicon solar cells, if the four terminal architecture can achieve additional 10% efficiency, the additional cost will be justified. With silicon as the base material, the optimum energy gap for top solar cell is about 2.0 eV [3], which is not the case of perovskite solar cells.

4.6 Economic Assessment

A convergence of distinct forces namely low cost photovoltaics system for power generation, falling prices of batteries for storing electrical power, carbon emission problems, rising cost of residential electricity, and the dominance of semiconductor based electronics in every sector is making it possible to transform the aging centralized alternating current (AC) electivity infrastructure in the United States and other developed economies by local direct current (DC) power based electricity infrastructure without the need for a long-range transmission and distribution network. Using free fuel of Sun, the local dc power generated by photovoltaics (PV) and stored in batteries is the only way to remove global energy poverty. Photovoltaics industry is one of the highest growth industries. Silicon based PV modules have taken the same role in power industry as has been the role of silicon complementary metal oxide (CMOS) based integrated circuits in microelectronics and nano-electronics. In an earlier publication, we have outlined the following economic requirement for manufacturing any PV module: (a) no constraint on the supply of raw materials, (b) the low variability of every key process and process-induced defects (c) low cost of manufacturing, (d) prospects for further cost reduction in the future, (e) green manufacturing to avoid environmental, health and safety problems, and (f) long-term reliability of PV modules. An examination of the performance and

reliability data of perovskite based solar cells r shows that these solar cells do not meeting manufacturing criterion. With huge investment in bulk silicon based PV module manufacturing and the success of PV industry, it is impossible for perovskite solar cells ever to enter into manufacturing. The hype created in the literature has no economic evidence to   support the claim that silicon solar cells will be replaced by perovskite solar cells.

4.7 Conclusion

In this chapter, we have investigated the prospects of perovskite solar cell technology for practical applications. High efficiencies in the 20% range have been reported for ultra-small device areas of the order of 0.1 $cm^{2.}$ For device area of 25 cm^2 the efficiency is of the order of 10%. In addition to the low efficiency, there are major issues of stability and toxicity of Pb. PV market is growing exponentially, and it is based almost entirely on bulk silicon solar cells. The thin film share of the PV market is constantly decreasing. Thus contrary to the hype in the literature, there is no truth that perovskite solar cells will replace silicon solar cells. There is no future of perovskite solar cells to increase the efficiency of silicon solar cells either by using two or four terminal device structure.

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CHAPTER FIVE

ULTRA-LARGE SCALE MANUFACTURING CHALLENGES OF

SILICON CARBIDE AND GALLIUM NITRIDE BASED

POWER DEVICES AND SYSTEMS

5.1 Introduction

Similar to low power electronics, the power electronics based products and systems

have relied for many decades on various silicon power semiconductor devices to control

and convert electrical power in an efficient and cost-effective manner. Silicon based power

metal oxide semiconductor field effect transistors (MOSFETs) and insulated-gate bipolar

transistors (IGBTs) are the workhorse chips that are used in the manufacturing of power

electronic systems. The potential of wide band gap (WBG) semiconductors for

manufacturing ultra-high performance power devices and systems is well known [1].

Historically, silicon carbide research is as old as is the discovery of transistors [2]. About

five years ago, some power electronics chipmakers claimed that two WBG technologies

based on gallium nitride (GaN) on silicon and silicon carbide (SiC) MOSFETs would

displace the ubiquitous silicon power MOSFET [3]. In addition, GaN and SiC based

transistors were supposed to pose a threat to higher-end, silicon-based IGBTs [3].

However, these predictions did not come to fruition. Other than some niche applications,

Si based power MOSFET and IGBT have the major market share at this moment, and it

may continue to hold the lead for a number of years [3]. Power electronics manufacturing

companies are still pushing to extract the best from Si based power MOSFET and IGBT

[4]. In recent years, significant progress has been made in reducing the defect densities of bulk SiC and GaN wafers [5]. However, as stated earlier WBG based power systems are commercially available only for some niche applications. The progress is not sufficient to bring the performance, yield and reliability requirements that are warranted for transformative changes in power electronics industry [1]. The objective of this chapter is to analyze the current SiC and GaN power device results and propose manufacturing changes that should have the potential of large-scale commercialization of these devices for manufacturing future power electronics.

5.2. Status of Current Silicon Carbide and Gallium Nitride Power Devices and Identification of Major Manufacturing Challenges

Fig. 5.1 shows the timeline of key events in manufacturing of WBG materials and devices [6]. Homo-epitaxial growth of SiC allows one to fabricate both vertical and lateral devices. However, hetero-epitaxial growth of GaN on either SiC or Si mostly restricts us to lateral devices. Though it had been asserted that GaN vertical device would deliver superior performance, the cost of bulk GaN substrate is prohibitive for manufacturing and its small wafer size renders it unsuitable for use in state-of-the-art fabs. However, some vertical GaN fabrication attempts were reported on Si substrate [7].
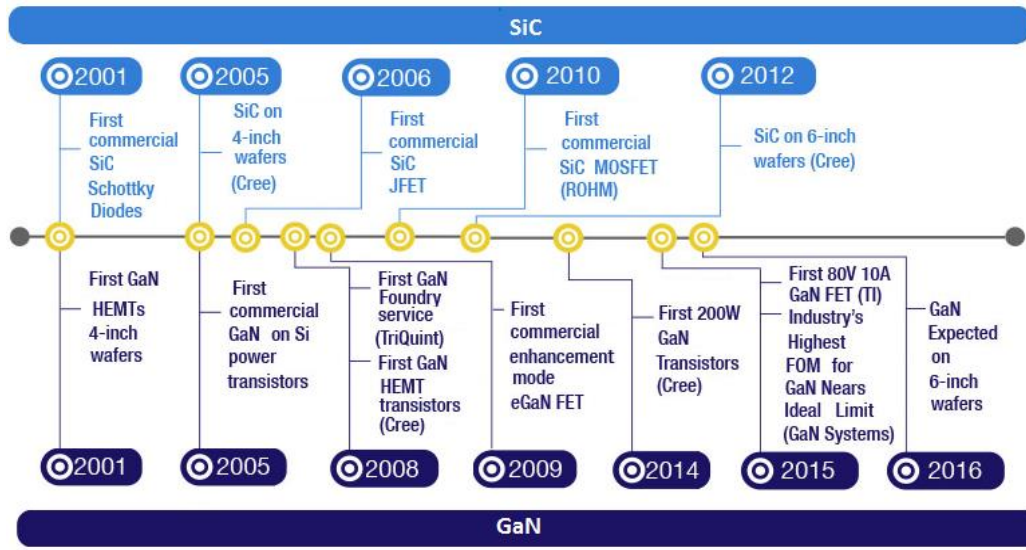
Fig. 5.1. WBG manufacturing timeline with some key products.

From [6]. © Mouser

On the other hand, lateral devices may allow heterogeneous integration i.e. Si based CMOS and GaN based power electronics can be fabricated on same piece of die [8, 9]. Fig. 5.2 [8] shows one such example where Si based p-MOSFET and GaN based HEMT are fabricated on a Si wafer. Innovative approach of chip-scale packaging enhancement-mode GaN field effect transistors has created niche market in low voltage (< 100 V) range [10].

