Advanced Innovative Solar Technologies for UNC - Chapel Hill:
Examining the Future Status of Emerging Solar Technologies in 2020 and 2025
for Placement on the New Football Indoor Practice Facility

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ABSTRACT

With the negative environmental and social impacts of relying on nonrenewable energy resources becoming more understood by society as a whole, a move to renewable-based energy resources is now and will be increasingly appealing and necessary in coming years. Solar photovoltaics that convert the sun's light into energy could lead the way to a more sustainable future. In recent years, solar technology as a whole has experienced impressive strides towards less expensive and more efficient cells. Additionally, a variety of new forms of solar technology has entered the stage, such as CIGS, CdTe, quantum dot, perovskite, and organic solar cells. The goal of this study is to identify the most practically and economically feasible emerging solar technology available in 2020 and 2025 and to develop a conceptual plan for its installation on the University of North Carolina at Chapel Hill's new football indoor practice facility, based on a site analysis, conversion efficiency, and cost projections.

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AEO	Annual Energy Outlook
a-Si	amorphous Silicon
ATaL	average tilt at latitude
BOS	Balance-of-systems
CdTe	Cadmium Telluride
CH	Chapel Hill
CIGS	Copper Indium Gallium Selenide
CQD	Colloidal Quantum Dots
C-Si	Crystalline silicon
DOE	Department of Energy
DNI	Direct normal irradiance
DSSC	Dye-Sensitized Solar Cell
EPBT	Energy Payback Time
GHI	Global horizontal irradiance
GW	Gigawatt
IEA	International Energy Agency
IPF	Indoor Practice Facility
kW	Kilowatt
kWh	Kilowatt-hours
MW	Megawatt
NC	North Carolina
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PV	Photovoltaics
ROI	Return on Investment
STC	Standard Test Conditions
TFPV	Thin-Film Photovoltaics
TW	Terawatt

CHAPTER 1: INTRODUCTION

As world human population grows rapidly and countries continue to develop economically and industrially, there will be an increased demand for energy globally. With an estimated world population between 8.3 billion and 10.9 billion people by 2050, approximately a total of 30 terawatts (TW) will be required to satisfy energy demands [1]. This is a significant increase from the estimated 17.7 TW world energy consumption in 2012 as reported by the International Energy Agency [2]. Currently, over 80% of the world's energy demand is met by burning fossil fuels in the form of coal, oil, and natural gas [2]. There are three major disadvantages to fossil fuels: i. they are nonrenewable, ii. they negatively affect the environment, and iii. they do not belong to this, or any, generation. The issues with relying on nonrenewable fossil fuels are that they will eventually run out—peak supply for coal, oil, and natural gas has likely already been met or will be met in the next 20 to 30 years—and reliance on unevenly distributed resources can lead to dependence on other countries, manipulation of prices, and warfare [1]. Burning fossil fuels also has a significant negative impact on the environment due to the harmful greenhouse gases they emit, which <u>threatens future human existence</u>.

The reliance on nonrenewable fossil fuels for energy, which is ingrained in the workings of society, is not sustainable due to rising prices, diminishing resources, and pollution emissions; therefore, society must turn to developing and integrating alternative sources of energy, such as geothermal, biomass, hydroelectric, nuclear, wind, and solar, in order to supply future energy demands. These alternative energy sources are both abundant and clean. According to a 2015 Renewable Electricity Futures Study completed by the National Renewable Energy Laboratory (NREL), existing renewable energy technologies <u>could</u> adequately supply 80% of U.S. electricity generation in 2050 [3].

Three important factors to consider when looking at potential new energy sources are capacity, sustainability, cost, feasibility, and efficiency. The sun supplies the Earth with 125,000 TW of solar incidence daily—enough to power over 7,000 Earths each year [4]. While typical costs for electricity from traditional sources are currently generally low at around $0.10/kWh and electricity from PV costs around $0.27/kWh, this costs trend will likely switch as "grid parity" is reached in the near future [1]. This will occur as a result of traditional energy sources prices rising as peak supply is met and PV prices falling as technology advances and efficiency improves. Additionally, rapid improvement in conversion efficiencies for various PV technologies is occurring now and is expected to continue in the future.

Unlike traditional energy sources, there essentially is an unlimited supply of solar energy; therefore, it cannot run out or be over-consumed [5]. Further, no single country is at a huge advantage or disadvantage for utilizing solar energy because it is distributed over the entire globe in both remote and populated areas [6]. In fact, even locations that are not typically sunny can thrive off solar energy [6]. For example, Germany has the largest solar panel market in the world, yet it receives about the same amount of insolation each year as Alaska, as shown in Figure 1 [7; 8]. The benefits of solar energy span from production to implementation in the field, as it requires minimal maintenance, does not cause noise, and causes no pollution beyond manufacturing, transportation, and installation [5]. The power of the sun drives life on Earth, and it could provide the solution to the energy problem, helping sustain life on Earth for generations to come. However, the question remains, what solar photovoltaic technologies will lead the way?

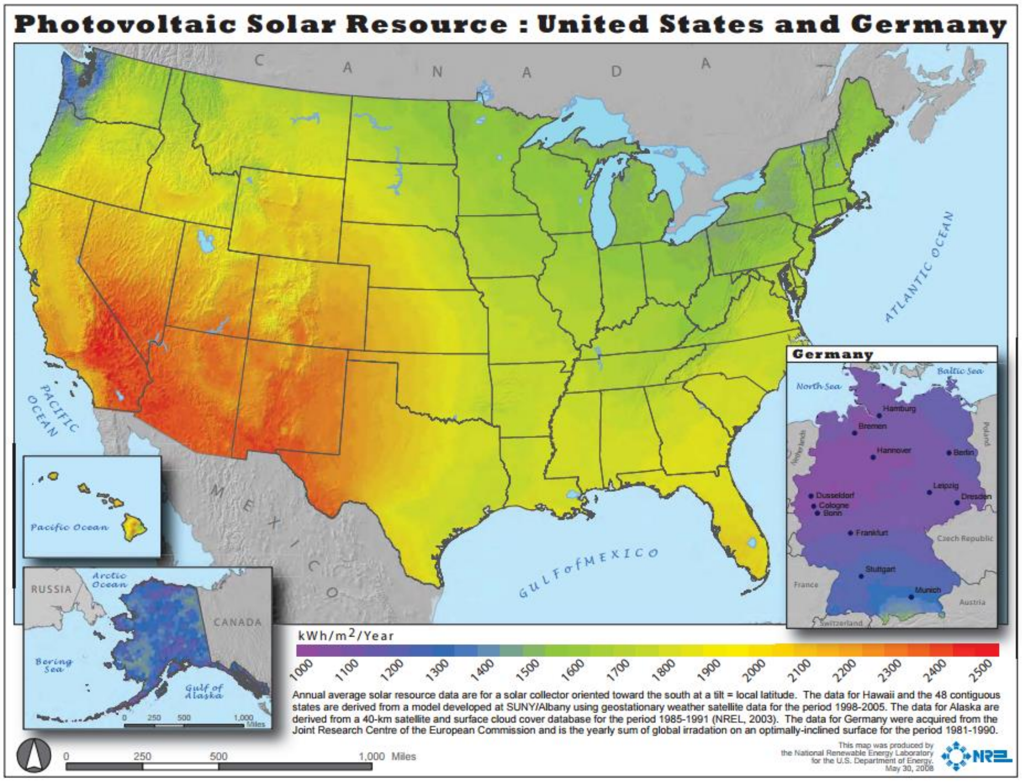

Fig. 1. United States and Germany Solar Insolation Comparison [7]. This figure shows that the annual solar resources for Germany and Alaska are comparable.

Each year, the U.S. Energy Information Administration publishes an Annual Energy Outlook (AEO) that projects energy production, consumption, and technology for roughly 25 years in the future. Jocelyn Keung, an undergraduate student at University of North Carolina at Chapel Hill (UNC - CH), scrutinized the solar energy projections for the AEO 2014 installment and determined that the AEO significantly underestimated the 2040 value for total expected generation from residential photovoltaics in the U.S. While the AEO 2014 projects solar generation of 0.2704 quadrillion Btu in 2040 (the AEO 2015 projects 0.29 quadrillion Btu), Keung's research indicates projections of 0.495 quadrillion Btu [9; 6]. Because she takes into account the impacts of state-of-the-art technological advances in materials and conversion efficiencies, the U.S. Depkuengartment of Energy's (DOE) SunShot initiative, declining costs, and novel solar applications, Kueng's projections more accurately reflects the potential capacity for solar energy generation in 2040 [6].

Building off of Keung's findings, many technological advances in materials and conversion efficiencies and new solar applications will emerge between 2015 and 2040. A number of technologies have already begun to emerge as potential competitors to more traditional silicon-based cells. Some of these include second-generation thin-films, quantum dots, perovskites, organics, and dye-sensitized solar cells. Where these technologies currently are, how quickly they are progressing, and where they will be in the near future are questions that are worth considered when planning new commercial or residential construction down the road. Anticipating where the technology and market for each will be when new construction plans are being developed could be hugely beneficial to the owner. In this study, 2020 - 2025 conversion efficiencies and costs are projected for emerging technologies. Based on these results, a conceptual design for a solar system to implement on a new, large, multi-use Football Indoor Practice Facility (IPF) on the UNC - CH campus is created. The IPF, funded by The Rams Club—UNC's athletic booster club and scholarship organization—and designed by HOK, is tentatively planned to begin construction in 2017 and become operational in 2018. Lastly, the economical and practical feasibility of the design is analyzed.

Project Overview

The scope of this report is on the developments of photovoltaic solar technologies and applications by 2020 and 2025. This research seeks to address three questions:

(1) What cutting edge technology will be at the forefront of the solar energy market in 2020 - 2025? This analysis will consider the availability, conversion

efficiencies and cost of such newer technology as thin-film, quantum dots, perovskites, organic, and dye-sensitized solar cells.

(2) What mix of these emerging solar photovoltaic technologies and applications is best suitable to provide energy for a complex, multi-use, 4,963,940 cubic foot indoor football practice facility?

(3) Is this design economically and practically feasible for UNC in Chapel Hill, North Carolina, given its spatial location and that The Rams Club will fund it?

CHAPTER 2: BACKGROUND

Section 1: Basics of Solar Energy

Using a variety of techniques, the sun can be utilized to provide benefits to society in a number of different ways. For example, sunlight can be used to passively heat homes, businesses, or water, nurture agriculture and to provide electricity. In this study, the focus is on solar photovoltaic (PV) materials and cells, which are used to convert sunlight into electricity directly. The solar cell's efficiency is calculated by determining the proportion of the sun's energy that hits the cell and is subsequently converted to electricity. Solar cells are typically connected electrically in series to produce high voltages, currents, and power levels [10]. A flat configuration of typically 40 electrically connected solar cells sealed in an environmentally protective laminate creates a PV module [10]. Next, one or more PV modules are combined to form a pre-wired, field-installable unit or PV panel [10]. Generally, it takes 10 to 20 solar panels to power the typical residential home [11]. Subsequently, combining several panels can create a solar array system. Finally, hundreds of solar arrays can be interconnected to create a utility-scale PV system [11].

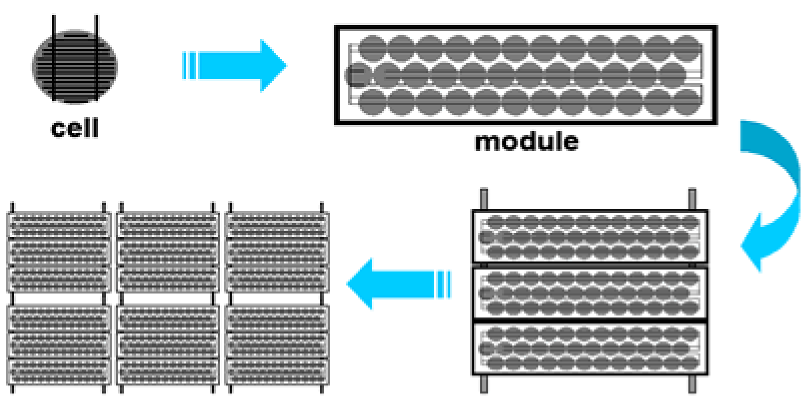

Fig. 2. Photovoltaic Cells, Modules, Panels, and Arrays [10]. This diagram shows the composition of PV cells, modules, panels, and arrays.

Solar cells produce direct current (DC) electricity but much of the electricity required for electrical appliances in the U.S. is alternating current (AC). Therefore, an inverter is needed to convert the generated DC electricity into consumable AC electricity. Fortunately, typical inverters have a conversion efficiency from DC to AC of 95% [12]. However, common products that are becoming more frequently used, such as phones, TVs, and computers, run off of DC electricity. Thus, a conversion from DC to AC back to DC is required. Unfortunately, the conversion from AC to DC, typically included with the equipment's transformer, is less efficient and 10-40% of power may be lost [12]. This is something that could be improved upon in the future.

A variety of materials can be used to create solar cells. Flat-plate solar cells made from silicon are traditional and the most efficient [11]. However, new generations of solar cells are being created using other materials. Second-generation cells are "thin-film" cells made from amorphous silicon or non-silicon materials, such as cadmium telluride (CdTe) or copper indium gallium diselenide (CIGS) [11]. Third-generation cells also utilize new materials instead of silicon, such as quantum dots, and tend to require more costly materials, but in smaller quantities; thus they are becoming more cost effective for practical use [11]. These generations of solar cells will be discussed in detail further on.

Three main components of the PV system or array are the PV module, power electronics, and balance-of-systems (BOS), all of which comprise the cost of the system [13]. As mentioned previously, the PV module refers to a collection of electronically connected solar cells. Power electronics refer to the inverter, which converts electricity from direct current to alternating current, and the transformer, which increases or decreases alternating current from a certain voltage level to another [13]. Lastly, the remaining costs, such as installation, fees, land, and other hardware, compose the BOS expenses [13]. For the remainder of the paper, power electronics will be considered part of BOS.

Most importantly is how solar energy can be used in this project. Electricity created from the IPF solar system could i) power all of the facility, ii) be used by collocated facilities, or iii) be used in a combination of options. Should the solar system <u>not</u> produce enough electricity to sufficiently power the facility on its own, supplemental electricity could be purchased from the grid. Should more than enough energy be produced, and then implemented battery storage could store the excess electricity for later use—most likely during nights when no solar energy is being generated. Option iii would occur if the solar system produces more electricity than the building consumes. Energy beyond the needs of the facility could be available to other UNC facilities on the University's grid. The estimated building consumption and energy production will be calculated and analyzed to determine which option is most fitting for the IPF.

Section 2: History of Solar Energy

There is a long history in the use of solar cells; however, it was not until recent decades that solar energy has been a widespread commercially viable option for large-scale applications. The sun's energy has been harvested in solar cells dating back to 1876 when William Grylls Adams discovered that exposing selenium to light produces electricity [14]. This important discovery proved that light could be converted into electricity without moving parts or heat [14]. Calvin Fuller, Gerald Pearson, and Daryl Chapin discovered the silicon solar cell in 1953. With their cell running small electrical devices, the New York Times raved that the discovery was "the beginning of a new era, leading eventually to the of harnessing the almost limitless energy of the sun for the uses of civilization"—a statement very telling of what has and has yet to come for present society [14].

By 1956, the first solar cells were available commercially; however, at $300/watt solar cell, they were far out of reach for the average consumer [14]. Beginning in the late 1950's and early 1960's, solar cells were found in novelty items, such as toys and radios, and in space program satellites [14]. In the early 1970's, research conducted by Exxon, which used solar cells to power rig lights, brought the cost of solar cells from $100/watt to $20/watt, leading to a change in solar usage from the 1970's to the 1990's [14]. Solar cells started being used in more remote places and for different uses. One example is in desert regions that did not have power lines now utilize solar power to move water [14]. Today, solar cells are used in an increasing variety of places and applications, from small devices to cars to aircrafts. The current and future role of solar will be discussed in greater depth throughout this thesis.

Section 3: Financing Solar Energy

The majority of federal and NC state solar incentives are applicable only to residential solar, but the cost of PV systems has and will continue in the future to steadily decrease, making them significantly more affordable at both utility and residential scales. This project will take into account the capital costs of the technology, installation fees, and operations for a commercial sized solar system. There are many incentives and financing options to make purchasing PV systems for residential applications even more economically appealing for electricity consumers. Among these benefits are state and federal tax credits, special loan agreements, net metering, discounts on utilities, and fee waivers. The federal Renewable Energy Tax Credit of 30% was extended until December 31, 2021 for solar technology but is only eligible for residential applications; therefore, this incentive is not relevant for the financing of this project and will not be factored into the economic analysis [15]. The non-federal programs available and specification of incentives vary by state [6]. For example, West Virginia only has

11 solar initiative programs, but California has 202 [15]. North Carolina falls in the middle with 115 programs. Again, most of these programs are for residential solar and, therefore, beyond the scope of this study, given the source of the IPF's funding.

