BUILDING INTEGRATED PHOTOVOLTAICS IN HONOLULU, HAWAIʻI: ASSESSING URBAN RETROFIT APPLICATIONS FOR POWER UTILIZATION AND ENERGY SAVINGS

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By

Parker Lau

D.Arch Project Committee:
David Rockwood, Chairperson
David Garmire
Frank Alsup
Tuan Tran

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“You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete.”

- Buckminster Fuller

I dedicate this dissertation to my Mother and to those I have lost along the on journey. Your love and life stands as a guiding light in times of darkness.

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Abstract

It is forecasted the human population will increase by 33% by 2050 and 70% by 2100. With exponential population growth there exists a global energy demand to power the lives of humans and the cities they dwell in. To meet this need it is imperative that society curbs its greenhouse gas emissions and resource consumption; clean energy is greatly needed. This requires major innovations in building technology, energy efficiency, power savings, recycling and renewable energy generation. This is paramount to sustaining natural resources and the human condition for future generations to continue into perpetuity. However daunting, this crisis gives rise to critical opportunities in the area of architectural design and resource augmentation.

This D.Arch dissertation presents a technological building solution through an intrinsic application of nature and energy: The Sun and its light. The design development of a Building Integrated Photovoltaics (BIPV) awning system digitally retrofitted on a high-rise building in downtown Honolulu, Hawai'i will be assessed based its energy savings and power utilization methods. Measurements of this system will be in examining a methodology, which focuses on the duality of its active (photovoltaic) energy generation merged with its passive (shading) energy qualities. Investigation will focus on how to consolidate a merger for increased power potential in electrical energy performance, on-site energy savings, and progressive architectural design.

The project looks at ten BIPV iterations, which use energy and daylight simulations, to judge the designs' form and function. This is done to achieve a 1-to-10 BIPV factor, which balances certain qualitative and quantitative outlines for final implementation. From the research, design, data collection and energy simulations, it was discovered that in implementing the preferred BIPV façade retrofit, in downtown Honolulu, produced power savings in the magnitude of 7.8%, generated over 404k kWh/year and established a payback period of 4 years.

Not only can BIPV design implementations provide for efficient cost dynamics but can also extend into future energy production and saving benefits. These aspects are crucial in providing a template for potential PV ubiquity and adoption within the built environment for better resource utilization and energy recycling in the 21st century.

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List of Acronyms

a-Si	Amorphous Silicon
BAPV	Building Applied Photovoltaics
BIM	Building Information Modeling
BIPV	Building Integrated Photovoltaics
BOS	Balance of System
c-Si	Mono-Crystalline Silicon
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
CFD	Computational Fluid Dynamics
CSP	Concentrated Solar Power
DB	Design Builder
DF	Daylight Factor
DSC	Dye-Sensitized Solar Cell
EPRI	Electrical Power Research Institute
GHG	Green House Gas Emissions
HECO	Hawaiian Electric Company
LEED	Leadership in Energy & Environmental Design
LCOE	Levelized Cost of Energy
NEM	Net Energy Metering
NREL	National Renewable Energy Laboratory
NURBS	Non-Uniform Rational B-Splines
OPV	Organic Photovoltaics
PDC	Pacific Davies Center
PGV	Puna Geothermal Venture (PGV)
poly-Si	Poly-Crystalline Silicon
PPA	Power Purchase Agreement
PV	Photovoltaics
ROI	Return on Investment

Preface

The purpose of this dissertation is to examine the development of the retrofit applications of Building Integrated Photovoltaics (BIPV) technology on existing high-rise buildings in Honolulu, Hawai'i, which can provide for the best use for alternative energy building and aesthetic design. The Hawai'i model can be the basis for future pan equator-tropical building application. An examination of BIPV theory, application, design and implementation shall be based on current technology, scientific restraints, and methodology. This approach provides for an intelligent application of BIPV to solve future energy consumption dilemmas currently encountered in architectural design and global urbanization problems. BIPV may provide for a key solution to these problems.

Although any examination of an alternative energy source merits a full discussion of all renewable energy sources and potentials, this paper is not intended to be a limiting factor to further research, examination and review, of other traditional and non-traditional methods of energy generation. Arguably, other renewable energy alternatives exist and may be more efficient and cost effective for the time being. Nor, is this an exhaustive economic examination of cost-benefit analysis in a true economic or accounting sense for the building or architectural industries.

This dissertation is based on a theory and concept of making buildings energy receptive to their own environment, to be able to produce the necessary energy to act as an auxiliary power source or possibly power all activities within, and not reliant on an outside grid or source power. Energy that utilizes site power is a focal point. The success of this endeavor will rely on design implementation, engaging the active vs. passive energy relationship of this BIPV technology and proving an economic payback period below the average of 6.6 years it takes on most buildings in Hawai'i.

Contemporary issues briefly examined include, but are not limited to, climate change, an examination of the special environments of the tropics, urban density dynamics and the utility grid are analyzed in Chapter 2. An examination of the energy conditions and constraints will be briefly reviewed, with the insight of changing the *status quo* of limited energy development with a replacement concept, that buildings should be self-sufficient in its own energy production through on-site energy producing elements.

Hawai'i provides for an ideal template in BIPV examination. The unique geographical and urban elements of Hawai'i provide an excellent proving ground for BIPV's acceptance. Current energy production, alternatives to BIPV, and BIPV problems and solutions presented are unique to Hawai'i's troubled energy dependency, antiquated and monopolistic utility grid.