An examination of the literature shows that large defect density (bulk defects in the SiC and GaN wafers, as well as process-induced defects) is the major barriers in realizing the full potential of these materials for power electronics. It is worth mentioning here that for low voltage applications (e.g. light emitting diodes) these defects may have minimal effect on the device performance and reliability, but at high electric field (e.g. power devices) these defects will have catastrophic impact on the device performance, reliability and electromagnetic interference (EMI). As an example, the temperature-dependent turn-

on loss in GaN devices has been attributed to decreased trans-conductance [11], which is directly related to defects and temperature controlling the mobility of the GaN material.
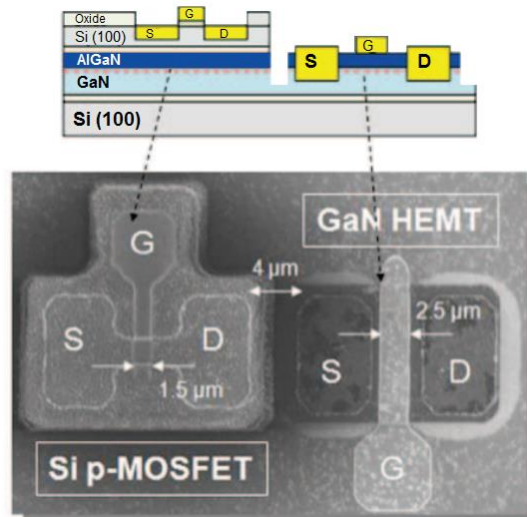
Fig. 5.2. Schematic and SEM image of Si p-MOSFET and GaN HEMT fabricated on Si(100) wafer [8].

A comparative study [12] of commercially available enhancement-mode GaN (e-GaN) devices with those of Si MOSFET devices of the same voltage and current ratings shows that devices show excellent reduction in switching times and switching losses over the Si MOSFET devices, indicating their suitability for high-frequency power conversion. However, as compared to Si devices, the reverse conduction drop and leakage currents are higher with eGaN devices [12]. Theoretically, due to higher band gap, the leakage current of GaN devices should be lower than Si devices. These observations can be attributed to defects that are responsible for higher leakage currents.

Table 5.1 shows the thickness variation of Si and SiC wafers. The larger percentage variation observed for SiC wafers raises the open question about the control system used

in the growth of SiC wafers. However, in this chapter we will not discuss the issues related to bulk defects of SiC and GaN wafers, which we have discussed in previous a publication [4]. In the following section, we will present manufacturing scheme that can reduce the process induced defect density of WBG devices.

Table 5.1. Thickness Variation of Si and SiC Wafers

Semiconductor	Thickness Variation	% Variation
Si	775 ± 25	3.23 [13]
SiC	350 ± 25	7.14 [14]

5.3 Manufacturing Changes for Reducing Densities of WBG Devices

Bringing a commercial product in market and maintaining its profit margin is a mammoth task for any manufacturer. A manufacturer's success is not only measured by the performance of a product, but also through its commercial success and sustaining profitability through these products in the long run. From the prototype and minimum viable product (MVP) to profitable margins, the manufacturer has to consider the market forces. As discussed in the previous section, bulk crystal defects and process induced defects are still the major road blocks in creating a SiC and GaN semiconductor based power electronics. This is due to the fact that best values of performance, reliability and yield of semiconductor products can be obtained only when the microstructure is homogenous and minimum defect density is observed [15]. The defects and process variation are directly related to the yield. From the manufacturing point of view, the loss of yield will can push the cost of ownership (COO) to higher values. The total cost of ownership is given as [16].

$$COO = \frac{CF + CV + CY}{TPT \times Y \times U} \qquad \text{... ... ...} \qquad (5.1)$$

where, CF = fixed cost, CV = variable cost, CY = cost due to yield loss,

TPT = throughput, Y = composite yield, and U = utilization.

Part of the success of silicon integrated circuit (IC) industry is due to the fact that in the last 50 years, the defect density as in Fig. 5.3 [17] of the materials involved in Si IC manufacturing has been reduced by more than four orders of magnitudes.
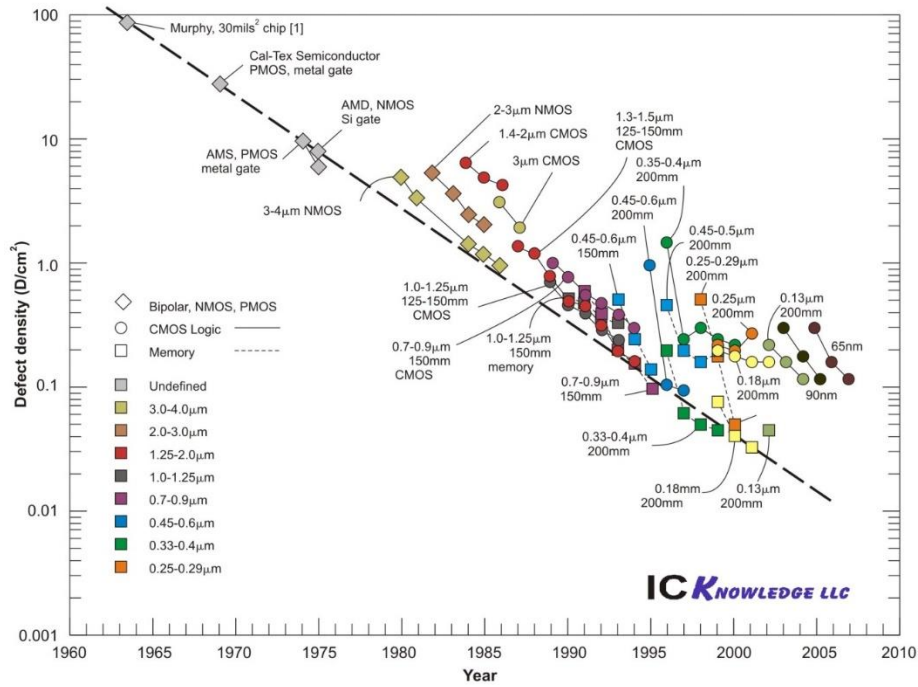
Fig. 5.3. Reduction of defect density over the last 50 years [17].

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Simplified expression of the yield of integrated circuit is given by:

$$Y = e^{-DA} \qquad \text{... ... ...} \qquad (5.2)$$

where, D represents the defect density and A is the die area. As shown in Fig. 4, (18) the reduction of defect density shown in Fig. 3 has allowed to use larger die size for

103

each generation of technology. The combination of line width reduction, increase of die size and increase of wafer size has allowed to continuously reduce the cost of silicon ICs.
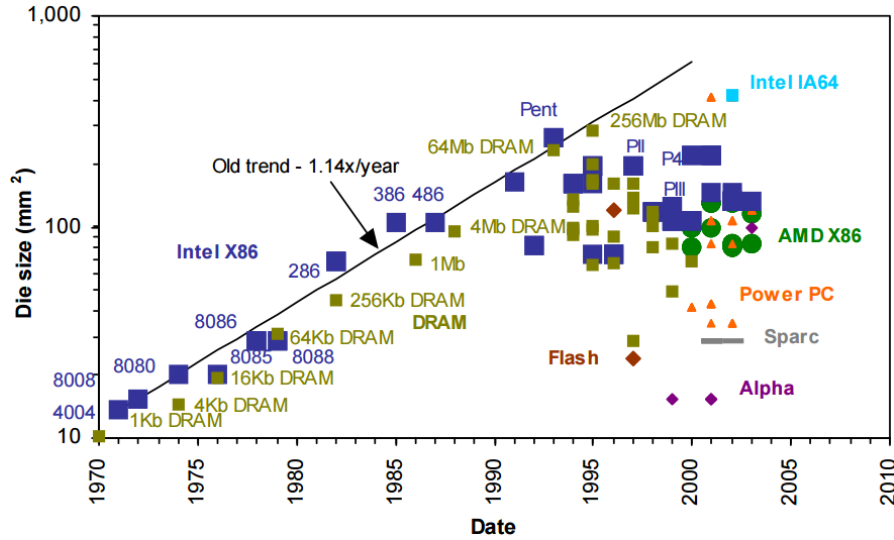
Fig.5.4. Use of larger die size with progression of time for manufacturing Si ICs [18].