The biggest solar incentive in North Carolina—and one applicable to larger scale solar systems—was the NC Renewable Energy Tax Credit; however, the tax credit expired December 31, 2015 and has not yet been renewed. In short, the tax credit covered 35% of constructed, leased, or purchased renewable energy property/materials in commercial, industrial, agricultural, and residential sectors [15]. It covered up to $10,500 per non-business installation, $2.5 million per business installation, and $5 million per business installation at an eco-industrial certified park [15]. In fact, North Carolina was one of few states with a tax credit in place for business renewable energy projects. A solar system on the new IPF would, by definition, be considered a business installation; thus, a tax credit up to $2.5 million would have been covered under the NC Renewable Energy Tax Credit. However, because the new IPF will be funded by The Rams Club, which is considered a 501(c3) organization or a tax-exempt nonprofit organization under the United States Internal Revenue Code, the project will not be taxed. Given this, the potential future State Tax Credits for business ventures will not be further considered in this study.

Section 4: Solar Energy in North Carolina

With the help of the state's Solar Tax Credits and Renewable Energy Portfolio Standards, North Carolina has consistently led the Southeast states in installed solar capacity [16]. With 2,087 MW of solar energy currently installed, North Carolina is third in the country in installed solar capacity [16]. In 2015, North Carolina installed 1,134 MW of new solar electric capacity—the most behind California [16]. Figure 3 shows the North Carolina's Annual Solar Installation growth since 2006. The large increase in solar installations from 2014 to 2015 may be attributed to the expiration of North Carolina's Solar Tax Credit at the end of 2015. Future installed capacity will depend on whether or not the state's Solar Tax Credit is renewed.

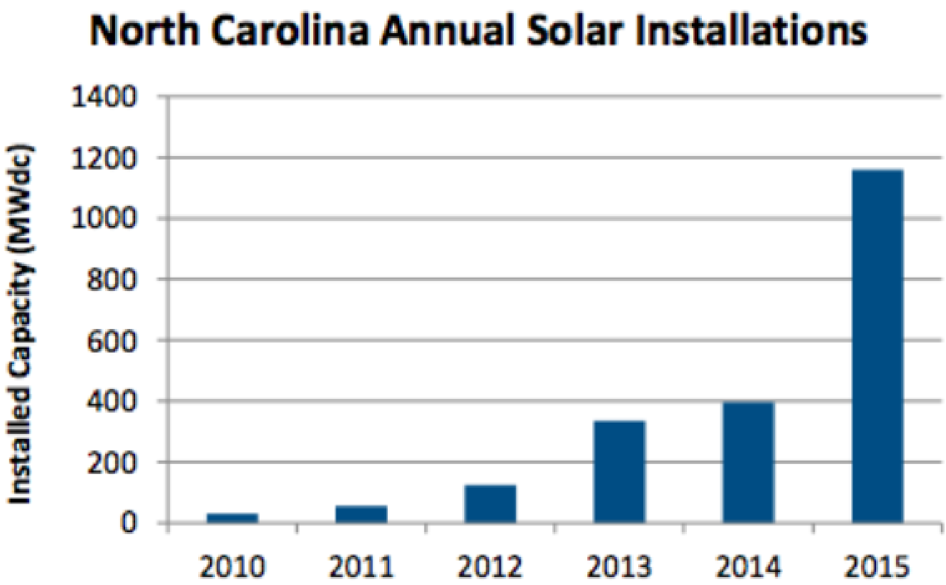

Fig. 3. North Carolina Annual Solar Installations [17]. This plot shows the annual amount of solar capacity installed in North Carolina.

Section 5: Solar Cell Efficiency

Through this study, solar cell efficiencies will be referenced. This refers to the portion of energy from the sun that the solar cell converts to electricity under "standard test conditions" (STC) [61]. The STC conditions have the solar cell surface aimed directly at the sun at approximate solar noon at the U.S. spring and autumn equinoxes [61]. Factors that impact the cell's conversion efficiency include wavelength of light, recombination of charge carriers, natural resistance to electron flow, temperature, reflection, and electrical resistance [60]. In 1961, William Shockley and Hans Queisser calculated a maximum theoretical efficiency for most solar cells, referred to as the "Shockley-Queisser limit" [61]. The Shockley-Queisser limit is 33.7% for a single p-n junction with a 1.34 eV band gap [62; 64]. Emerging thin films have various theoretical maximum efficiencies around this value, and these will be addressed later in the study. Lab conditions are carefully monitored to produce the highest possible efficiency when testing research cell efficiencies. As a result, actual solar modules tend to have lower efficiencies than their lab cell equivalents. This is taken into account during the energy output calculations.

Section 6: Traditional Solar Technology and Use

Globally, solar industry growth has been remarkable. On average, solar grew 23% per year from 19.6 GW (1 GW = one billion watts) in 2010 to 55.0 GW in 2015 [18]. Figure 4 shows the annual globally installed capacity each year and Figure 5 shows the cumulative global growth. Solar capacity has steadily grown in the United States from 3.4 GW in 2012, to 4.8 GW in 2013, to 6.2 GW in 2014 [18]. Currently, crystalline silicon panels dominate the global market, holding roughly 90% of the share, while thin film holds roughly the remaining 10% of the market in 2014 [18]. In fact, this 90% market share is an increase for crystalline silicon as Chinese manufacturers have ramped up production while reducing their costs and prices [18]. Advancements in thin film efficiency and cost should reshape the future solar market share.

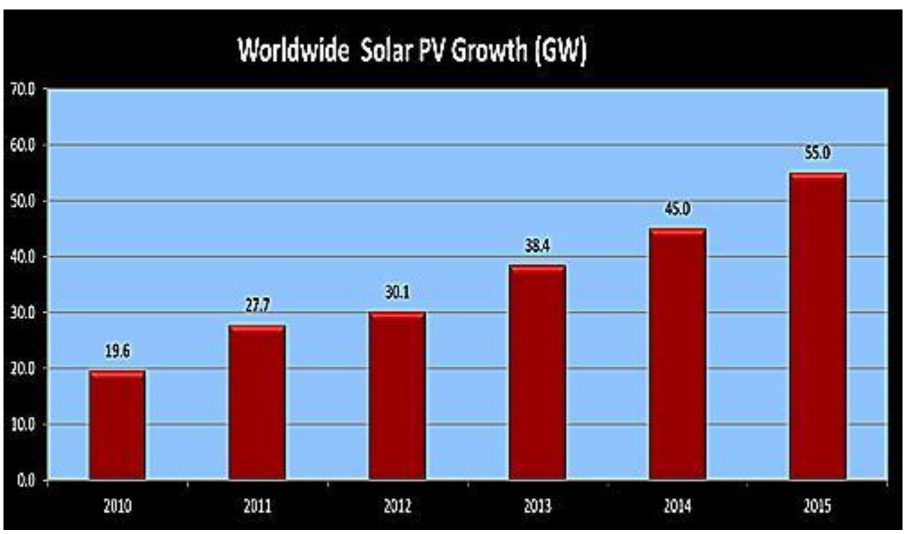

Fig. 4. Worldwide Solar PV Growth [18]. This plot displays the annual global solar growth.

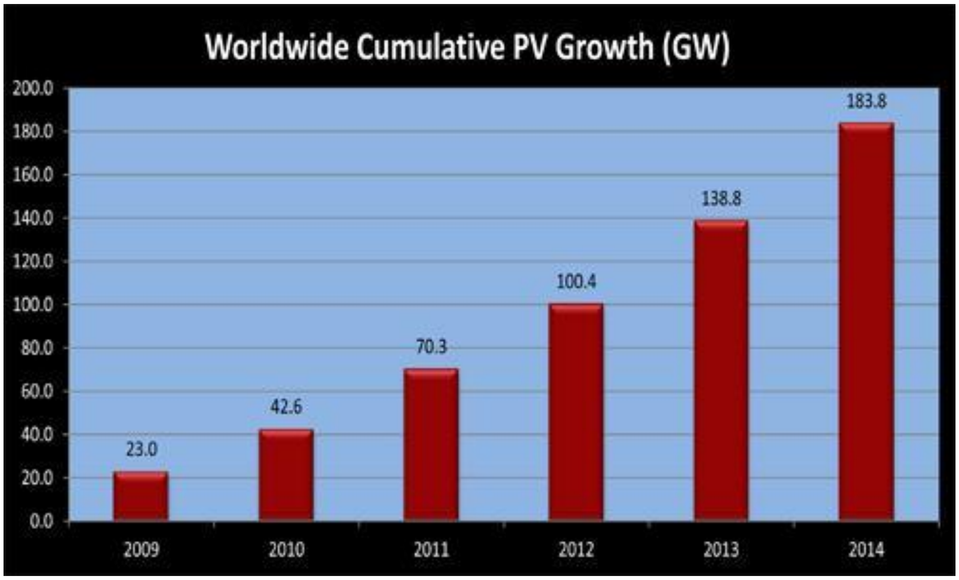

Fig. 5. Worldwide Cumulative PV Growth [18]. This plot displays the cumulative global solar growth.

As the most commonly used solar cells, crystalline silicon cells (c-Si) are stable with conversion efficiencies between 15% and 25% [19]. Because they have such widespread use and have proved reliable, the process technology for manufacturing panels is established with an enormous database [19]. Interestingly enough, c-Si does not absorb light well; thus, c-Si cells must be thick and rigid, resulting in the seven-layer cell shown in Figure 6 [19].

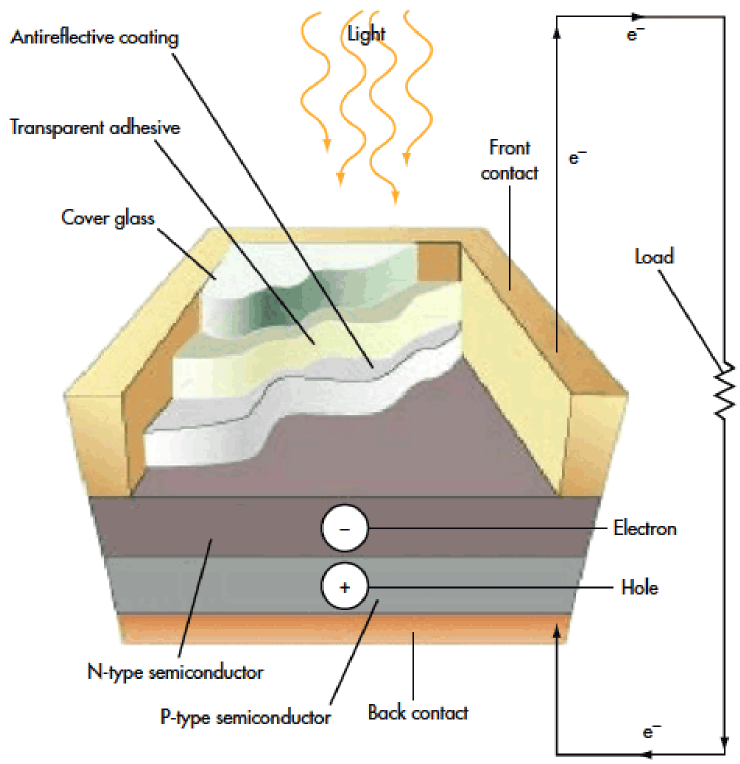

Fig. 6. C-Si Cell Diagram [19]. This image shows the seven layers that compose c-Si cells.

There are several types of c-Si cells; however, the most commonly used types are single crystal (monocrystalline) and multicrystalline (polycrystalline) silicon. Non-concentrated single crystal cells have achieved high record conversion efficiencies at 25.0% due to their high-grade silicon input [20]. Unfortunately, this makes them more expensive than multicrystalline cells, but they typically have a long lifetime of about 25 years [20]. Multicrystalline cells have a record conversion efficiency of 21.3%, and while they don't require high-grade silicon, they are more involved to make [19]. Because c-Si cells are a well-established and growing technology with decreasing costs, they will likely continue to dominate the future solar growth market, at least near-term, though other technologies are beginning to emerge. C-Si cells will be considered as one type of solar cell that could be used in the IPF solar system design.

Another traditional solar cell is multijunction cells. While multijunction cells have the highest conversion efficiencies of any technology with efficiencies higher than 30%—something no other solar cell has achieved—, they are more costly and best suited for large utility-scale applications and, consequently, are not covered in this study due to the commercial-scale size of the IPF [21]. This study focuses on the emerging new technologies rather than c-Si cells based on their potential for greater efficiency, lower costs, and widespread, revolutionary applications.

Section 7: The Future of Solar

While traditional solar cells have become more efficient and cost competitive with fossil fuels, new generations of solar cells are entering the scene. Though not currently as efficient and cost competitive with traditional solar cells, these second and third generation solar technologies are rapidly improving and provide more versatility for solar applications. Figure 8 below shows how these technologies are related to each other.

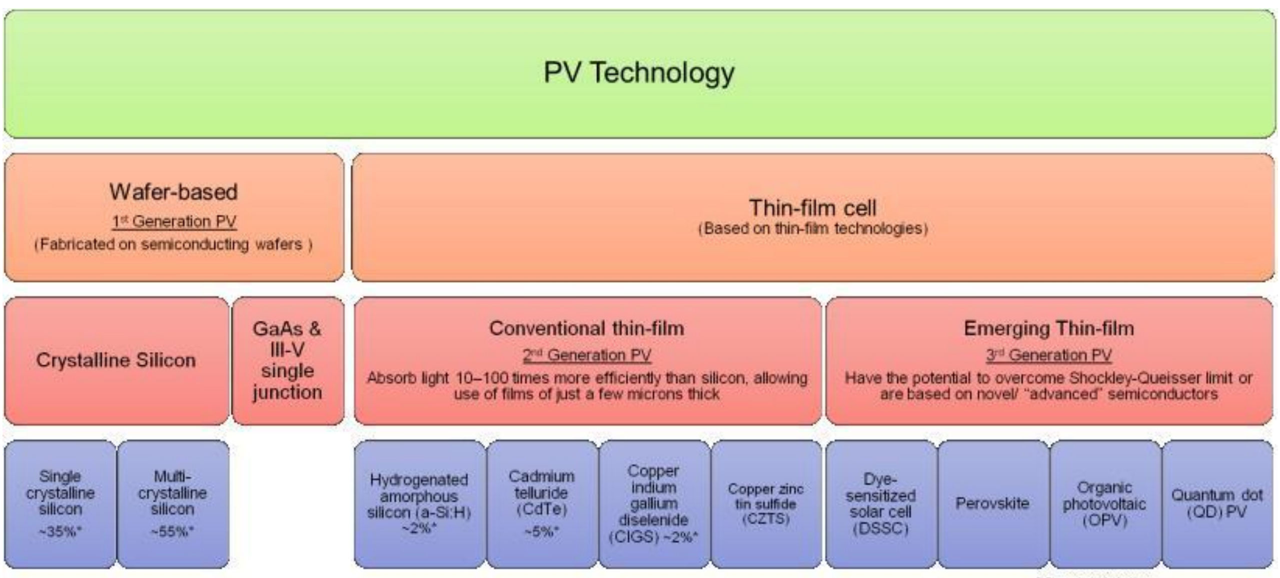

Fig 7. PV Technology Overview [26]. Tree diagram of overarching PV technology is shown.

NREL has compiled a Best Research-Cell Efficiency chart for all three generations of PV technology, showing how each technology's conversion efficiency has progressed over time. As seen in Figure 8, the chart is organized by color into five categories by overarching technology type—multijunction cells, single-junction GaAs, crystalline Si cells, thin-film technologies, and emerging PV—with more specific types of technology in each category. Updated whenever new records are set, the chart shows what laboratory, company, or organization that set the record next to each data point. This chart will be referenced and used throughout the paper to cite current and project future efficiencies.

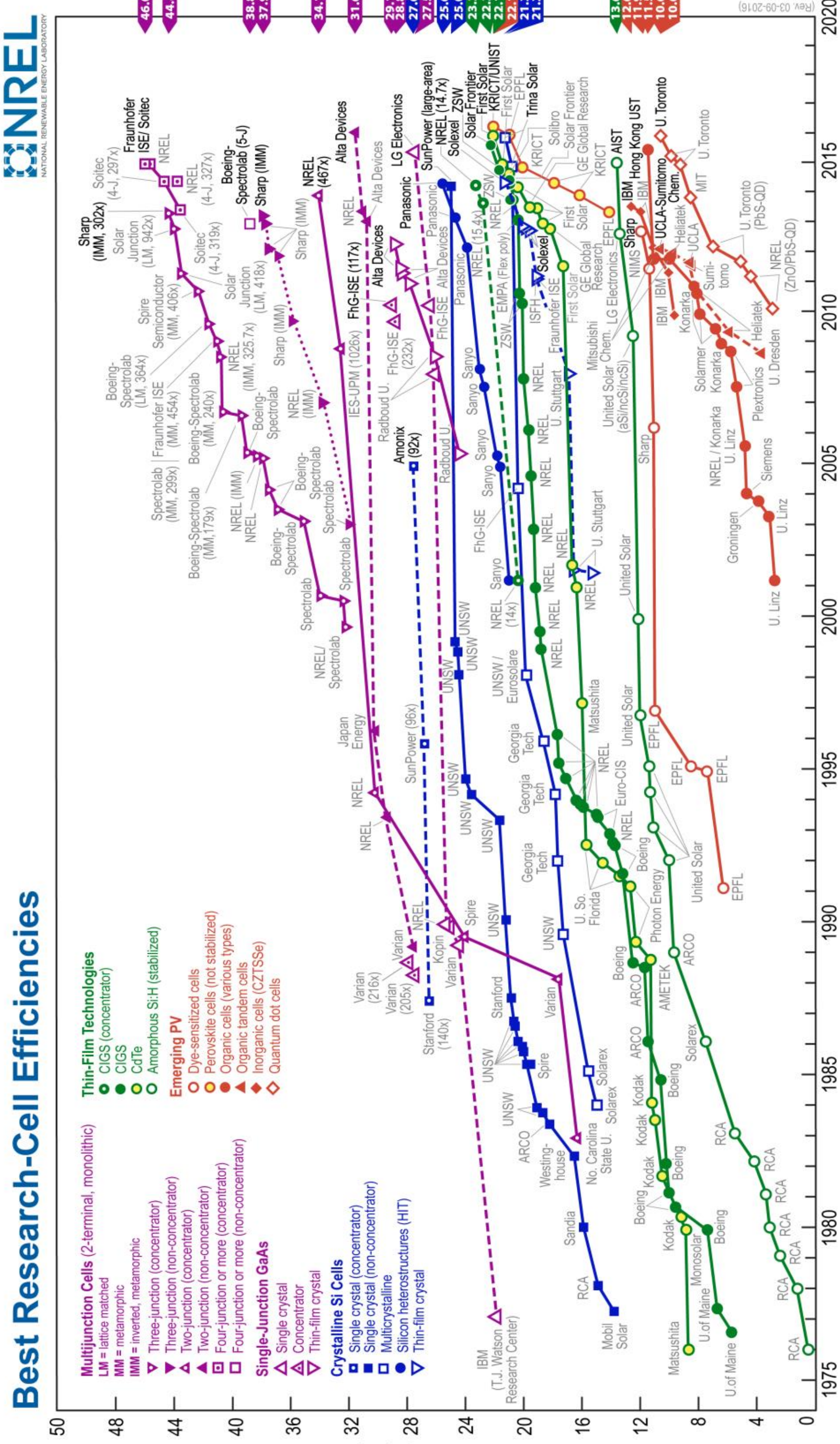

Fig 8. NREL Best Research-Cell Efficiencies [21]. Record efficiencies for various solar PV technologies are shown.

Section 7.1: Conventional Thin Film Photovoltaics

As a second-generation solar cell, thin film photovoltaics (TFPV) are one of the most promising solar technologies for the future thanks to their ability to absorb the solar spectrum much more efficiently than first generation solar cells while containing only a couple micrometers thickness of active materials [1]. Their manufacturing process is simple: deposit one or more thin layers of photovoltaic material onto a substrate. This is appealing because many types of materials, such as glass, plastic, or metal, can be used as a substrate. Given this simple manufacturing process, mass-production is easily achieved. In fact, First Solar—the largest thin film solar cell company in the world—can produce a complete thin film module that has been flash tested, boxed, and ready for shipment in less than 2.5 hours, resulting in a 2 GW annual production capacity [34; 35]. According to First Solar, a thin film module completes production about every 1.2 seconds. This ability to be mass-produced can potentially make thin film solar cells cheaper to manufacture than common crystalline-based solar cells [36].

In addition to its manufacturing simplicity, thin film also has many other advantages over crystalline-based solar cells, making the technology more versatile. Thin film ranges from a few nanometers to tens of micrometers thick; whereas, most crystalline-based solar cells are up to 200 micrometers thick [36]. This thin nature of the solar cells makes the modules very flexible and lightweight. This is key to their success because rather than needing a rigid glass backing, the solar cells could be placed on more malleable substrates, like plastic or foil, improving their functionality and increasing thin film's potential for new applications and innovations (Noorden, 2014). Those on flexible substrates can be cut to any shape and bent to suit the application. Additionally, in contrast to traditional modules comprised of pure silicon wafers, thin film technology can be made out of smaller amounts of impure materials (Noorden, 2014). The need for fewer materials to construct the solar cells also contributes to thin films lower manufacturing costs. Figure 9 shows the drastic decline in thin film manufacturing cost per watt since 2010. Other advantages include that shading and high temperatures do not greatly impact the performance of thin film cells and that thin film modules have a homogenous appearance, making them more visually appealing [36].

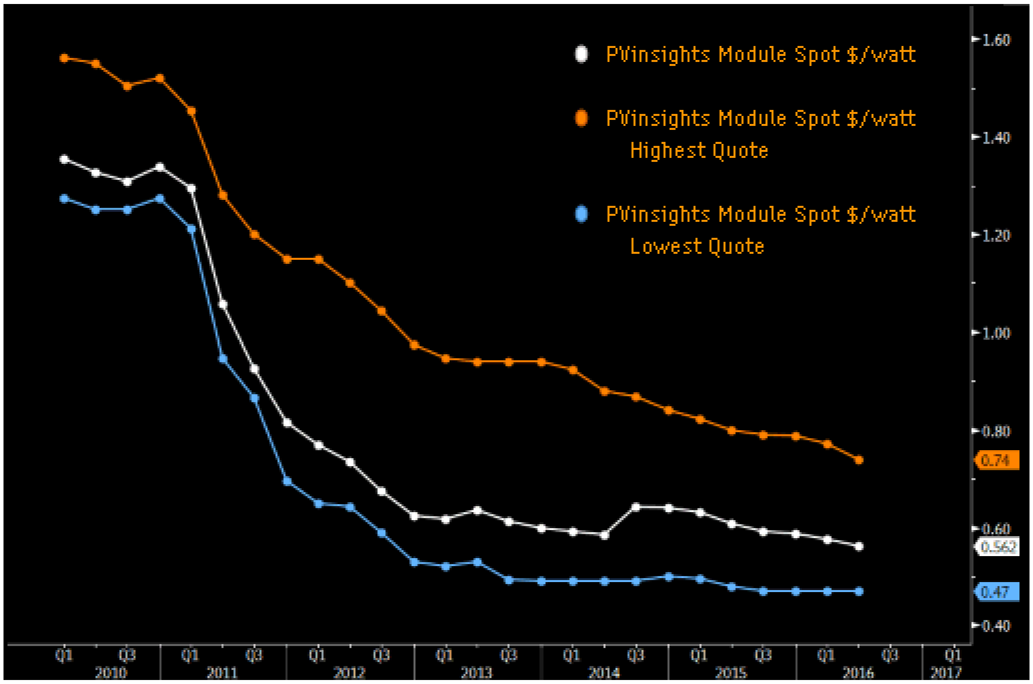

Fig. 9. Thin Film Module Spot Price [81]. Plot retrieved from Bloomberg showing a times series of the lowest, highest, and average thin film module cost per watt since 2010. Currently, the average is $0.562/watt.

The first thin film solar cells were amorphous silicon (a-Si). While a-Si solar cells comprise 32% of the thin film market, they still have low efficiency rates and are not making significant future progress; thus, they are not included in the study [37].

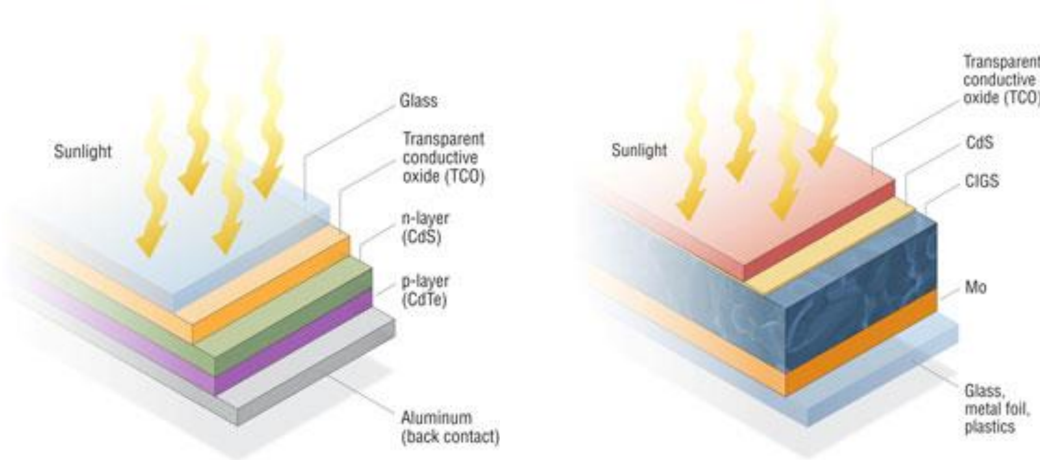

Fig. 10. CdTe (left) and CIGS (right) Composition [37]. Composition of CdTe and CIGS solar cells are shown.

Currently, two thin film technologies that dominate the market and show great promise are cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). When comparing the CdTe and CIGS, CdTe is known for lower manufacturing costs while CIGS has slightly higher efficiencies [37]. Because of their low manufacturing costs, CdTe solar panels can surpass the cost-efficiency of mono- and polycrystalline silicon solar panels in the multi-kilowatt portion of the market in higher temperatures [37]. Additionally, CdTe and CIGS have faster energy payback times (EPBT) —the amount of time it takes the panel to offset the energy costs of producing and installing it—than silicon panels. It takes CdTe 0.8 years to offset the energy required to produce it and 1.4 years for CIGS [78]. However, there are drawbacks to CdTe. As indicated by its name, CdTe modules rely on cadmium—a heavy metal and a potential bioaccumulating carcinogen [37]. Although the cadmium should be safely contained within the solar panel for the duration of its lifetime, recycling the cadmium could be hazardous and costly [37].

CIGS-based solar cells are highly efficient—holding the record within thin film technologies for efficiency at 22.3% for research-cells (CdTe is 22.1%)—, but require more expensive processing, although the manufacturing cost is decreasing [21]. Additionally, CIGS has more variety in substrate materials—in addition to glass, they can be backed by flexible materials, such as foil or plastic. In fact, CIGS solar cells created at Empa, the Swiss Federal Laboratories for Materials Science and Technology, that set the record efficiency for CIGS and thin film as a whole at the time in 2013 were backed on flexible polymers, showing that flexible substrates can be successful [37]. While CIGS requires less cadmium than CdTe, one concern for the future of CIGS is how the scarcity and high price of indium—a key component of CIGS cells—will impact its ability to compete with other technologies as its market share increases [1]. If current rates of production continue, sources of indium will be depleted within a decade; however, reducing the solar cell's thickness without significantly reducing efficiency would, in turn, reduce the importance of indium in the composition of the cell and help avoid the effect of cost and scarcity of indium [38; 1]. Overall, according to Global Business Intelligence Research, CIGS technology is projected to emerge as the thin film market share leader, with 40% of the market by 2020 [39].

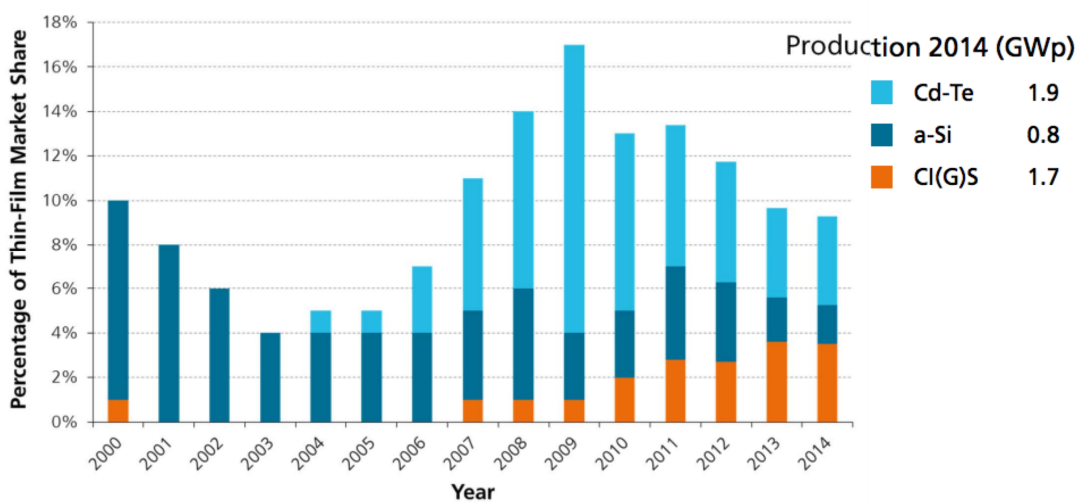

Fig. 11. Market Share of Thin Film Technologies [59]. The percentage of total global PV production in GW for each type of thin film technology from 2000 to 2014.

Three manufacturing companies are currently leading the way in the thin film solar cell sector: First Solar, Solar Frontier, and Hanergy Solar [35]. The module capacity growth in MW for each company since 2006 is shown in Figure 12. Prior to 2008, annual global solar installations were less than 5,000 MW but have rocketed to 40,000 MW today and are still increasing [35]. Price reductions have resulted from the consolidation of solar cell and solar panel suppliers, and First Solar, Solar Frontier, and Hanergy Solar have risen to the top [35]. Hanergy is a Chinese company that has bought out its competition, including Miasolé, Global Solar, and Solibro [35]. The Japanese company, Solar Frontier, has survived the competition because of a large and protected home market; however, it will need to expand into other markets soon to stay successful [35]. Lastly, the U.S. company First Solar has become the largest thin film solar company in the world through vertical integration; thus, they have increased control over the value chain, higher margins, better control of cost, smoother operations, technology security, and customer ownership [35]. Increased frequency of vertical integration, acquisitions, and third-party-owned solar should increase profitability in the solar industry, as prices slowly rise from there being fewer competitors [35]. First Solar specializes in CdTe technology, while Solar Frontier and Hanergy specialize in CIGS.

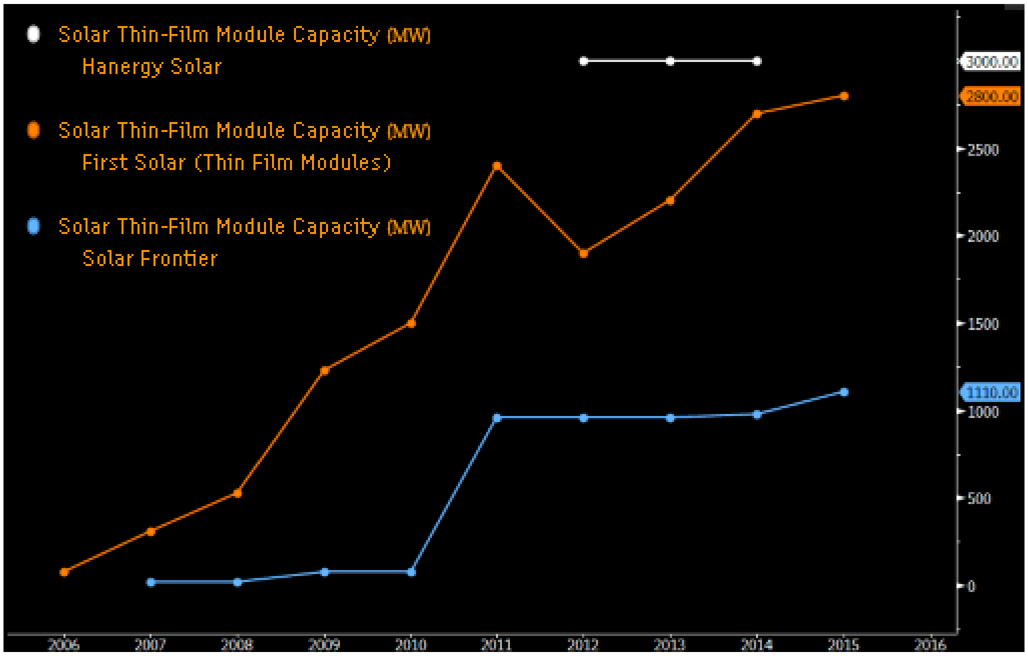

Fig. 12. Thin Film Module Capacity per Company [81]. Plot retrieved from Bloomberg showing a times series of the module capacity in MW held by each company.