The prime reason for the success of silicon manufacturing is that the process control of semiconductor manufacturing has evolved from classical statistical process control (SPC) to advanced process control (APC). In other words silicon IC industry has virtually adopted single wafer processing (SWP) to address the issue of defect density and other manufacturing considerations [19]. The use of advanced process control in SWP allows the control of defect density as well variability of device parameters. In place of conventional thermal processing, rapid thermal processing is used to provide shorter processing time and lower processing temperature resulting in lower defect densities. In addition, the use of high-energy incoherent photons in single wafer thermal processing [20] and single wafer chemical vapor deposition [21] provides ultra-high performance, reliable and low-cost devices. The general notion in the WBG semiconductor based power devices and power

system community has been that older generation of silicon manufacturing is good enough to manufacturer WBG based power devices [22]. This assumption is not true, since unlike silicon the substrate defect density is much higher than the silicon wafers. In case of WBG materials, most of the commercial epitaxial growth systems are also using batch processing [23]. Due to high process variability the batch processing tools provide higher defect density and lower yield and lower reliability than corresponding APC controlled SWP tools.
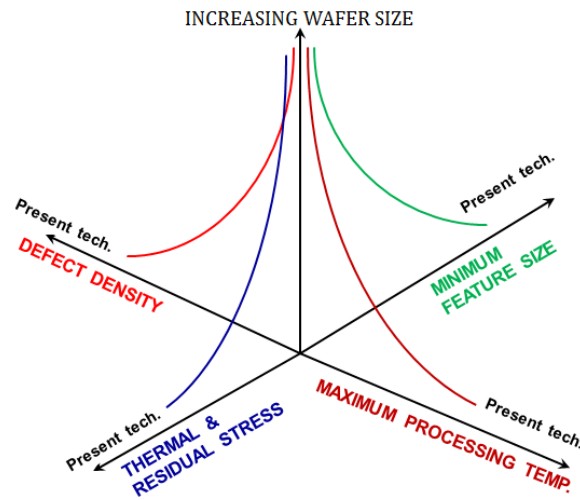
Fig. 5.5. Process integration of WBG devices manufactured by
single wafer processing.

Based on the continued success of silicon IC industry, the WBG equipment manufacturers have to develop new processing equipment based on advanced process control. In Table 5.2, we have summarized the core requirements of new APC based processing tools. From process integration point of view the approach shown in Fig. 5.5 will lead to devices with reduced defect density. Equipment manufacturers have to develop

APC based processing tools that can be used in cluster tool architecture leading to reduced

cost of ownership [19].

Table 5.1 Process control fundamentals [24]

Key Issue	Process Control Concerns
Quantifying	Capability to measure is the pre-requisite of controlling something
Locating	The reasons/ origins have to be known before taking a control action
Cost-effectiveness	Over-inspecting is better than inspecting less and taking risk
Change incorporation	It is necessary to quantify the possible losses in worst case
Variability	It is unwanted in process control realm
Reliability	Improved yield has positive impact on reliability
Time	Delay causes loss in throughput and revenue
Late-stage discovery	Problems / defects found later costs and wastes more
Scaling down	Process control requirements increase
Critical problems	May require layered process control strategy
Overall impact	Reduced production cost and cycle time through more process control

5.4 Conclusion

In this chapter, we have examined the status of SiC and GaN power semiconductor

devices. Current practice of the use of statistical process control based batch processing

leads to larger process variability, and higher defect density leading to lower performance,

lower reliability, lower yield and high cost of power devices. Advanced process control

based single wafer processing tools are proposed to realize the true potential of SiC and

GaN in manufacturing power semiconductor devices.

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CHAPTER SIX

FURHTER COST REDUCTION OF BATTERY MANFACTURING

6.1 Introduction

Energy storage has evolved at a rapid rate in the last couple of decades. For a long time, battery storage was mostly used for starting engines, few emergency backup and portable devices, toys, etc. Ubiquitous zinc-carbon (dry cell) battery and lead-acid battery were the key players for portable applications and automotive industry respectively. However, due to the rise of consumer electronics and convenience of recharging Nickel Metal Hydride (NiMH) and Nickel Cadmium (NiCd) batteries also gained mainstream popularity. The arrival of lithium-based batteries changed the scenario by offering higher energy efficiency and density, in addition to its longer shelf life, fast charge and discharge, etc. [1]. Though it was reported that lithium-ion batteries (Li-ion) have slight memory effect [2], it is less prominent than NiCd and NiMH batteries. Li-ion batteries have high gravimetric (Wh/kg), high volumetric (Wh/L), high cycle life, and high energy efficiency, etc. [3]. Li-ion has gravimetric energy density in the range of 110-160 Wh/kg, while such ranges for lead acid, NiMH and NiCd are 30-50, 45-80 and 60-120, respectively in Wh/kg [4]. Armand *et al.* published [5] a detailed comparison of battery chemistries in terms of future applications and their environmental impacts where Li-based batteries performed better than the others. With ramped up production, Li-battery price is showing downward trend, and manufacturers, such as Tesla, are utilizing volume manufacturing to push the cost down [6]. In order to curb dependence on fossil fuel and reduce carbon emission, the

world is leaning more towards renewable energy (wind and solar) for electricity generation, and also towards EVs for surface transportation. Both of these sectors have high degree of correlation with battery cost and performance. Apart from the portable electronics, at this moment the emerging market for the Li-ion battery can be categorized in two key segments: (a) renewable and grid energy storage, and (b) electric transportation. As sustainable energy sources, there is plenty of renewable energy (sunlight and wind) [7] for human beings on earth, and in recent years, energy harvesting installations (PV and wind turbine) are growing at an astronomical rate. Due to the intermittent nature of solar and wind energy generation, it is also creating a large demand for energy 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 [8]. Local generation of direct current (DC) power by PV [9] and the use of batteries for storing electrical power have the potential of transforming global electricity infrastructure [10]. This scheme also offers better efficiency and resiliency [11]. As the energy infrastructure is undergoing a gradual transformation, smart grid is also gaining attention. The use of front-of-the-meter (central grid energy storage) and behind-the-meter (energy storage at consumer premises) are increasing and thus, driving up the demand for batteries [12]. One of the largest batteries of the world, the 400-MW peak hour battery, is based on Li-ion technology [13]. The PV industry has used practices that were tested, implemented and perfected in semiconductor manufacturing, and thus made significant improvement in reducing the process variability [14]. This adoption of technology allowed PV industry to deliver superior performance and to reduce cost. The battery industry can use similar fundamental

111

concepts to transform the battery manufacturing processes. Driven by the continuous increase in energy density and reduction in cost [15], a recent report predicted 11.6% compound annual growth for Li-ion battery that will reach $77.42 billion in 2024 [16]. Solid-state battery is also garnering attention [17], [18], and it is projected to grow in near future [19]. Li-ion with silicon anode [20], Li-air [21], etc. are also showing promises for future applications.