While thin film technology has progressed rapidly in recent years, continued improvements are needed before widespread adoption over crystalline-based solar cells occurs. According to the 2015 IHS Marketbuzz Annual Report, the thin film module production market share within global solar PV manufacturing is projected to dip from 8% in 2014 to 7% in 2015 and remain at 7% through 2019 [40]. Annual production of a-Si modules is projected to drop to below half its 2014 level, but total global thin film PV capacity is expected to increase to 177% times its 2014 level by 2019 [40]. Because of this, IHS Technology solar industry analyst, Susanne von Aichberger, predicts that CdTe and CIGS technology segments will drive thin film growth [40]. This prediction is echoed by James Watson, chief executive officer of the European Photovoltaic Industry Association (EPIA), who says CdTe will remain prominent within US, but CIGS will gain more share globally as the technology matures [40]. The Marketbuzz Annual Report pinpoints CIGS-based utility scale and rooftop projects in both emerging and established markets as the key contributor for keeping thin film market share from decreasing, while CdTe market share stays about the same [40]. With the innovations of First Solar, Solar Frontier, and Hanergy, CdTe and CIGS thin film solar cell technologies are steadily improving in both efficiency, cost, and applications; thus, they are included in this study.

Section 7.2: Emerging Thin Film

The following sections analyze third generation solar cells or emerging thin film technologies.

Section 7.2.1: Quantum Dots

Quantum dots are miniscule, man-made semiconducting nanocrystals that show a lot of potential for highly efficient solar cell applications as the research continues to rapidly evolve [29]. For being 10,000 times narrower than a human hair, quantum dots are surprisingly powerful [41]. Depending on their size and shape, quantum dots can convert light into most colors in the visible light spectrum very efficiently; therefore, the color of light given off by a quantum dot can be controlled by changing its size [41]. Quantum dot technology can be used in applications such as image sensors, optical communication, transistors, lasers, LCD displays, and, most importantly to this study, highly efficient solar cells [29].

Quantum dots have a number of properties that make them very appealing to PV applications: high absorption, tunable band gap, broader coverage of the incident spectrum, low production costs, high theoretical efficiencies, and application flexibility [43]. First, quantum dots are commonly made of materials such as cadmium selenide, lead sulphide, cadmium sulphide, and indium phosphide, which typically result in higher orders of absorption than silicon and other thin film materials [43]. Because this property of higher absorption, quantum dots can significantly reduce the absorption materials needed, which is important given their limited nature [43].

Secondly, one advantage to quantum dots is that their band gap—energy range where electron states cannot exist—can be tuned by changing the nanoparticles' size [29]. Given the right sizes and combination of quantum dots, broader coverage and absorption of the solar spectrum can be achieved—something that is challenging and more expensive with conventional solar [43]. Because about half of the sun's energy is infrared radiation, this ability to relatively inexpensively absorb underutilized parts of the solar spectrum makes quantum dots solar cells attractive [29]. Unlike traditional solar cells, quantum dot solar cells created by Solterra Renewable Technologies Inc. can absorb energy during the day and night because they can absorb power from the ultraviolet, visible, and infrared lighting ranges [42]. Power absorption 24/7, rather than just during daylight hours, is a significant asset; however, their conversion efficiencies at night are lower.

Additionally, quantum dot solar cells are inexpensive to produce. Quantum dots are not as sensitive to temperature conditions than existing technologies, making them cheaper to produce and manufacture [44]. Multi-junction solar cells with a series of differently sized quantum dots absorbing different areas of the solar spectrum would drastically reduce the cost and complexity of manufacturing solar cells [29]. An even cheaper option would be single-junction quantum dot cells, where the band gap could be tuned to absorb abundant, underutilized infrared light [29]. However, as a whole, quantum dot manufacturers are able to produce a high volume of product for a low cost.

Currently, the conversion efficiency of quantum dots is lower than any other emerging PV; however, they have very high theoretical efficiency rates up to 66% and have shown significant growth in the past 5 years [71]. While the current research cell efficiency is currently only at 10.6%, research and development has been rapidly improving since its birth in only 2010

[21]. If quantum dot efficiencies continue to steadily improve, then cheap and efficient quantum dot solar cells could create a winning combination for the future of solar power.

Finally, quantum dot solar cells have the potential for flexible and easy to integrate applications. Researchers at the University of Toronto have made significant progress manufacturing and testing colloidal quantum dots (CQD) [46]. Recently, they have developed a new kind of CQD that resists binding with oxygen atoms they encounter. Previously CQD would bind with oxygen atoms they came in contact with and lose performance as the dots lost electrons; thus, the only way to integrate CQDs into materials without exposing it to air was through an inefficient and expensive procedure called batch processing (Lavar, 2014). However, with the development of a new type of CQD n-type lead-sulfide material that does not bind with oxygen, spray-on solar cells are possible [46; 29]. SprayLD is a system built from inexpensive and readily available components that sprays CQDs onto any surface, such as car roofs or outdoor furniture, without major loss of performance of the cells [46]. Currently, such technology has only achieved an efficiency of 7.2%, but quantum dot solar technology is attractive and advancing rapidly [46]. Quantum dot - dye-sensitized solar cells (QD-DSSC) are also inexpensive to produce and could achieve efficiencies above 33.7% - a winning combination [46]. The versatile nature of quantum dot applications makes it an interesting and unique technology to include in this study.

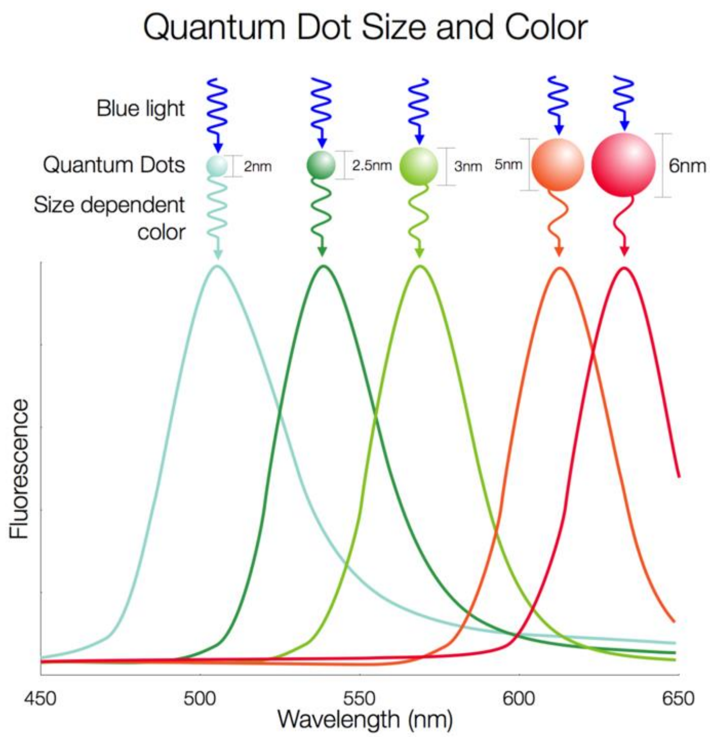

Fig. 13. Quantum Dot Size and Color [41]. Colors blue light it converted to depending on quantum dot size.

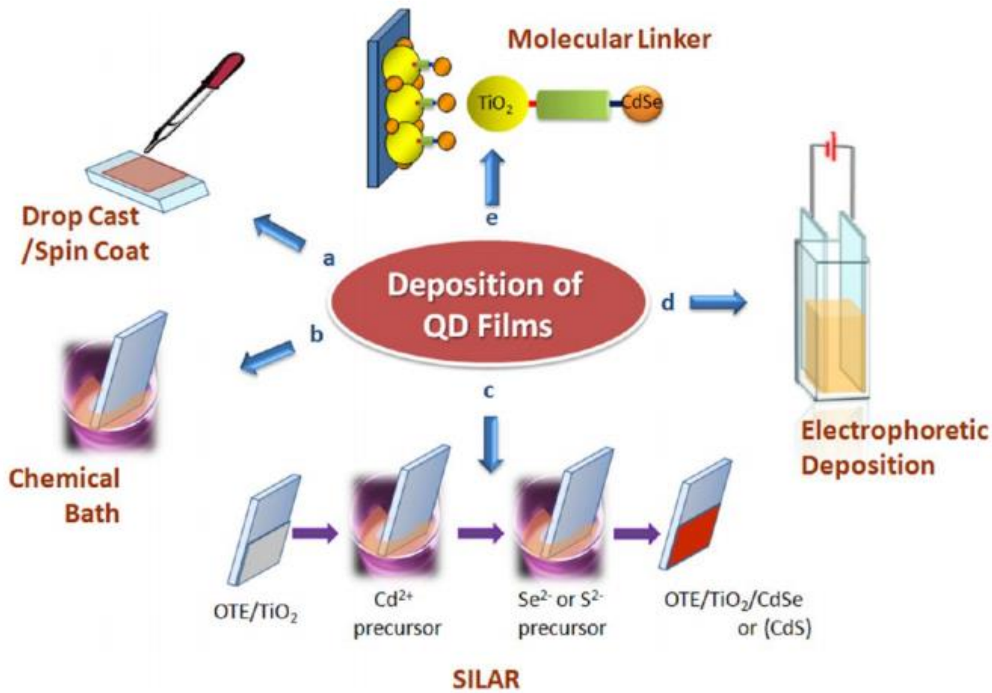

Fig. 14. Illustration of quantum dot film deposition on electrode surfaces [47]. Methods of quantum dot film deposition are a) drop casting or spin coating, b) chemical bath deposition, c)

Successive Ionic Layer Adsorption and Reaction (SILAR) method, d) electrophoretic deposition, and e) a bifunctional linker approach.

Section 7.2.2: Perovskite Solar Cells

An emerging technology that converts light energy directly into electricity has made remarkable progress in conversion efficiency and cost since its arrival on the solar scene in 2009: perovskite solar cells. The term “perovskite” is used to reference a particular salt-like, mineral crystalline structure [31]. Most commonly, perovskites are composed of calcium titanate, which has an ideal structure for solar conversion [28]. When perovskite materials were first used in solar cells in 2009, they had a conversion efficiency of 3.8%; however, the conversion efficiency has dramatically improved quickly over the years since [26]. Trina Solar achieved a conversion efficiency of 22.1% in 2015, and unlike some solar technologies like silicon-based PV that have stagnated, this rapid increase is expected to continue [21].

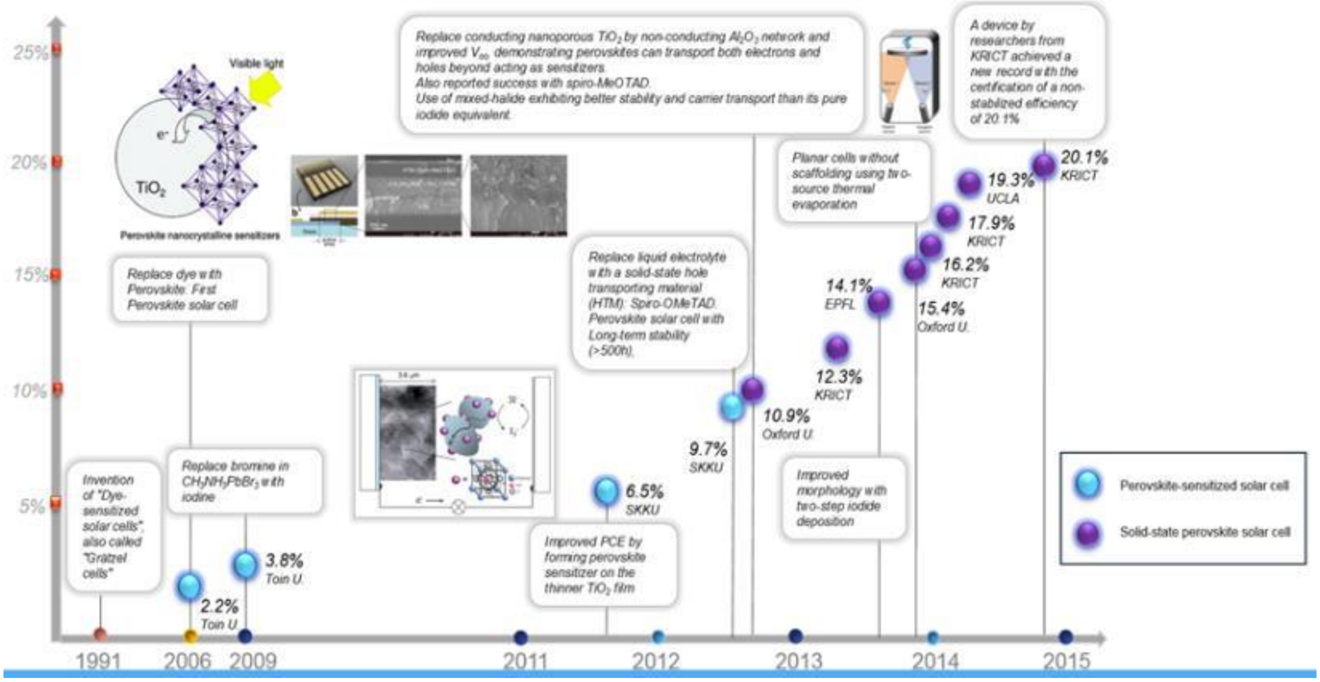

Fig. 15. Perovskite Solar Cell Conversion Efficiency Timeline [26]. This figure shows the accelerated conversion efficiency growth of perovskite solar cells by 18.3% from when perovskite materials were first used in solar cells in 2009 to 2015.

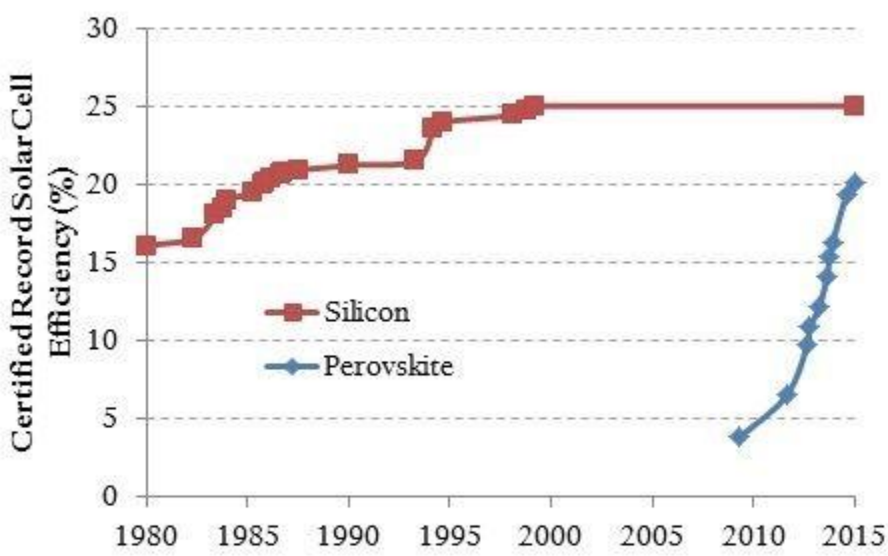

Fig. 16. Record Efficiency of Silicon and Perovskite Solar Cells [27]. Record conversion efficiency growth of perovskite solar cells compared to silicon solar cells is shown.

Not only are perovskite solar cell efficiencies improving, but their production costs are also already impressively low and expected to continue to decrease. Perovskite cells are improving faster than any other solar technology and are already much cheaper to produce than traditional panels because they require very low energy cost, unsophisticated equipment, and few steps in production [29]. As a result, the cost of clean electricity could drastically drop if perovskite cells are commercialized [29]. In 10 years, costs for perovskites could fall well below where costs for silicon will be after the same time period [31]. It is also important to consider environmental costs, such as carbon emissions saved and the amount of energy consumed during the panels cradle-to-grave life. Typical silicon solar panels usually have an EPBT of two to three years [29]. In contrast, Northwestern University scientists determined that perovskite solar cells' EPBT is between two to three months, which is the quickest EPBT of any commonly available solar cell [29]. Unlike silicon panels that require large energy inputs to manufacture due to the need for specialized high-temperature furnaces, perovskite manufacturing can be done with small energy inputs [29].