On the other frontier, surface transportation sector is also creating a huge market for batteries that actively participate in drive train rather than just supplying starting power to engine. Energy economics, carbon foot-print reduction and eco-minded consumer behavior are driving the growth of electric vehicle (EV), hybrid electric vehicle (HEV) and plug-in hybrid vehicle (PHEV) markets, and thus, demand for batteries for such applications are also increasing. Li-ion battery is also used for such applications. In some car batteries, Li account for approximately 5% of materials and less than 10% of the cost [22]. There is even an example where an EV manufacturer ventured into its own battery manufacturing (Tesla Gigafactory) [23], and then introduced battery storage for PV generated electricity (Tesla Powerwall) [24].

Electric vehicles, power grid management, energy storage requirements, along with growth in in renewable energy, will fuel the growth in battery industry [25]. For low-cost manufacturing, the abundance of raw materials is a necessary criterion [26]. At current usage rate, recent survey and estimation data indicate that there is enough lithium for the next 365 years [27]. New process for lithium extraction from minerals are also being explored [28]. There are some volatility in spot price of lithium and its commonly used

compound i.e. lithium carbonate. Moreover, lithium is sourced from few countries and handful of companies control the major part of the supply [29]. The peak price in recent times was US $20,000/ton (approx.) at March 2016 [29]. Recent (January 2017) pricing is in the vicinity of ~$15,000/ton [30]. In most cases, the manufacturers alone cannot control the price of the raw materials. Large-scale manufacturers can buy in larger quantities and claim discounted bulk pricing in some cases. However, the manufacturers have more control at every step of in-house manufacturing. It is very important for battery manufacturers to find processing and manufacturing changes that will further reduce the manufacturing cost for lithium and solid-state batteries. The purpose of this chapter is to present process variability in battery manufacturing and provide other manufacturing directions that can provide further cost reduction of manufacturing of Li-ion and solid-state batteries.

6.2 Problem Definition

All manufacturing processes have inherent statistical variability. It is also true for the electrochemical and solid-state cells that form a complete battery. For control purposes, the measurement has to be precise enough before any corrections can be made [31]. In manufacturing, unidentified problems cannot be fixed, and control cannot be meaningful without measurements [31]. However, the best and suitable measurement system will be different for each specific process. Therefore, the measurement scheme, data collection, analysis and feedback need to be tailored for each process. A useful measure of this can be

expressed in terms of process (P) to tolerance (T) ratio. The ratio P/T is defined as [32]:

$$\frac{P}{T} = \frac{6 \, \sigma_{precision}}{lim_{upper} - lim_{lower}} \qquad \ldots \ldots \ldots \qquad (6.1)$$

where, $\sigma_{precision}$ is square root of sum of repeatability and reproducibility of measurement, lim_{upper} and lim_{lower} are upper and lower limits of tolerance, respectively. Semiconductor industry uses a value smaller than 10% for P/T [32]. As the transistor size shrunk, the process control also became more stringent to maintain the final yield [31]. In spite of having a very small tolerance, semiconductor industry has achieved high yield for integrated circuits (IC) with ultra-small dimensions. Even, 10nm transistor technology is now at mass production [33]. Meticulous attentions have been paid to defect of semiconductors and interfaces [34]. The whole IC industry is a noteworthy example of process control. Their cost reduction is mostly contributed by the in-house cost control i.e. yield improvement, increased process efficiency, increased throughput, etc. Through process improvement, the silicon wafer manufacturers are able to offer superior quality wafers at lower price. Most importantly, the successful IC manufacturers achieved high yield with tight process control, and are able to ship more number of finished products. The manufacturers that used tighter process control and larger Si wafer in their manufacturing process, remained competitive. The reliability of semiconductor products has helped this industry enjoy a stable growth. The reliabilities of transistors and their gates are treated with high importance in semiconductor fabrication [35]. Now, the reliability of battery and lifetime modeling is also drawing attention [36]. Apart from all these, researchers at industry or academia may discover that a new electrode, a new electrolyte, particular

material substitution, or a new chemical processing step in battery can reduce cost and improve yield. However, this ongoing type of research is beyond the scope of this manuscript. Instead, manufacturing practice and cost reduction will be key focus of this manuscript assuming that the desired chemistry, recipe, material, etc. are already selected.

As stated before, PV industry has made immense improvement in processing by adapting many well-known practices from semiconductor industry [37]. Battery industry can also adapt some proven practices and process from PV and semiconductor industries.

In this article, we would refer to an individual electrochemical or solid-state cell as 'cell'. When several such cells are combined together, it would be referred as 'battery pack', which may include the battery management system (BMS) with sensors, controllers, processing unit, etc. On many instances of real life application, cells may be arranged according to need for achieving desired voltage level and capacity.

Due to tolerances during the manufacturing process, the final product may exhibit variability among them. This is applicable for battery manufacturing as well. These variability issues present a big challenge for battery since its manufacturing process consists of assembly of sub-components (e.g. electrolyte, electrode, separator, etc.) which may come from different locations and by different vendors [38]. However, cell-to-cell variability had been analyzed from the viewpoint of chemical and physical phenomena, the system-level design requires analytical models that accounts for the variability in manufacturing process [38]. The electrochemical models, such as pseudo 2-dimentional (P2D), single particle (SP), porous electrode polynomial (PP), etc. are powerful tools and their contribution cannot be undermined. Detailed comparison among these models can be

found in review articles, such as [39]. It is possible to use an electrochemical model to accurately estimate the effects of process variation on a cell. However, the system-level design and variation of electric systems might be handled effectively by analytical electrical models [38]. Stroe *et al.* [40] also used electrical model to characterize battery performance. When multiple electrochemical cells are present, it is important to understand the role of variability on the behavior of the final battery pack. Zhang *et al.* [41] demonstrated one such example by experiment, modeling and parameter extraction for multi-cell battery.

Shin *et al.* [38] demonstrated a combined cell-to-cell variation model by (i) identifying the target lithium battery structure, (ii) modeling capacity and internal resistance and (iii) model parameter analysis. By random variable assignment (based on mean and variance), 10,000 random cells were generated, arranged in arrays and simulated in MatLab Simulink [38].
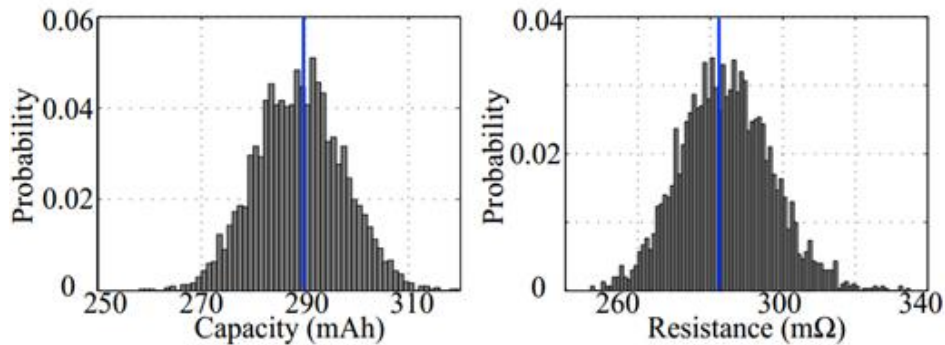
Fig. 6.1. Probability distribution of the cell capacity and resistance

profile of the sample cells. From [38]. © IEEE.