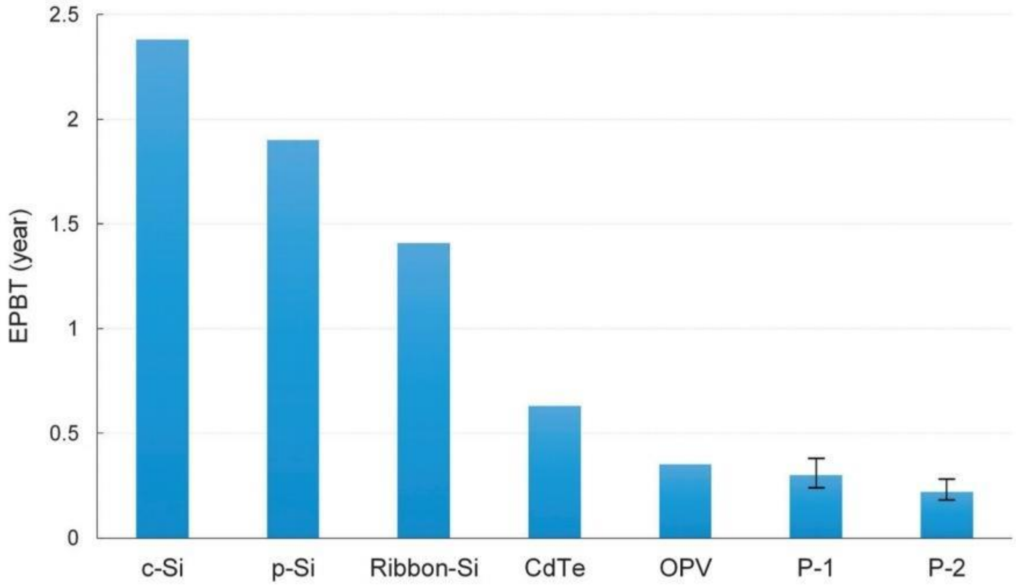

Fig. 17. Energy Payback Time (EPBT) for Various PV Modules [32]. This plot displays the EPBT, including cost of production, for some best-known types of solar cells, where P-1 represents the TiO2 perovskite module and P-2 represents the ZnO perovskite module.

While their efficiencies and costs of production make perovskite solar cells very appealing, there are still technological improvements that must be made in order to make them practically feasible. One major downside to perovskite cells is that they are partially composed of organic molecules that will degrade quickly upon exposure to the elements; therefore, perovskite cells are unable to brave the environment, especially highly humid conditions [29; 30]. As a result, they have a very short lifetime of about 2 years [32]. This makes the overall impact on CO_2 emissions for perovskite cells higher than traditional silicon-based cells that last around 20 years [29]. However, incorporating a protective layer to make the system impervious to moisture and humidity that does not reduce the cell's conversion efficiency into the cell's design could lengthen their lifetime [29; 30]. Some researchers believe a solution that does not diminish the efficiency of the cell could be reached within two years [29].

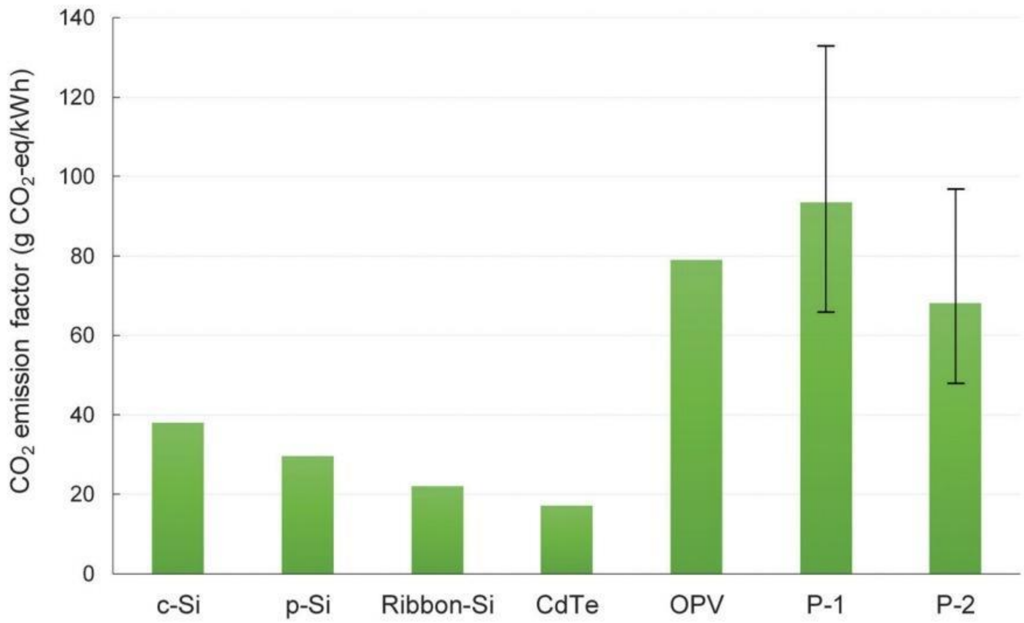

Fig. 18. Carbon Dioxide Emission Factor for Various PV Modules [32]. This plot displays the CO_2 emission factors for some best-known types of solar cells during module construction, where P-1 represents the TiO2 perovskite module and P-2 represents the ZnO perovskite module.

Another concern with perovskite solar cells is their reliance on the potentially toxic mineral lead to absorb sunlight and improve efficiency [29]. However, researchers in both the U.S. and U.K. think they have found an alternative to lead: tin. In addition to being non-toxic, tin is inexpensive and abundant, which could drive down costs, make the cells easier to mass produce with less intensive energy input requirements, and alleviate supply chain concerns [28]. However, prototypes of solar cells using tin instead of lead experience much lower conversion efficiencies around 6% with the potential to reach only 20% as the technology progresses [28]. This raises questions as to whether or not tin is an adequate substitute for lead in perovskite solar cell production, but if the costs are low enough, it may be able to replace lead.

There are differing opinions on how close researchers are to definitively solving these issues. Some researchers say a breakthrough could happen within two years, but others say it could be longer or never because of the "barrier versus bridge" dilemma and applied research has less notoriety than research that sets new record efficiency [27]. Current technology can either act as a bridge to new technology or as a barrier to its acceptance [27]. Silicon-based technology may be a barrier to thin film technology, as manufacturers want to recoup their investments; however, conventional thin film is a bridge for the emerging thin film technologies discussed in this section. The future success of perovskite solar cells will depend on if people in the public and private sectors can work together to solve the application issues. This study will examine where perovskite cells will be in the coming years, and if they are a viable option for powering the IPF.

Section 7.2.3: Organic Photovoltaics

Another promising emerging type of PV technology is organic PV's. Organic PV's have many properties that make them appealing for solar applications: ability to generate electricity at any sun-angle, mass-producibility, low environmental impact, flexible substrates, and lightweight structure [48]. Organic solar cells are composed of two plastic polymer, semiconducting layers that absorb light photons of generate electricity [22]. An electric current is produced as electrons that are knocked out of the polymer atoms, as a result of the absorbed proton's presence, move throughout the material [22]. The manufacturing process for organic PV's is significantly less costly than for conventional inorganic PV's and can take advantage of state of the art printing techniques [24]. Eventually, organic PV's could be produced on a roll-to-roll process, much like newspaper printing, allowing them to be cheaply mass produced [33]. Because of their flexibility, lightweight structure, and colored or transparent nature, organic PV's could be used for new solar cell applications that are not possible with rigid silicon-based solar cells. This includes integrating solar cells into the structure of a building or object, such as a car. In fact, the German companies BASF and Daimler have partnered together to create a concept vehicle called Smart Forvision that features a transparent organic solar cell roof to maximize energy efficiency in the car [23]. The development of solar technologies that could be cheaply and easily integrated into objects with high solar energy potential, such as buildings, cars, and roads, would revolutionize the energy market.

Fig. 19. Smart Forvision Conceptual Design by BASF and Daimler [23]. This image displays the conceptual design for a car utilizing transparent organic solar cells in the roof to improve the vehicle's energy efficiency.

However, like the other technologies discussed, organic PV's have their disadvantages. The main downside to organic PV's is that their record conversion efficiency is only 11.5% [21]. Organic PV advanced quickly technologically from 2008 to 2011, but it had not shown major increases in record efficiencies since its record efficiency was 11.1% in 2011. Recent progress was made in late 2015 when Hong Kong UST achieved a new record efficiency of 11.5% [21]. However, according to the U.S. DOE, the theoretical maximum efficiency for organic PV modules is only 14% [65]. This is not competitive with current solar technology and the theoretical maximum efficiencies for the other technologies studied; therefore, organic PV will no longer be considered in this study.

Section 7.2.4: Dye-sensitized Solar Cells

Dye-sensitized solar cells (DSSC) are another third generation solar cells that have been researched since 1988 but with minimal growth since 1997 [21]. Despite improving to a conversion efficiency of 11.9% around 2012, DSSC will not be included in this study due to its stagnated improvement and therefore limited potential compared to other thin film technologies.

CHAPTER 3: METHODOLOGY AND DATA AND ANALYSIS

Section 1: Location Selection

The first task completed in this study was choosing a location or building site for which to create the conceptual design. The basic criterion for building selection were

I. affiliation with UNC,

II. planned retrofit, re-roofing, or new construction within the next five to ten years, and

III. solar feasibility based on its building orientation and its surroundings.

After considering several locations for the conceptual design, including the Friday Center, Quail Hill, Carolina North, Woollen Gymnasium, Morehead City Field Site, and Outer Banks Field Site, the newly planned construction of a Football IPF was selected. The reconstruction project was brought up as a possibility during a meeting with the Assistant Athletic Director of Facilities, Mike Bunting. Given that the building will serve as a practice site for the football program, the location met criteria I. With the new building already approved, the design process in motion with the engineering company HOK, and construction originally planned in 2020, the location also met criteria II; however, the timeframe for the construction project shifted forward to breaking ground in 2017 and completion in 2018. Despite this change, the location is still ideal for the project and the PV system could be added to the roof after construction. After a trip to the location site to examine if the surroundings and building orientation were conducive to solar, criteria III was met. As shown in Figure 20, there are no surrounding trees or tall buildings nearby that will shade the new IPF's roof from the sun, due to its tall height. It met the criteria and also struck a personal interest, given its status as an athletic facility.

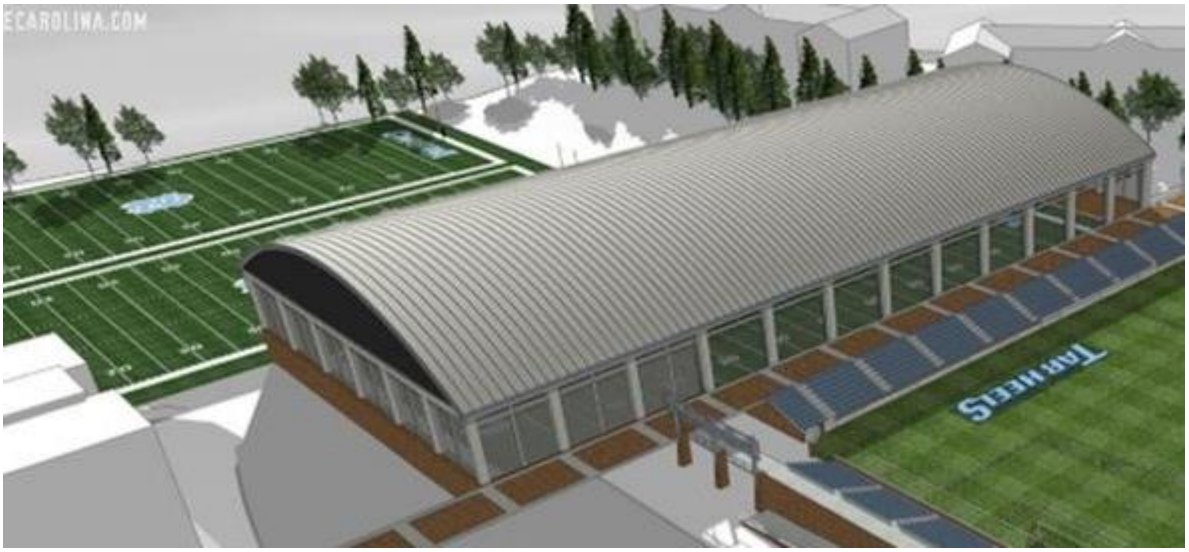

Fig. 20. Aerial Perspective of the IPF and its Surrounding [52]**.** Conceptual design of the IPF, showing its vaulted roof with no concerns of shading from its surroundings.

Section 2: Site Analysis

After choosing a location for the study, an analysis of the building was conducted to determine the layout of the roof, average irradiance the roof will receive, and expected energy usage within the IPF, in order to ultimately calculate the expected output from various PV roof systems based on projected efficiencies and to what extent the PV system will serve the building's energy demands.

The IPF is a unique building for several reasons. Unlike most non-residential buildings, the IPF is a large and open space, as shown in Figure 21. Its primary function is to act as a normal football field, but indoors; thus, electricity demand within the building will be driven mostly from lighting and heating/cooling. Additionally, its arched roof (commonly referred to as a "vaulted roof") is nontraditional, providing both benefits and challenges for solar system analysis and application.

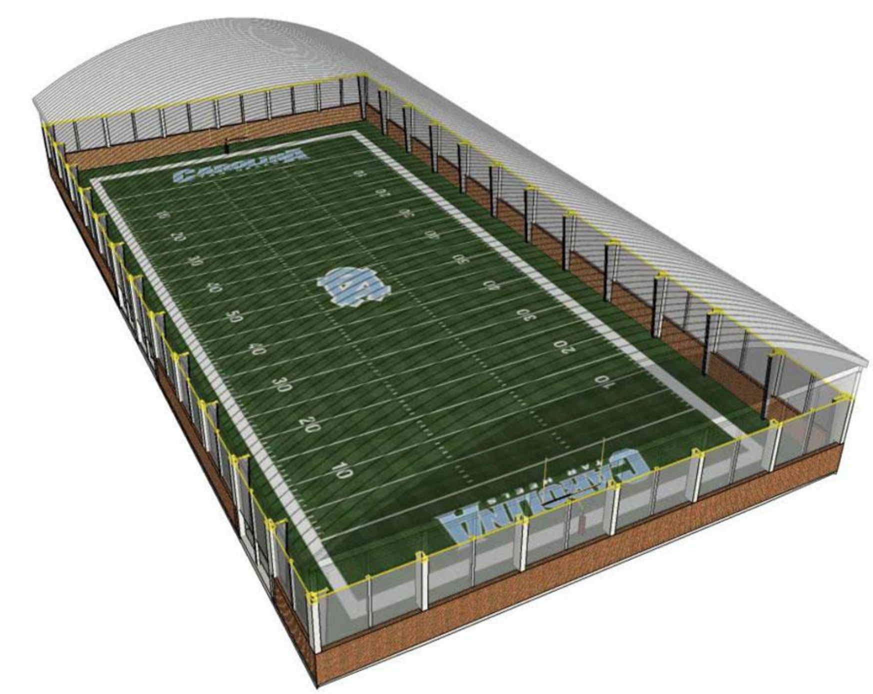

Fig. 21. Aerial View of Inside the IPF [52]. Conceptual design of the IPF, showing the interior space is just a football field.

Section 2.1: Area and Volume of Roof Space

To help calculate potential roof output, the area of the roof was calculated by multiplying ά the roof arc length by the width of the building. The dimensions of the building are shown in Figure 22. Given a wall height of 41’-0”, a peak roof height of 76’-6”, and a building width of 190’-0”, the arc length of a circular segment, **s**, was calculated from circular segment geometry. The circular segment dimensions and symbols are shown in Figure 23. Based on a segment height, **h**, of 35’-6” and a chord length, **c**, of 190’, the arc length was calculated to be 207.22’ from the following equation:

$$s = \frac{\alpha}{180}\pi R = \theta R = \arcsin\left(\frac{c}{h + \frac{c^2}{4h}}\right)\left(h + \frac{c^2}{4h}\right)$$

Consequently, the area of the roof is 82,888 ft^2 or 7700 m^2 from multiplying 190’ by 207.22’.

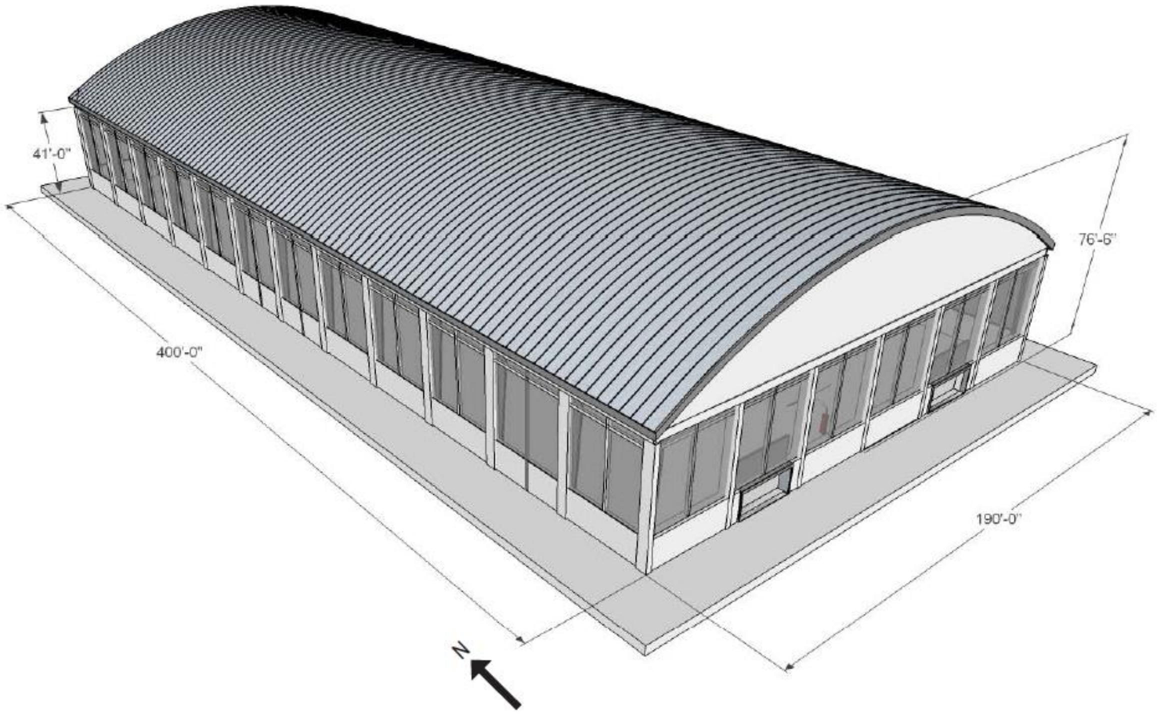

Fig. 22. Aerial Perspective of IPF. HOK's design of the IPF, showing dimensions of 400' by 190' with a wall height of 41' and peak roof height of 76'-6".

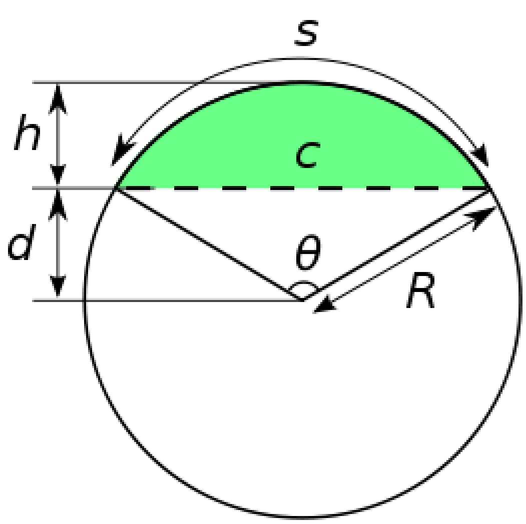

Fig. 23. Circular Segment Dimensions [50]. Diagram of a circular segment (in green), where **R** is the radius of the circle, **ϴ** is the central angle in radians, **c** is the chord length, **s** is the arc length, **h** is the height of the segment, and **d** is the height of the triangular portion. Additionally, the central angle can be measured in degrees, represented by **α**.

Next, the volume of the vaulted roof was calculated in order to calculate the building's total volume. This was done by multiplying the area of the circular segment face connecting the roof to the wall by the length of the building, 400'. The following equation was used to calculate the area of the circular segment, equivalent to the shaded green portion of the circle in Figure 23 with a chord length of 190'-0" and a segment height of 35'-6".

$A = \frac{R^2}{2}(\theta - \sin\theta)$, where $R = h + d = h/2 + c^2/8h$ and

$$\theta = 2\arctan\frac{c}{2d} = 2\arccos\frac{d}{R} = 2\arcsin\frac{c}{2R}$$

Using these equations, the radius of the circle, **R**, is 145 ft, the central angle, **ϴ**, is 1.43 radians (82 degrees), and the area of the circular roof segment is 4,615 ft^2. Multiplying this area by the length of the building results in the volume of the vaulted roof—1,847,940 ft^3. Adding this to the volume of the rectangular prism portion of the building, 3,116,000 ft^3, results in a total volume of 4,963,940 ft^3 or 140,563 m^3.

Section 2.2: Irradiance Analysis

In order to calculate the expected energy output, the expected solar irradiance—solar power per unit area—of the roof was calculated based on solar energy data for Chapel Hill, compiled by Solar Energy Local, and a study on absorbed solar radiation of vaulted roofs compared to flat roofs.

Solar Energy Local collects data for solar radiation measured in three ways: direct normal irradiance (DNI), average tilt at latitude (ATaL), and global horizontal irradiance (GHI). Each method measures the total amount of solar radiation received per unit area, but with a different orientation of the receiving surface to the sun. DNI has a surface always positioned perpendicularly to the incoming sun rays, and ATaL has a surface tilted toward the equator at an angle that is equal to the current latitude, often producing optimal energy output [51]. For GHI, the surface is always positioned in a horizontal manner—much like a flat roof. The different average monthly values for each type of measurement are displayed in Figure 24. As shown, GHI has the largest seasonality within the data, with higher amounts of irradiance in the spring and summer than in the fall and winter. In this analysis, the monthly GHI values for Chapel Hill were used because they represent irradiance of a flat roof, which can be related to radiation absorption of a vaulted roof.

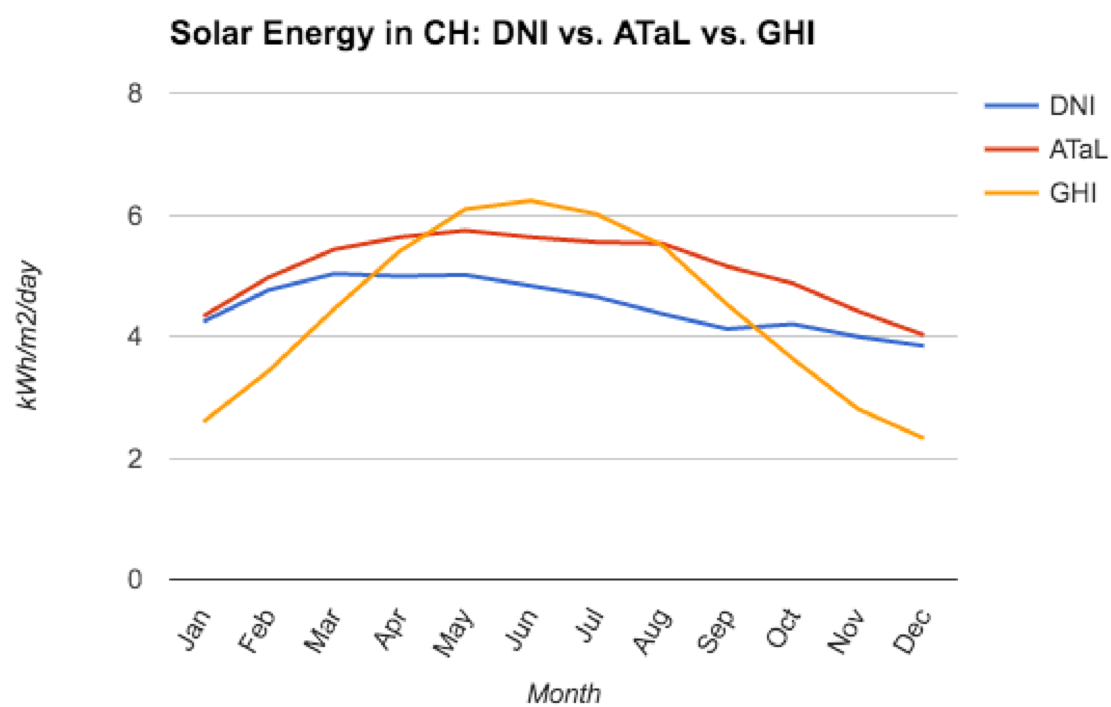

Fig. 24. Various Monthly Solar Energy Values in Chapel Hill [51]. This chart depicts the monthly trend for solar radiation in kilowatt hours per square meter per day (kWh/m^2/day) for DNI, ATaL, and GHI surface orientations.

After collecting the global horizontal irradiance data for Chapel Hill, this flat roof irradiation was converted to a vaulted roof irradiation based on conversion ratios calculated by the Desert Architecture Unit of the J. Blaustein Institute for Desert Studies at the Ben-Gurion University of the Negev in Israel. The resulting ratios from the study were calculated to take into account angular dependence of absorption and solar geometry. The GHI irradiance in CH was converted to vaulted roof irradiance by using the ratios found in the study, shown in Table 1.

First, it is important to define the parameters and terms used in the vaulted roof analysis and how they relate to this study. A "south-north facing vaulted roof" describes a roof that curves from south to north and has flat planes on the east and west ends. Figure 25 shows a diagram of a south-north facing vaulted roof on a coordinate axis. Figure 26 depicts the spatial orientation of the IPF. As shown, south-north facing best describes the orientation of the roof, so that assumption will be carried out throughout the study.

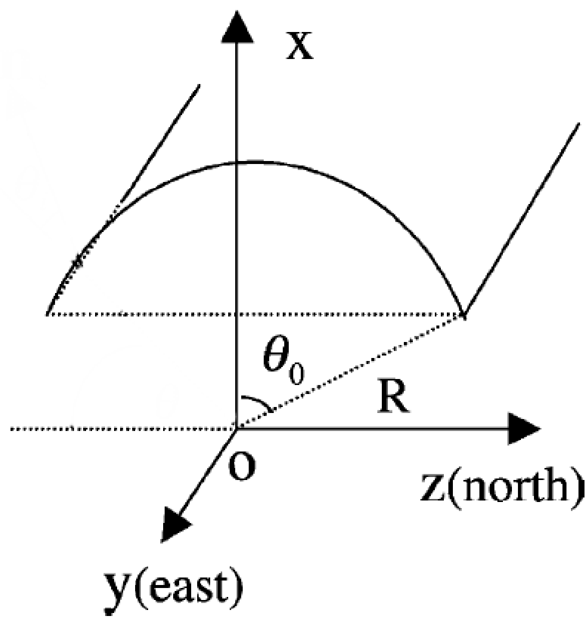

Fig. 25. South-North Facing Vaulted Roof [53]. Illustration of the orientation of a south-north facing vaulted roof, where **R** is the radius of the circular segment and **Θ_0** is the half angle of the central angle in degrees.

Fig. 26. Aerial View of IPF Spatially [52]. This map shows the roof orientation coincides most closely with a south-north classification.

Similarly to the circular segment, **R** represents the radius of the circle. In contrast, $\mathbf{\Theta_0}$ represents the half angle of the central angle in degrees, rather than in radians. Given that the central angle of the roof is 82 degrees, the half angle is 41 degrees. $\boldsymbol{\lambda}$ represents the latitude of the building geographically. The latitude of Chapel Hill is 35.9 N. $\mathbf{K_T}$ represents the average clearness index from 0 being the least clear to 1 being the most clear. $\mathbf{Q_b}$ and $\mathbf{Q_d}$ represent monthly average daily absorbed beam radiation and diffuse radiation, respectively. $\mathbf{Q_{tot}}$ is the sum of $\mathbf{Q_b}$ and $\mathbf{Q_d}$. Adding the subscript "flat," for example, $\mathbf{Q_{d,\,flat}}$, indicates that the radiation is received by a flat roof. $\mathbf{K_{b,\,vault}}$ and $\mathbf{K_{tot,\,vault}}$ are defined as $\mathbf{Q_b/Q_{b,\,flat}}$ and $(\mathbf{Q_b} + \mathbf{Q_d})/(\mathbf{Q_{b,\,flat}} + \mathbf{Q_{d,\,flat}})$, respectively. Using a computing program, the researchers computed ratios $K_{b,\,vault}$ and $K_{tot,\,vault}$ for various values of Θ_0, λ, and K_T. The results for $K_T = 0.65$ and $\lambda = 32$ N are shown in Table 1.

Table 1. Irradiance Conversion Ratios. Ratio $K_{b, vault}$ and $K_{tot, vault}$ varied with half angle Θ_0 (K_T = 0.65 and λ = 32 N) for a south-north oriented vaulted roof [53].

θ_0	June		July		August	
	$K_{b,vault}$	$K_{tot,vault}$	$K_{b,vault}$	$K_{tot,vault}$	$K_{b,vault}$	$K_{tot,vault}$
90	0.9911	1.0957	0.9855	1.0914	0.9861	1.089
80	0.9872	1.066	0.9815	1.0618	0.9749	1.0553
70	0.9916	1.0479	0.9869	1.0445	0.9762	1.036
60	0.9955	1.0349	0.993	1.0324	0.9844	1.0257
50	1.0	1.0247	0.998	1.0232	0.9925	1.019
45	1.001	1.0203	1.0	1.0195	0.9961	1.0165

As shown, the $K_{tot, vault}$ ratio decreases as the half angle decreases. The parameters that most accurately resemble the IPF's parameters (λ = 35 N, Θ_0 = 41) from the study are λ = 32 N and Θ_0 = 45. Because ratios are only given for the months June, July, and August, ratios for the remaining months of the year were extrapolated from a full set of monthly data of $K_{tot, vault}$ for a south-north facing vaulted roof at Θ_0 = 90, shown in Table 2. Total annual solar irradiance for Chapel Hill was calculated to be 1770 kWh/m^2/year by multiplying monthly GHI by monthly $K_{tot, vault}$ ratios for Θ_0 = 45, K_T = 0.65, and λ = 32 N and summing the values.

Table 2. Annual Irradiance Conversion Ratios. $K_{tot,\ vault}$ ratios for $\Theta_0 = 90$ and $\Theta_0 = 45$ at ƛ = 32 N for a south-north facing vaulted roof. Extrapolated values are shaded red.

Month	**$K_{tot,\ vault}$, Θ_0 = 90**	**$K_{tot,\ vault}$, Θ_0 = 45**
Jan	1.35	1.28
Feb	1.29	1.22
Mar	1.18	1.12
Apr	1.10	1.02
May	1.09	1.02
Jun	1.10	1.02
Jul	1.09	1.02
Aug	1.09	1.02
Sep	1.12	1.05
Oct	1.22	1.15
Nov	1.40	1.33
Dec	1.51	1.44

Section 2.3: Expected Energy Output

The expected energy outputs for the various technologies were calculated using the formula $E = A \times r \times H \times PR$, where E is the energy output in kWh, A is the total solar panel area in m^2, r is the solar panel yield or efficiency as a percentage, H is the average annual irradiation on the panels in kWh/m^2/year, and PR is the performance ratio or coefficient for losses based on certain criteria. Ten scenarios were considered. In each scenario, A and H remained the same, while the r value changed based on 2020 and 2025 solar panel efficiency projections for CIGS, CdTe, quantum dots, and perovskites and the performance ratio fluctuated slightly for each type of technology.

As indicated in Section 6.1, the total roof area was calculated to be 7,700 m^2. This study considers the case where 95% of the roof is covered in solar panels, resulting in a total solar panel area of 7,315 m^2. The average annual irradiation of 1,770 kWh/m^2/year, calculated in Section 2.2, was used as the value for *H*. Lastly, the performance ratio was calculated for each technology based on estimated inverter losses of 8%, DC cables losses of 1%, AC cables losses of 1%, shadings of 0%, losses due to weak irradiation of 3% , losses due to dust, snow, etc. of 2%, and temperature losses of variable percentages based on technology. Because CIGS, CdTe, and quantum dots remain efficient at low and high temperatures, they have temperature losses of 0%, resulting in a *PR* of 0.86. In contrast, perovskite cells are less efficient at high temperatures, so they were given temperature losses of 12%, resulting in a *PR* of 0.75. The solar cell efficiencies used for each technology scenario are shown in Table 3. Because these efficiencies are measured under lab conditions, the realized efficiencies of the cells in solar modules are lower. Currently, solar modules are a few percentages less efficient than their research cell counterparts [54]. This study conservatively estimates that cell to module efficiency losses will be 4.0% in 2020 and 3.5% in 2025 for each technology [55]. Using the adjusted module efficiencies rather than estimated record cell efficiencies in the calculation, the expected energy output for each scenario is shown in Table 3, where 100 tWh is equivalent to 100,000,000 kWh.

Table 3. Expected Energy Outputs for 90% Roof Coverage. Values are rounded to the nearest million.

Technology	2020 Energy Output (tWh)	2025 Energy Output (tWh)
CIGS	235	250
CdTe	218	241
Quantum Dots	137	200
Perovskite	267	262

Section 2.4: Expected Energy Demand

The annual energy demand for the new IPF was estimated by looking at energy demand data for NC State University's Close-King IPF. Both facilities have similar designs, climates, and football practice schedules; thus, the energy usage per cubic foot will be comparable. Annually, Close-King IPF uses 805,863 kWh, or 0.167 kWh/ft^3. For UNC's IPF that will be 4,963,940 ft^3; this translates to 830,315 kWh or 95 kW of energy annually. All of the technologies available in 2020 and 2025 would more than cover the internal energy demand of the building if 90% of the roof is covered with solar panels. For the remainder of the study, it is assumed that a <u>200 kW system</u> is installed. This size estimate is based on 170 kW peak demand for the King-Close IPF. A 200 kW system will generate enough electricity for the building's peak demand and excess energy generated could be used to supply nearby energy demand.