Fig. 6.1 [38] shows a statistical distribution of cell performance for Li-ion cells in terms of capacity and resistance. The desired statistical distribution of the cell capacity in

116

Fig. 6.1 should have (a) a mean centered at higher value i.e. the mean should move right, and (b) have a smaller (narrower) variation. Similarly, the statistical distribution of resistance should have (a) smaller mean value i.e. move towards left, and (b) have a smaller (narrower) variation. As shown in Fig. 6.2 [38], it was demonstrated that if an array consists of cells with less variance, it could perform better than the one that has more variance among its constituent cells. Therefore, with narrower statistical distribution, it is possible to extract more power from the array of cells.
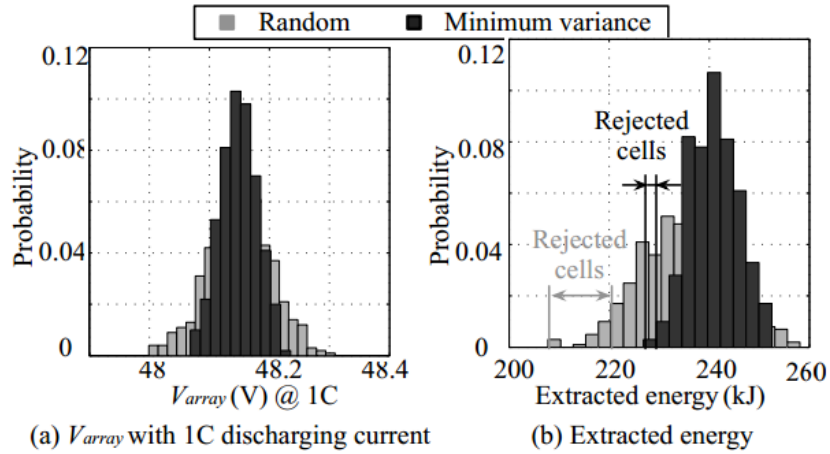
Fig. 6.2. Comparison of estimated array voltage (V_{array}) and extracted energy from sample battery arrays formed by random selection and variance minimization. From [35]. © IEEE.

We may consider single electrochemical cell as the building block, and can connect such cells to form battery pack of desired voltage (e.g. 12V). Using smaller battery packs in series and parallel combination, higher voltage (e.g. 48V) and higher capacity (e.g. 100KWh) can be achieved. Therefore, the variation of output from one cell to another one is unwanted as its adverse effect will ripple to battery pack and eventually, to the whole

(large) battery installation. Therefore, variation reduction should start from the smallest constituents -the cells, and then, applied on subsequent steps or blocks gradually. Variation reduction among cells can contribute significantly in boosting the overall performance of a large energy storage installation. While investigating the thermal imbalance between cells, Christen *et al.* [42] mentioned that variation in resistance can significantly reduce lifetime of a battery.

Any kind of high variation in electrochemical cell performances may require discarding many of the manufactured cells. Moreover, due to the presence of different types of materials e.g. anode, cathode, solvents, and other chemicals, the statistical distribution can become wider, and eventually produce inferior end results. Santhanagopalan *et al.* [43] have shown that the variation in cathode thickness and cathode particle size can cause measurable difference in their Nyquist responses.

The importance of process control and variation can be illustrated through a very relevant example from photovoltaic (PV) manufacturing process. A PV module is the series and parallel arrangement of solar cells. Due to the series and parallel types of connection, the worst performing solar cell dominates the overall performance of the whole PV module. The statistical distribution and non-uniformity among solar cells cause lower efficiency in energy conversion in a PV module when compared to the efficiency of the best performing solar cell. The improvement in individual solar cell efficiency does not translate directly into improved PV module efficiency. Cell-to-cell performance variation can reduce the achievable power output, because the worst performing cell will pull down the overall performance of the module [14]. The percentage change in module efficiency from single

cell efficiency can be considered as an indicator of how closely the process could be controlled and the degree of variation among cells. A smaller change in silicon solar cell to module efficiency is a clear indicator that these cells can be manufactured with least amount of variation. Due to process uniformity, the efficiency of silicon PV module is only slightly lower than the efficiency of individual cell, and best among commercial solar panels [44]. On the other hand, for many R&D cells, high variability and inability to control the process are key hurdles for entering mass production [45]. This is a stellar example of what can be achieved through process control.

Li-ion batteries employ battery management systems (BMS) to ensure safe and reliable operation of the battery pack. The BMS needs to monitor many parameters (e.g. total and individual voltage and current, temperature, impedance, etc.). It also performs critical tasks of estimation of battery states which includes state of charge (SOC), state of health (SOH), state of function (SOF), etc. Moreover, depending on the specific application, BMS may perform on-board diagnosis, safety control and alarm, charge control, equalization, thermal management, networking, information storage, etc. SOC estimation can be done through several methods, such as open circuit voltage, ampere-hour integral, battery model-based estimation, neural network model, Fuzzy logic, Kalman filter, sliding mode observer, etc. Each of these has its advanteges and drawbacks, and significanlty different in their computainal loads and error margins [46]. Lu *et al.* [46] also presented a table comparing different BMS chips available on the market. Stuart *et al.* [47] demonstrated BMS for large Li-ion cells used in EVs. If more uniformity is present among cells and they perform in a harmonious way, a less computationally powerful (and cheaper)

BMS may be used. Equalization can be done at battery (with several cells) level, or at individual cell level. The non-uniformity in remaining capacity and the need for equaliztion can be caused by, among other reasons, non-uniformity of self-discharge or non-uniformity in Coulombic efficiency [46].

In essence, for achieving higher performance and lower manufacturing cost of batteries, the electrochemical cells need to have smaller process variation, i.e. uniform physical and chemical properties.

6.3 Proposed Changes in Li-ion Battery Manufacturing to Address Process Variability

Li-ion manufacturing has several steps that vary from manufacturer to manufacturer. Processing steps are also dependent on the selected chemistry. After prototyping, a desired cathode, anode and other chemicals are selected for forming the cell. Depending on the selections and arrangements, the cell potential and performance will be different. Common steps that are carried out in manufacturing include the anode and cathode preparation and coating with chemicals. For solvent removal, usually some drying steps are used. Electrodes, electrolytes, binders, separator materials, etc. are assembled to form a complete cell. Finally, the cells are tested, graded and packaged as a full battery, which may just contain one cell or multiple cells. The goal from a manufacturer's point of view is reducing the variability of each step at minimum level, and get the final product without having large deviation from the targeted numbers. Implementing several changes in manufacturing process that are described in the following paragraphs would help accomplish this goal.

6.3.1 Advanced Process Control

To reduce process variability, battery manufacturing processes need to shift from statistical process control (SPC) to advanced process control (APC). Besides semiconductor industry, the benefits of APC have been well documented in other industries, such as petroleum [48] and pharmaceutical [49]. Battery manufacturing facilities should deploy more *in-situ* measurements so that process can be kept within tighter control. Harks *et al.* published [50] detailed review on in-situ measurement for Li-ion battery. Adaptation of '*within the batch control*', '*batch-to-batch control*' and '*batch production control*' can establish control and optimization on '*one batch*', '*multiple batches*' and '*all produced batches*', respectively.

Based on concepts discussed in [51], we can consider a simplified case of qualitative relationship between yield and performance as depicted in Fig. 6.3. The current production point 'P' is on a line that defines a simplified linear relation (with negative slope) between yield and performance. In real world such correlations will not be so simple, but this simple linear relation is good enough to illustrate the point being discussed. Along this line, increase in either production or performance will sacrifice the other. In other words, if the allowed window for quality is narrow, more products will have to be
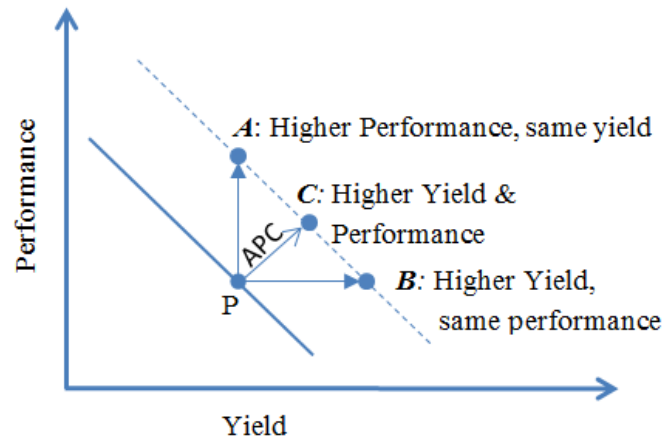
Fig. 6.3. Shifting a simplified Yield-Quality line with the use of advanced

process control (APC). Modified from [51].

discarded, and eventually, the yield will decrease. Similarly, if more products are passed as acceptable, then the overall quality will be compromised. Inclusion of APC can slide the line to the right, and move the point P to the new position with higher performance (point A) or higher yield (point B) while keeping the other parameters unchanged. Even improvement in both performance and yield may be achievable (point C). For R&D and small-scale manufacturing, there are commercially available battery manufacturing tools and equipment that closely resemble the technology used in IC manufacturing [52].

6.3.2 Modifying process mechanism

In a study carried out on solid-state electrolyte for Li-ion cells, the researchers concluded that variation in cooling rate results in variation of ionic conductivity [53]. Therefore, the thermal process needs to be controlled precisely to keep cooling rate consistent in all batches. The improvement in battery technology can come from utilizing

the insight gained from the equivalent circuit model of the battery proposed in [54]. Young *et al.* [55] included battery capacitance (C_b), self-discharge resistance (R_p), internal resistance for charge (R_{2c}), internal resistance for discharge (R_{2d}), over-voltage resistance for charge (R_{1c}), over-voltage resistance for discharge (R_{1d}) and over-voltage capacitance (C_1). The equivalent circuit of Fig. 6.4 [55] provides a simple guideline for uniformity which dictates that when connecting more than one cell to form a battery pack, the contributing cells need to have same values of C_b, R_p, R_{2c}, R_{2d}, R_{1c}, R_{1d} and C_1.

C_b = battery capacitance, R_p = self-discharge resistance, or insulation resistance,
R_{2c} = internal resistance for charge, R_{2d} = internal resistance for discharge,
R_{1c} = overvoltage resistance for charge, R_{1d} = overvoltage resistance for discharge,
C_1 = overvoltage capacitance.
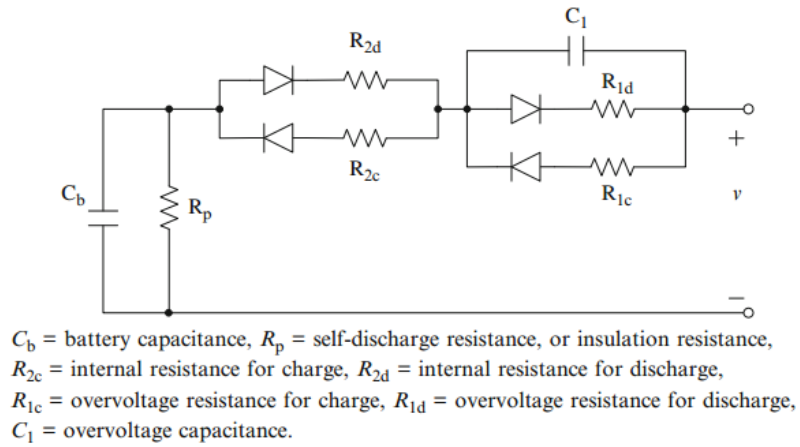
Fig .6.4. Equivalent circuit model of a battery. From [55].

With desired goal of reducing cell-to-cell variation, the focus has to be on the contributing factors that are responsible for the process variation. Analytical expression presented by Sikha *et al.* [56], and the resistance and capacitance models of Shin *et al.* [35] provide insight into the battery performance. This model can be used to further breakdown and identify the key contributors to cell properties as shown in Fig. 6.5 [38]. Controlling these variables will eventually lead to the control over the cell performance.
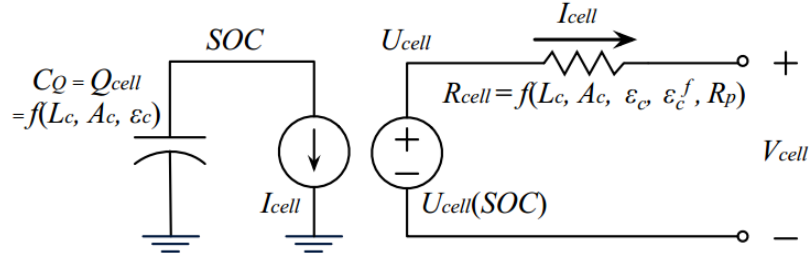
Fig. 6.5. Equivalent circuit model considering the cell-to-cell variation

of capacity and resistance. From [38]. © IEEE.

The most important parameters that control the resistance of the cell (R_{cell}) are thickness of cathode (L_c), area of cathode (A_c), porosity of cathode (ϵ_C), filler porosity of cathode (ϵ_C^f) and radius of solid spherical particles (R_p). The cathode thickness variation leads to undesired results [38]. Since the reactions take place on the surface of the electrode, surface roughness plays a very important role in determining the resistance in an electrochemical cell.

As compared to conventional furnace processing (CFP), the semiconductor industry uses rapid thermal processing (RTP) for most of the thermal processing steps. In case of CFP, resistive heaters are used to create photons with wavelength in infrared region and the thermal mass of the system is large. On the other hand, incoherent light sources are used to create photons with wavelength from ultra-violet to infrared region and the thermal mass is small. Due to different operating mechanisms, the processing temperature and thermal cycle times are lower in RTP and the performance, yield and reliability of semiconductor products processed by RTP are superior to CFP [57]. Detailed mechanism of operating principles of RTP can be found in [57]. The photon-matter interaction can be

summarized by the simple expression: "*photon + matter = thermal effects + quantum effects*". The wavelength of photon dictates degree of thermal and quantum effects in RTP. The effects of different wavelengths in RTP are illustrated in Fig. 6.6. The typical radiation spectrum of furnaces operating in temperatures less than about 1500 °C lies in the infrared region.
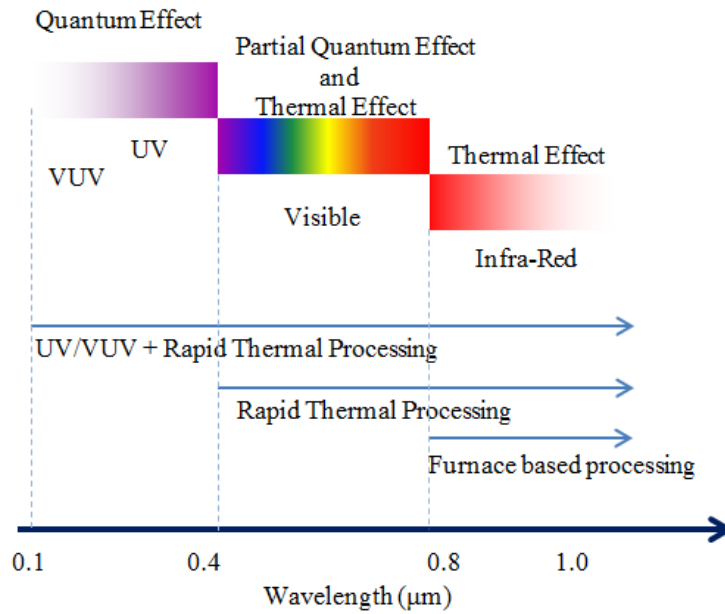
Fig. 6.6. Radiation spectrum distribution for thermal processing techniques.