Section 3: Conversion Efficiency Projections

Using the data for CIGS, CdTe, quantum dot, and perovskite technology from the NREL chart for Best Research-Cell Efficiencies, projections for 2020 and 2025 best research-cell efficiencies were made. There is much uncertainty in predicting solar cell efficiencies because it is a rapidly evolving field. Figure 27 shows how drastically First Solar's module efficiency roadmap changed over the course of one year from 2013 to 2014. The company went from a goal of 17.2 module efficiency by 2017 in 2013 to 19.5 by 2017 in 2014. In 2015, First Solar set a world record in efficiency for a full sized CdTe module at 18.6% [54]. While First Solar has not yet published a new module efficiency roadmap, it is likely that their 2015 goal for 2017 has risen since this record setting efficiency accomplishment. First Solar's chief technology officer Raffi Garabedian stated that he cannot say where the company's CdTe progress will be in the next few years because it is making new, unpredictable discoveries every day [57].

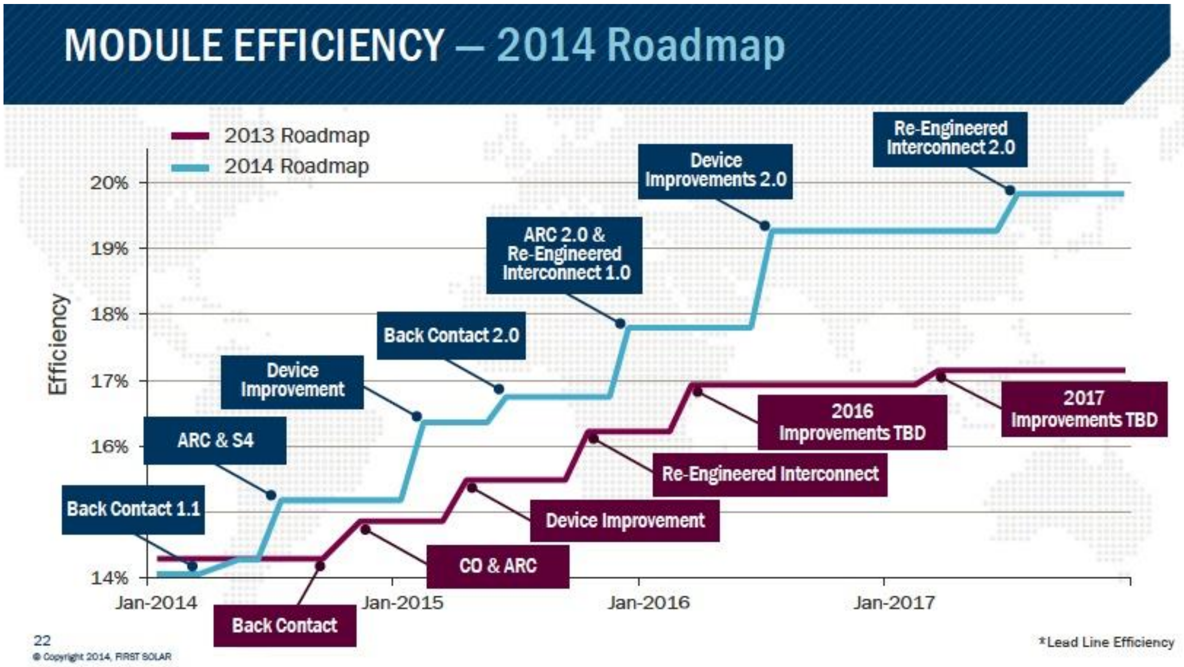

Fig. 27. First Solar Module Efficiency Roadmap [56]. Change between First Solar's 2013 and 2014 module efficiency goals.

This lack of updated efficiency projections was prevalent across the board for all of the emerging technologies examined in this study. In general, the last major publication for efficiency projections was made back in 2010 by the International Energy Agency (IEA) in their Solar Photovoltaic Energy Technology Roadmap, featured in Figure 28. These projections proved to be conservative, as many projections for 2020-2030 have already been surpassed. Interestingly, no efficiency projections were given in the IEA's 2014 Solar Photovoltaic Energy Technology Roadmap.

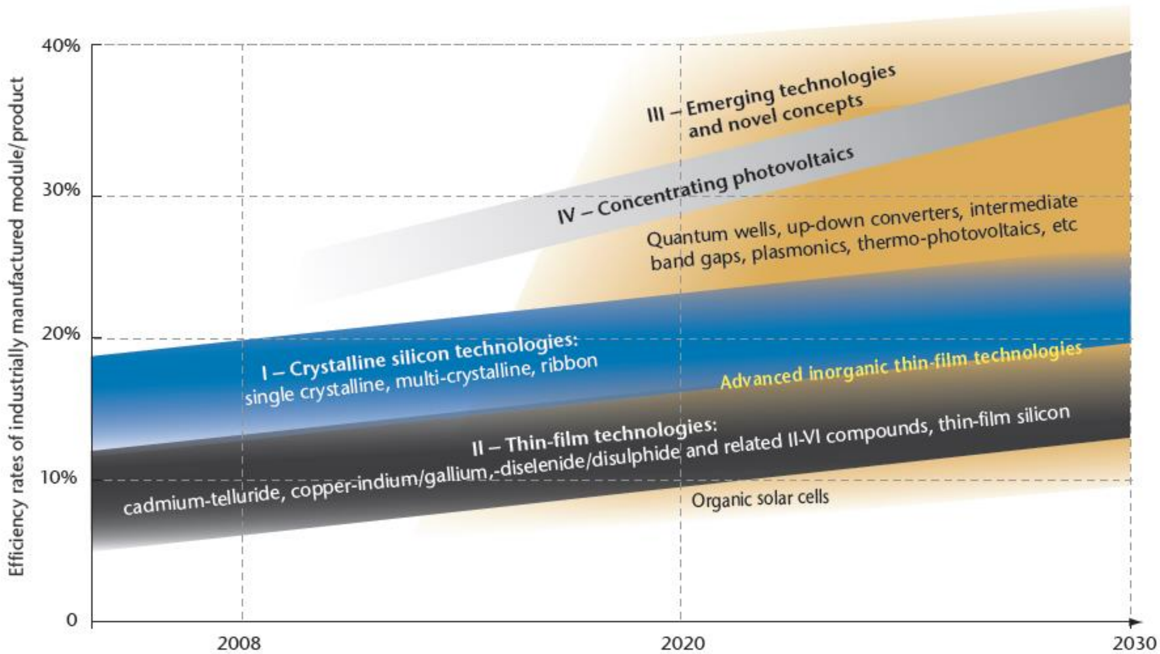

Fig. 28. IEA Solar Module Efficiency Projections [58]. This figure shows where the IEA thought solar technology efficiencies would be in the future. Many of these projections have been surpassed.

Given that many companies are hesitant to state efficiency goals and that major publications no longer release estimates for future efficiencies due to rapidly evolving technology, the projections in this study were based on regressions of past conversion efficiency data. Upon examining various regressions, a mix between linear and power regressions was used to project efficiencies in 2020 and 2025 because they are long extrapolations. Linear regression was used for CIGS, quantum dot, and perovskites, while power regression was used for CdTe. Figures 27, 28, 29, and 30 show the regression equations, r-squared values, and 2020 and 2025 efficiency projections. The perovskite projection surpassed its Shockley-Quiesser theoretical maximum efficiency of 31% as presented by the U.S. DOE in their 2012 SunShot Vision Study; thus, this study estimates it will reach 31% by 2020 and no longer increase thereafter [65]. Table 3 displays the projected efficiencies in chart format.

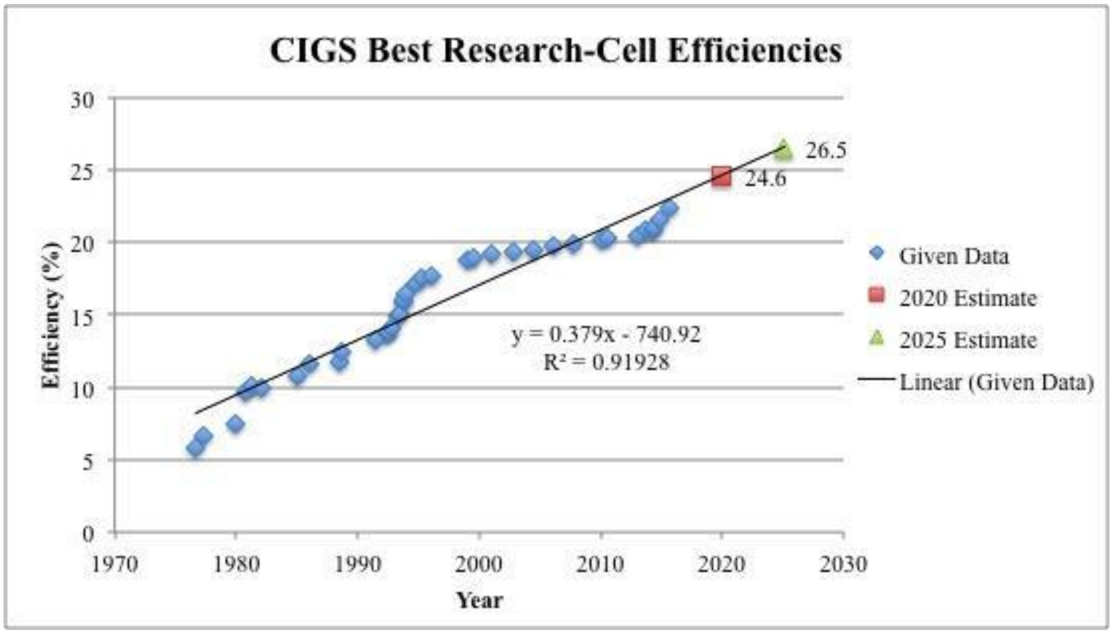

Fig. 29. CIGS Best Research-Cell Efficiencies. Linear regression used to estimate an efficiency of 24.6% in 2020 and 26.5% in 2025. These values are below the theoretical maximum efficiency for CIGS of 29%; thus, the values are accepted [65].

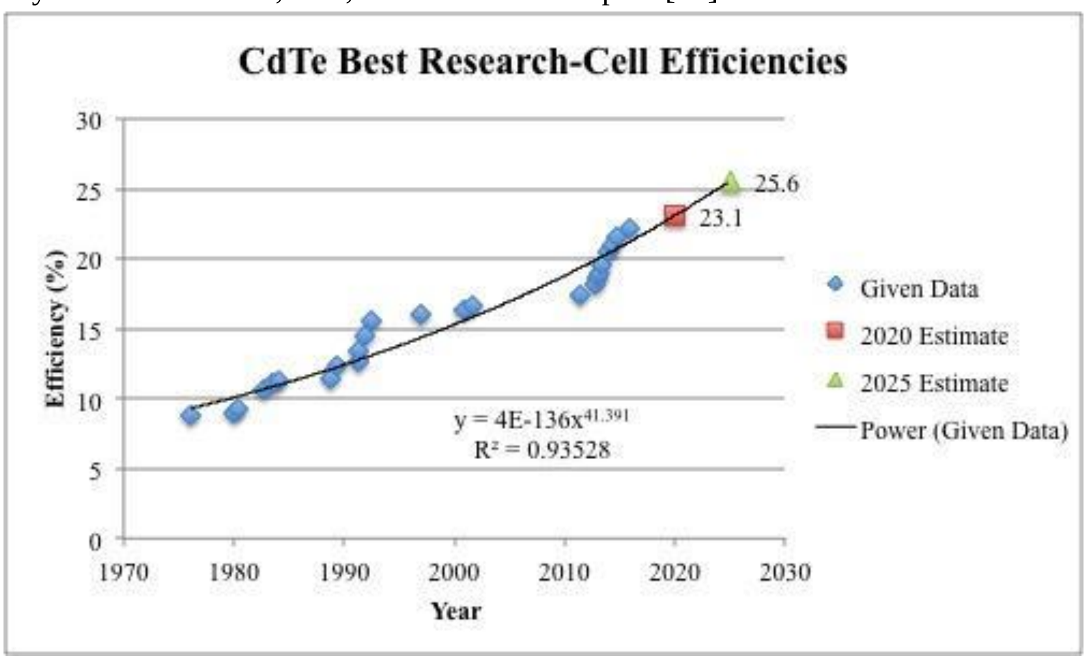

Fig. 30. CdTe Best Research-Cell Efficiencies. Power regression used to estimate an efficiency of 23.1% in 2020 and 25.6% in 2025. These values are below the theoretical maximum efficiency for CdTe of 30%; thus, the values are accepted [68]. This estimate matches industry leading First Solar's technology vision for 23% efficient CdTe cells in the short-term and l25% efficient CdTe cells in the long-term [56].

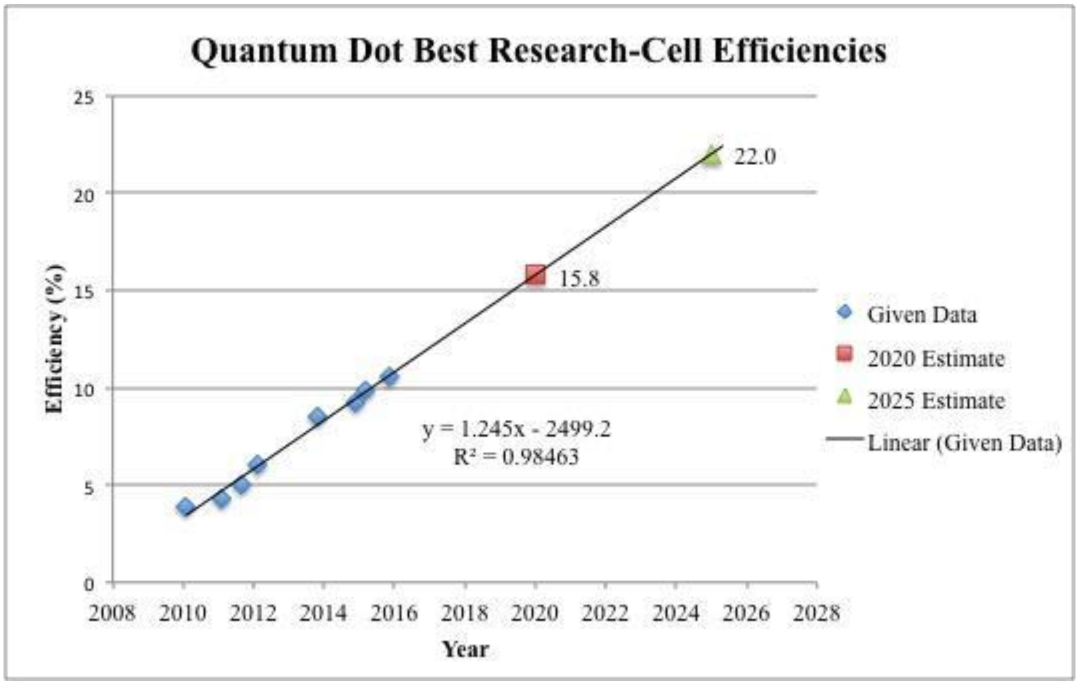

Fig. 31. Quantum Dot Best Research-Cell Efficiencies. Linear regression used to estimate an efficiency of 15.8% in 2020 and 22.0% in 2025. These values are below the theoretical maximum efficiency for quantum dots of 45%; thus, the values are accepted [65].

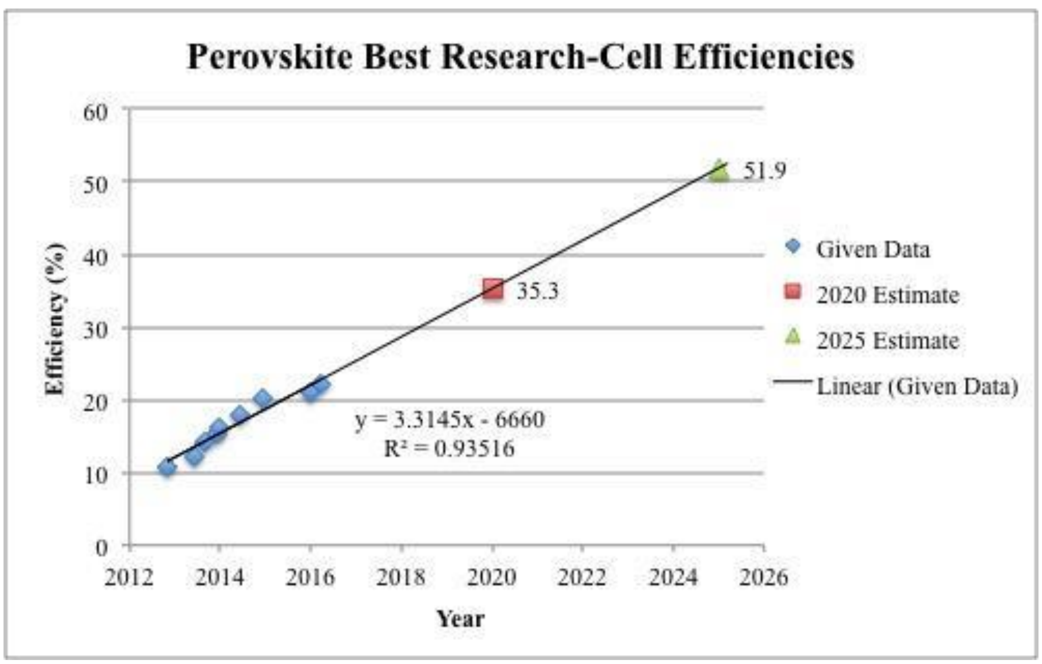

Fig. 32. Perovskite Best Research-Cell Efficiencies. Linear regression used to estimate an efficiency of 35.3% in 2020 and 51.9% in 2025. The theoretical maximum efficiency for perovskites is 31%; thus, this study estimates that the theoretical maximum will be reached for

organic by 2020 [66]. This estimate is close to industry leading Oxford PV's expectation to reach 30% efficient perovskite solar cells by 2017 [72].