When the materials are exposed to photons of infrared region, (>0.8μm) only the thermal effects are operative. When infrared and shorter wavelength photons (<0.8μm) interact with the materials, both quantum effects and thermal effects take place. As compared to CFP, RTP provides (i) higher throughput, (ii) lower microscopic defects, and (iii) lower operating temperatures [57]. RTP can also lead to lower surface roughness. For identical processing temperatures, Ratakonda *et al.* [58] reported the surface roughness of RTP samples processed for 122 second and CFP samples processed for 162 second. The

surface roughness of screen printed silver contacts were 189 nm and 548 nm, respectively [58]. In line with our previous work on rapid thermal processing [57], very recently Xue *et al.* [59] have shown that the use of ultraviolet light in the curing process of composite electrode fabrication can reduce the processing time. These results prove that UV assisted curing is a promising route to substantially reducing the capital and operational costs of lithium-ion battery electrode manufacturing [59].

In Li-ion cell formation process, the films of the chemical composites are put on electrodes and then dried by heating to drive out the solvents. In this step, higher temperature assists faster drying, but higher temperature has adverse effect on metal electrode surface. Adverse effects of high temperature curing are also observed in wafer-level packaging chips. The increase in curing temperature leads to cracking and warping [60]. The RTP assisted drying in Li-ion cell manufacturing will allow the process to take place at a lower temperature, and thereby no adverse effects will be observed. Similar to semiconductor manufacturing, RTP is expected to make a positive impact in Li battery manufacturing.

6.3.3 Synthesis of the raw materials with uniformity, supply chain and industrial internet of things (IIoT)

Synthesis of the raw materials with more uniformity can lead to variation reduction in the final product. The properties like porosity of cathode (ϵ_c), filler porosity of cathode (ϵ_c^f), radius of solid spherical particles (R_p) can be tuned through chemistry as well as careful sourcing. As reported by Sikha *et al.* [48], when solid particles are present in the cell, their radii are important in determining the electrical properties. As shown in the

following equations, for both anode or cathode of Li-ion cell, the local impedance (Z_{loc}), single particle impedance (Z_p), and solid phase diffusion resistance (R_{diff}) are correlated [52]:

$$Z_{loc} = f(Z_p) + f(other\ variables) \qquad \text{... ... ...} \qquad (6.2)$$

$$Z_p = \frac{1}{f(R_{dif}) + f(other\ variables)} \qquad \text{... ... ...} \qquad (6.3)$$

$$R_{dif} = -\frac{R_p}{D_\theta F}\frac{dU}{dc} \qquad \text{... ... ...} \qquad (6.4)$$

In the above equations, D_θ is diffusion coefficient of Li^+ ion in solid phase, U is open circuit potential, and c is solution phase concentration. Thus, the particle's geometric dimension can contribute to electrical properties. Whenever permissible, APC should be used in the synthesis so that that the distributions of radius of these particles stay in a tight range of distribution. In reference [61], the Li-ion battery reaction and parasitic reaction were modeled, and it was shown that the performance of battery depends on particle radius and film thickness. For certain composition, the Li_4GeS_4-$LiPS_4$ ionic conductivity as high as 2.2×10^{-3} S/cm is observed [62]. However, the undesired variation in the composition reduces the ionic conductivity by almost three orders of magnitudes to 10^{-6} S/cm [62]. This decreased conductivity will cause higher interfacial resistance at the interfaces, and this effect becomes more dominant in bulk type solid state Li-ion battery compared to its thin film counterpart [63].

In any manufacturing process, the operation technology (OT) is comprised of devices, sensors, and software to control the equipment and the plant. Information technology (IT) utilizes all necessary technology for information processing. In recent years, the convergence of information technology (IT) and operation technology (OT) has

127

given rise to internet of things (IoT) which improves the overall system performance. Virtually every facet of human life is supposed to benefit from IoT and by year 2025, the potential economic impact of the order of 11.1 trillion USD is estimated [64]. In the context of manufacturing, IoT is referred Industrial internet of things (IIoT) [65]. IIoT is a potential pathway to increase efficiency in manufacturing [66]. As shown in Fig. 6.7, the incorporation of IIoT can provide business critical information that can prove to be crucial in manufacturing of products. In battery manufacturing, the materials are to be sourced from different vendors and the finished products are also distributed through distributors or sold to customer companies. IIoT can significantly impact the supply chain [67]. For example, the manufacturer can instantly be aware of the entry of the raw materials in its premises from the suppliers, and track it throughout the manufacturing facility. Inclusion of IIoT across the global supply chain can offer an end-to-end visibility and mitigate the instances of downtime [68]. Traditional method of manual entry to and exit from inventory can be inaccurate or out of date whereas IIoT can streamline the inventory. As discussed earlier, minute changes in material properties (e.g. variation in particle radius) can affect the battery performance. Thus sourcing of material can be improved by IIoT. The manufacturing line can prepare for any changes in previous stages (including material properties data from suppliers) through use of information communicated via IIoT. Thus, a smart supply chain can provide efficiency and superior performance in final product.
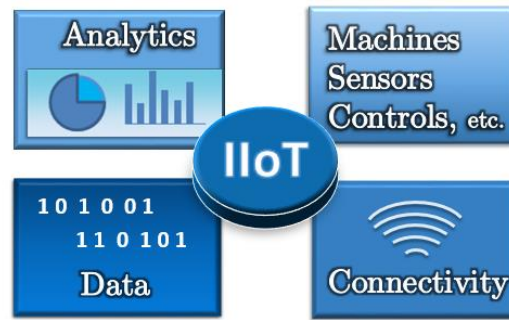
Fig. 6.7. IIoT framework that utilizes connectivity, data, analytic

tools to communicate effectively with machines.

Due to adequate data gathering through IIoT, many potential problem can be detected at an early stage of manufacturing. The early detection of manufacturing problems can lead to corrective measures saving wastage in discarded products, compensation, product recalls, etc. [69]. The data gathered through IIoT platform can point out inefficiencies and problems at a faster pace, save time and money and support integrated business intelligence approach. In conventional manufacturing, quality check of the finished product may reveal defects and then corrective actions may be initiated by human operator. In IIoT, the quality issues can be relayed to the beginning of assembly line, even to another location, in seconds, and corrective actions may be administered within a short period of time. IIoT with radio frequency identification (RFID) tags can be a very powerful tool for tracking material/product movement inside the factory premise. If some of the components or materials are identified to be the cause of a quality problem, RFID tags can point to all the materials, components, finished/unfinished goods that contain that possibly defective materials or parts. Our proposed approach of *in-situ* measurements and sensor deployment, incorporation of tighter process control are in line with the current practices

in some industries (e.g. IC manufacturing, solar cell manufacturing, etc.). On top of that, IIoT will add an additional reach and provide visibility to the overall manufacturing process control that may span from raw materials supply chain to end user.

In this era, customers may look for manufacturers who are capable of making necessary changes in the product to meet a set of provided requirement. Therefore, this has given rise to the Agile Manufacturing (AM), which allows manufacturer to respond quickly if there is a change from customer or market while maintaining the quality and cost [70]. Digital manufacturing [71] has the potential of changing every link in manufacturing value chain, R&D, supply chain, factory operations, even marketing and sales. Complex manufacturing systems, such as aerospace and defense are making efficient use of such technology [71].

6.4. Discussion

The strategies for a manufacturer should be selected based on its size, business models and goals. Large-scale global battery manufacturers (Panasonic, Samsung, LG Chem, Tesla, Hitachi, etc.) enjoy economy of scale, and each has their own strength in chemistry, process, expertise, innovation and intellectual property. Tesla even tried to go further in vertical integration and buy lithium mine [72]. The smaller companies lack the large-scale advantages, but may have some certain market segment and customers with specific requirements or advantages for niche applications. Regardless of size, all manufacturers need to innovate and implement manufacturing practices that would allow to survive and help remain profitable. The points put forward in preceding sections are not

alternatives to innovation in chemistry, and battery research. Rather, these outlined points are to be practiced when the battery work has moved into production phase form R&D phase. As outlined earlier, the adoption of some new steps can lead to potential improvements in battery manufacturing with the net result of lower cost. First of all, variability from one electrochemical cell to another one should be reduced. Then, this practice can be expanded for the case of battery-to-battery variability. To accomplish this, APC should be adopted to establish precise measurement and control. Metal electrodes can benefit having less surface roughness, which can be achieved by using RTP in place of conventional furnace processing. RTP also allows faster and lower temperature processing while keeping the thermal stress at the minimum level. In semiconductor manufacturing, RTP has a proven track record of improving reliability, increasing yield and reducing variability. Similarly, adoption of RTP in battery manufacturing will be beneficial. The uniformity of materials that constitute an electrochemical cell is also important since some of their physical properties (e.g. particle radius) dictate their behavior and movements during the cell operation. IIoT can establish an efficient and streamlined manufacturing process that can transform the dynamics of production.

Precise measurement is the pre-requisite for controlling the process [31]. This might add some capital cost for the equipment. However, better process control can outweigh the capital cost factor by providing higher throughput, better use of raw materials, re-processing cost reduction, etc. [73].

Overall, these proposed improvements will require some capital investments in equipment, software and manpower, but the resulting improvement in yield due to defect reduction will help reduce the cost of ownership (COO) given by following equation [74]:

$$COO = \frac{Fixed\ Cost + Variable\ Cost + Cost\ Due\ to\ Yeild\ Loss}{Throughput \times Coposite\ Yeild \times Utilization} \qquad ……… \quad (6.5)$$

The steps proposed in this chapter would increase the throughput, yield and material utilization and decrease the battery manufacturing cost due to higher yield. Thus, the net result will be reduction of COO. With incorporation of all the proposed changes, we expect to manufacture higher quality batteries at a cheaper cost. All the proposed changes are presented in concise graphical form in Fig. 6.8.
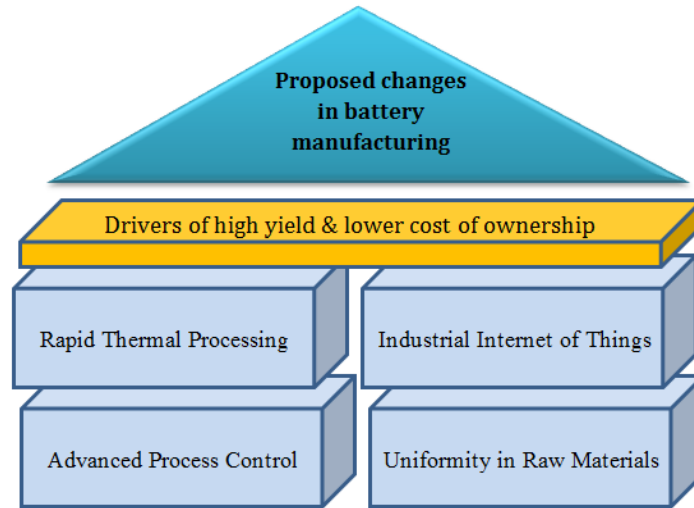
Fig. 6.8. Proposed changes and their impact to bring down cost of ownership

6.5 Conclusion

The process variation in manufacturing is one of the key reasons that reduce the optimal battery performance and leads to higher manufacturing cost. There is room for improvement in controlling the process variations observed in battery manufacturing. In this chapter, we have emphasized that the variation from cell-to-cell is crucial for energy storage application. The statistical process control used currently by battery manufacturers should be replaced by APC to gain better control over the manufacturing process. The use of RTP in place of CFP is suggested in all thermal process steps to reduce process variability and improve the performance and reduce cost of batteries. IIoT has a potential to manage manufacturing in more efficient and agile manner. Besides research in materials and chemistry, these steps can help a manufacturer to run the production in efficient way while delivering the best quality product. Battery industry needs to act quickly to be prepared for the future where battery storage is going to play very important role for stationary applications for power storage as well as in electric vehicles used in surface transport sector.

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CHAPTER SEVEN

CONCLUSION

Photovoltaics, due to its tremendous improvement in manufacturing process and cost reduction, are experiencing a rapid growth. Bulk-Si based solar cells have the largest market share, and are capable of competing with other electricity generation technologies. Though some other solar cell technologies have attempted to make an entry, due to the inherent problems and limitations, they have not been successful. The perovskite solar cell, despite its vast media coverage, is plagued with stability, uniformity and process control issues that are the major roadblocks for its commercialization. Mulit-junction application of perovskite solar cell with Si is also not going to work due to the technical limitations and the big difference of lifetimes of Si cells and perovskite cells.

With improvements in power electronics and batteries, the concept of PV powered DC-based local generation, storage, distribution and consumption, i.e. DC based nanogrid, is becoming more lucrative. For SiC and GaN based power electronics, it is necessary to incorporate advanced manufacturing techniques like advanced process control and single wafer processing.

Technical advancements in battery technologies, particularly Li-ion and solid-state batteries, are paving the path for efficient DC storage. Moreover, the volume manufacturing is driving the price lower. Further cost reduction is possible by following the established manufacturing practices from other technologies. Use of advanced process control, rapid thermal processing, industrial IoT, etc. can reduce the cell the cell variation

in electrochemical cells. This would result in higher throughput, reduction in quality failure and reduce the overall cost of ownership.

The conventional way of DC generation from PV, storing in DC battery, using AC inverter to feed the load and internal rectification, is inefficient. Using the capability of PV, battery, power electronics and IoT, the DC based nanogrid can function in a much efficient way. Besides the efficiency advantages, there is also possibility of cost saving.

The future energy networks have to be efficient, reliable, resilient, cyber secured, ready for IoT and ultra-low cost. The PV based DC nano-grid with local storage meets all these criteria. This model is suitable for all types of economies. With appropriate policy in place, the growth of PV based DC nanogrid will benefit the environment and the population of the whole planet.