Table 4. Best Research-Cell Conversion Efficiencies

Solar Technology	2016 Efficiency (%)	Estimated 2020 Efficiency (%)	Estimated 2025 Efficiency (%)
CIGS	22.3	24.6	26.5
CdTe	22.1	23.1	25.6
Quantum Dot	10.6	15.8	22.0
Perovskite	22.1	31.0	31.0

Section 4: Cost Projections

As mentioned in Chapter 2, Section 1, the cost of a PV system is composed of expenses for the PV module, power electronics, and BOS (for the remainder of this study, the term "BOS" will include power electronics). The cost of these components is dropping in the U.S. [67]. The cost of PV modules has dropped at a remarkable pace in recent years. In 2008, the PV module composed 67% of an average project's total cost [73]. As of 2012, the module composes 32% of total cost, while BOS, including power electronics, labor and soft costs, comprise the remaining 68% [73]. With module prices declining even further since 2012, this study assumes that BOS accounts for 75% of total system costs now. Given the cost per watt for modules of each technology type, the BOS cost was calculated by the following equation: $BOS\ Cost = (Module\ Cost * 0.75)/0.25$. Then the total system costs in Table 5 were calculated by summing module costs and BOS costs. Unfortunately, perovskites do not have cost data available because they have yet to be installed by industry leaders. While perovskites promise to be cheap in the future, with no data to support an estimation analysis they will no longer be included in this study; however, perovskite costs should be reevaluated in 2020 and 2025.

According to a study completed by Deutsche Bank on solar markets, solar costs will fall another 40% by 2017, as shown in Figure 33 [74]. Factors leading to this decrease are falling panel prices, declining inverter and roof attachment costs, installation costs decreasing by one third, and the falling cost for sales/customer acquisition [74]. Based on the value of 40% by 2017, this study estimates that solar costs will fall 42% by 2020 and 46% by 2025. The 2020 and 2025 cost estimates shown in Table 5 were calculated according to these cost reductions.

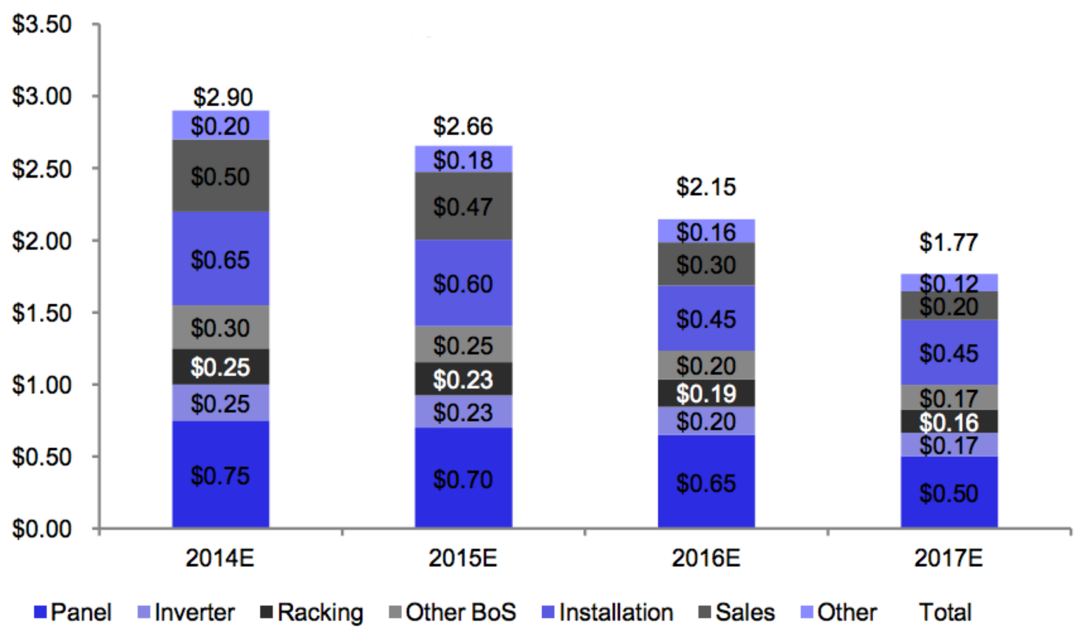

Fig. 33. Estimated Solar Cost to 2017 [74]. Cost trajectory on pace of a ~40%+ reduction by the end of 2017.

Table 5. Installed Solar System Cost

Solar Technology	2016 Module ($/Watt)	2016 BOS ($/Watt)	2016 Total ($/Watt)	2020 Total ($/watt)	2025 Total ($/watt)
CIGS	0.58[1]	1.74	2.32	1.35	1.25
CdTe	0.54[1]	1.62	2.16	1.25	1.17
Quantum Dot	1.25[2]	3.75	5.00	2.9	2.7

[1] Module price extrapolated from PVinsights on Bloomberg [75; 81]
[2] Module price sourced from Solterra Renewable Technologies, Inc. as their quantum dot manufacturing cost [76]
[3] Module pricing not available from industry leaders

The estimated 2016 total solar system costs are somewhat conservative given where industry leaders prices are for each technology. Currently, CIGS and CdTe costs range between \$0.74/Watt and \$0.46/Watt, but are \$0.56/Watt, on average [75]. CIGS manufacturer Siva Power anticipates manufacturing CIGS modules at \$0.40/Watt in the near future, and CdTe manufacturer First Solar anticipates having installed system costs per watt of less than \$0.99 by 2017 [77; 56]. The total system cost for quantum dots is also high, given that the total cost of a Solterra system is \$3.29/Watt [78]. Because UNC must bid out the project, industry leading costs were not used; rather, more conservative cost estimates were used.

Section 5: Error

Within this study, there is error associated with the projections and calculations for energy demand, energy output, and payback period. First, the design and dimensions of the IPF are not yet final. Should the design company, HOK, change the design of the building, the energy demand and energy output would need to be recalculated, thus altering the cost and payback period. Second, the ratios for the converting GHI to vaulted roof incidence are only an approximation of the actual ratio. The $K_{tot, vault}$ ratios for June, July, and August were for $\Theta_0 = 45$, $K_T = 0.65$, and $\lambda = 32$ N since these were the closest values to the real values of $\Theta_0 = 41$, $K_T = 0.65$, and $\lambda = 35$ N. The ratios for the real conditions will be slightly different given the half angle is more shallow and the latitude is greater. This would impact the irradiance on the roof and, as a result, the total energy output. Additionally, the $K_{tot, vault}$ ratios for the other months were extrapolated from annual ratios from conditions of $\Theta_0 = 90$ instead of $\Theta_0 = 45$; however, the extrapolation might not match what the actual values would be, affecting the calculated energy output further. Third, the expected energy demand for the IPF was calculated under the assumption that it would require the same energy per cubic feet as NC State University's King-

Close IPF. There is error associated with this assumption based on weather, practice schedule, and building uses. Additionally, energy data from the Close-King IPF did not span a whole year, so energy usage was estimated for the months of April and May. Fourth, the realized solar modules efficiencies may differ from the projected solar module efficiency projections based on whether or not the best research cell efficiencies follow the regression models used and if the estimated efficiency difference between best research cells and typical modules for 2020 and 2025 hold true. Module efficiency plays a large role in the energy output; thus, differences between realized and projected module efficiencies could significantly impact the success of a PV system, should one be implemented. Fifth, the performance ratios for each technology depend on a number of factors that could have been overestimated or underestimated, which would negatively or positively impact the expected energy output. Lastly, there are errors associated with the cost projections. The estimated BOS costs were based on the assumption that BOS composes 75% of total solar system costs in 2016, but they may compose more or less than this percentage. Similarly, the 2020 and 2025 cost projections were based on the assumption that costs will decline 42% and 46% by those years, respectively, but the realized percentage decline could differ.

CHAPTER 4: RESULTS

Given the total volume of the IPF is 4,963,940 ft^3 and the estimated energy consumption for an IPF in NC's Triangle is 0.167 kWh/ft^3, UNC's new IPF will require 830,315 kWh or 92 kW of energy annually. With a total roof area of 82,888 ft^2 and with average annual solar irradiance of 1770 kWh/m^2/year, each solar technology, CIGS, CdTe, and quantum dot, could produce significantly more energy than the IPF demands if only 90% of the roof is covered. In order to ensure that the system supplies enough demand for the building, the size of the proposed solar system is 200 kW. Based on the costs per watt for each technology shown in Table 5, installation costs for each type of 200 kW system were calculated. The installation costs are face value with no tax credits, subsidies, or rebates, and the results are displayed in Table 6.

Table 6. Installation Cost for 200 kW Solar System

Solar Technology	2020 Cost (k$)	2025 Cost ($)
CIGS	269	251
CdTe	251	223
Quantum Dot	580	540

Given that UNC has a reduced rate for electricity of $0.06/kWh, the payback period for each technology was calculated. The lowest payback periods are shaded orange. The results are displayed in Table 6.

Table 7. UNC Payback Period for 200 kW Solar System

Solar Technology	2020 Payback (years)	2025 Payback (years)
CIGS	5.57	5.18
CdTe	5.18	4.82
Quantum Dot	12.0	11.2

CHAPTER 5: CONCLUSIONS

Section 1: Introduction

UNC at Chapel Hill's Athletic Department should consider the application of a CdTe thin film solar system to the roof of the new Indoor Practice Facility in 2025. A 200 kW system purchased in 2020 or 2025 would cost $250,560 or $233,280 in 2016 U.S. dollars, respectively. Based on the current University's reduced utility rate of $0.06/kWh, it would pay for itself in 5.18 or 4.82 years, respectively. After paying itself back, the panels will save the University approximately $50,000 each year. Additionally, according to Solar Simplified, it would prevent over six million pounds of CO_2 from entering the atmosphere over 25 years [80]. Implementing such a solar system will provide the University and Athletic Department with positive publicity, long-run financial savings, a reduced carbon footprint, and a sense of environmental stewardship.

Section 2: Discussion

Among the six emerging solar technologies, CIGS, CdTe, quantum dot, perovskite, organic, and dye-sensitized, only four—CIGS, CdTe, quantum dot, and perovskite—have displayed enough progress and potential to show that they can compete with traditional, silicon-based solar panels on an efficiency basis. Based on efficiency projections and site analysis of where the IPF will be, all four technologies will be able to sufficiently provide enough energy for the IPF; thus, <u>CIGS, CdTe, quantum dot, and perovskites will be practically feasible for the IPF</u>. Of the four technologies, only three—CIGS, CdTe, and quantum dot—have made enough progress in the market to have cost data that can be examined to estimate future costs. Based on the projected conversion efficiencies and the resulting estimated costs in 2020 and 2025, <u>CIGS and CdTe technologies will be economically feasible for the University</u>. It is clear that unless significant improvements to module costs and BOS costs are made for quantum dots, they will not be economically feasible or competitive with conventional thin film in these time frames. It is very possible that significant improvements will be made in cost and efficiency due to the versatile nature of quantum dots. Additionally, they are used for purposes aside from solar cells, so researchers will continue to study quantum dots extensively. They also show potential for very cheap application methods, such as spray-on cells. While a quantum dot system would pay itself back in around twelve years, the current data does not support quantum dots as the best solar option for the IPF in 2020 or 2025; however, quantum dot costs should be reevaluated closer to 2020 and 2025.

The remaining two technologies, CIGS and CdTe, will both be excellent options for solar systems in 2020 and 2025. Because these technologies have been around since the 1970's, they are well understood and have already penetrated the market and shown success in competing with traditional solar panels. While they both experienced periods of stagnant conversion efficiency growth, they, especially CdTe, are in the process of resurgence and will continue to grow in the next ten years. In 2010, CIGS had a 3% efficiency advantage over CdTe [21]. Since, both technologies have improved significantly, and now CIGS only leads CdTe by 0.2%. In the short- and long-term, CIGS efficiencies are projected to remain higher than CdTe. Because both technologies will be efficient enough to provide for the building with only about half of the roof covered, a difference in efficiency of this size will not have a great impact on the size or the output of the system, given the low demand for the building and the large roof size. In contrast, cost has a larger impact in determining which technology is best. CdTe cells can be manufactured and installed at a lower price per watt than CIGS because of the higher price of indium in CIGS cells—something that may increase in the future as indium becomes scarcer. This makes CdTe more appealing from a financial standpoint; however, both CdTe and CIGS have great financial metrics and payback periods, making them wise investments for the University.

What further differentiates CdTe from CIGS for future application at UNC is its proven success and prominence in the U.S. While the global market share of CdTe has shrunk since 2007 and the global market share of CIGS has grown, CdTe has a larger prevalence in the U.S. than CIGS. This is because the largest global thin film company, First Solar, is located in the U.S., while the largest CIGS companies, Solar Frontier and Hanergy, are located in Japan and China, respectively [35]. First Solar is rapidly progressing CdTe technology, and it is reasonable to expect that CdTe will remain the dominant thin film technology in the U.S.; therefore, <u>CdTe thin film is the most practically and economically feasible solar technology for implementation on the IPF in 2020 or 2025</u>.

Implementing solar technology to the IPF roof will provide the University not only long-run financial savings of $50,000 per year, but will also provide additional benefits. Recently, colleges and universities have been making strides towards green initiatives, including greener athletic facilities. Arizona State has embraced its over 300 days of sun each year and equipped nine of the program’s athletic facilities with solar panels, including their football IPF [82]. When projects like this are completed, they receive wide national media. Given UNC’s prominent status in the athletic world, implementing cutting edge solar panels on the roof of the IPF would provide the football team with important, positive publicity. It would also encourage other athletic programs to move toward more sustainable athletic facilities. Additionally, it would lower the University’s carbon footprint. While UNC has an efficient co-generation power plant, it has not yet divested from coal; thus, utilizing the sun for electricity would help lower its carbon footprint. In implementing solar technology, UNC and the Athletic Department would show their support for not only environmental stewardship and moving towards a more sustainable campus, but also their support for cutting edge technologies and research.

Section 3: Future Work

In this study, developing and emerging thin film solar technologies were evaluated for economical and practical feasibility on a specific, commercial-scale UNC building with a vaulted roof. The same technologies could be evaluated for practicality on a utility-scale project and compared to traditional solar PV to determine which technology provides the best option for systems on the ground with capacities ranging from a few megawatts to hundreds of megawatts. In addition, the use of solar PV for small-scale, on-campus projects, such as using solar to power outdoor scoreboards or stadium lights, could also be considered.

Additionally, building-integrated photovoltaics (BIPV) applications could be considered for the IPF or other University buildings. BIPV systems serve as a structural outer layer and generate electricity for the building or export to the grid [69]. BIPV systems can be added to the building facade on the sides and/or windows, the rooftop as solar shingles or replacement roofing, or glazing of surfaces [69]. When considering BIPV, similar environmental factors, such as insolation, weather conditions, shading, latitude, and structural factors, such as building energy requirements and solar system layout, that were considered during this study would have to be taken into account. The IPF is an ideal structure for BIPV because it is tall, has large wall/window spaces, and is not shaded. However, BIPV systems have the greatest value when they are built into the building during initial construction, as opposed to a retrofit [69]. This way, standard materials can be substituted for PV so that builders can “reduce the incremental cost of PV systems and eliminate costs and design issues for separate mounting systems” [69]. While the construction of the IPF is too soon to consider BIPV, BIPV could be considered for future construction projects on campus.

As shown in Chapter 3, Section 2.3, if 90% of the IPF roof is covered with the various types of solar panels, the energy output would be over twice the demand. In the case that there is a large amount of excess energy output if a system over 200 kW is installed, a storage device could be paired to the solar system to store excess generation for use by nearby buildings during times of peak demand. A study on the future of storage technology in relation to the IPF could be conducted.

Solar PV is a large field with a wide array of solar technologies that are rapidly developing. Each day, new progress is made and new applications are discovered. While this study did not consider all types of applications for each solar technology, there are a number of unique and promising applications, such as spray-on quantum dot or perovskite solar cells, whose progress should be monitored for potential future and groundbreaking applications on UNC’s campus.

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