The origins of BIPV, elements, current and future technology applications and designs, are reviewed and considered in chapters 2. Lastly, case studies of BIPV applications will be presented in chapter 3. Chapters 4 – 6 define the basis of design, methodology, concepts, energy, location, orientation and site design analysis, total building energy baselines and provides energy and daylighting simulations. Chapter 7 completes and tests the design development of the BIPV awning scheme and measurements of the 1-to-10 iterations, as stated above. The conclusion of chapter 8 will cover findings and future considerations on what was learned, gathered and how the contribution to the body of knowledge of BIPV was achieved.

BIPV is not a dream but a tangible reality that requires discussion, technology expansion, and public acceptance. However, we must first explore the contemporary issues to be able to understand why BIPV is a viable alternative to the current energy and architectural debate.

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CHAPTER 1:
Introduction

1.1. Contemporary Issues

In order to comprehend Building Integrated Photovoltaics (BIPV) utilization in Honolulu, Hawai'i, we must first look at the shift in contemporary issues and global thinking that has created a demand for photovoltaic technology and a potential in BIPV adoption. Additionally, other important renewable energy technologies will be analyzed to compare and contrast the different yet shared goals of sustainable energy autonomy. This will be done to show the emerging importance of BIPV. What follows is a summation of the key factors that has lead towards the adoption of BIPV and its use in the built environment.

1.1.1. The Triple Convergence

The perpetual relationship between humans and the earth requires averting irreversible climate change and natural resource depletion. There exist a convergence of three issues that are starting to shape the way humans and the ecosystem interacts with the world: climate change, increased urban density and the inefficiencies and devastation of fossil fuels attributed to the utility grid. These factors require urgent action. Human innovation, power density management and technological responses are necessary to achieve ecological and energy parity.

Natural resources used to create energy are running scarce and the drive of governments to achieve annually higher capital growth requires a proportional increase in exponential use of traditional fuels. As the world's population is estimated to hit 9.6 billion by 2050 and 12.3 billion by 2100, the need to adapt buildings to meet this expected demand in energy and building density is currently underway.[1] The opportunity for new technologies in energy efficient building systems, materials and products, hold great promise.

One of the primary issues of the 21st century will be in resolving infrastructural deficiencies and our buildings' and responding to the problem of climate change via gains in sustainable building technologies and measures. One of these focuses on

[1] "World's Population Unlikely to Level Off Anytime Soon — May Hit 12 Billion by 2100," Washington Post, accessed September 22, 2014, http://www.washingtonpost.com/national/health-science/worlds-population-unlikely-to-level-off-anytime-soon-may-hit-12-billion-by-2100/2014/09/22/aa6689a0-3f68-11e4-9587-5dafd96295f0_story.html.

reducing a building's dependence on the standard "source energy" (the utility grid), and maximizes its potential in "site energy" (energy consumed on a building's site). This creates building's that can be energy neutral and or energy less dependent on the grid as an auxiliary power source. This leads to longer energy efficiencies, as resources are created and consumed on location, greater utilization of local resources and less uses of traditional fossil fuels.

One potential solution is the application of BIPV. BIPV is defined as "…photovoltaic materials that are used to replace conventional building materials in parts of the building envelope such as the roof, skylights, or facades."[2] This building replacement concept holds great promise and broadband application for energy utilization practices.

In the next chapter, details about the conceptual and technological potential within this architectural approach, and its implications to the future merger of energy and architecture will be covered. First however, an examination into the triple convergence is warranted to report on what has pushed BIPV into the category as a viable alternative to the current energy and resource depletion crisis.

I. Climate Change

The effects of climate change are evident and starting to shape the way we live, think and feel. For instance, a recent report published by the White House on *The Cost of Delaying Action to Stem Climate Change*, addresses these ecological transformations by the fact that, "The average temperature in the United States during the past decade was…1.5° Fahrenheit…warmer than the 1901-1960 average, and the last decade was the warmest on record both in the United States and globally". Furthermore the report goes on to state that, "Global sea levels are currently rising at approximately 1.25 inches per decade, and the rate of increase appears to be accelerating."[3]

To put that increase into perspective, since 1900 the average globally sea level rise has been 8 inches, with satellites recording that the majority of this rise has taken place in the last 20 years.[4] Due to anthropomorphic activity, it is projected that need to cut global greenhouse gas emissions by 80% if we are to avert sea level rise of 4' – 5'

[2] Strong, "Building Integrated Photovoltaics (BIPV)"
[3] Council of Economic Advisers (U.S.). July, 2014. *The cost of delaying action to stem climate change*. http://purl.fdlp.gov/GPO/gpo51127, pg 1.
[4] 2014 National Climate Assessment, Hawai'i and U.S. Affiliated Islands, 26.

at the end of this century.[5] If we do not adhere to this prediction we could see every major costal city either flooded, taken over by a new sea level, adapting with sea barriers, going more vertical in architecture or a combination of these factors.

The result of this environmental acceleration is a mix of accelerated global temperatures and seawater rising. In the *2014 National Climate Assessment*, the report finds that by 2055 air temperatures will increase by an average of 3.4°F and by 2090 a mean temperature increase, based on two modeled deviations (Fig. 1.1) of low and high climate change, of 5.75 °F.[6] This will have dire consequences on all populations as the need to adapt, mitigate and create solutions to this problem becomes far more apparent in the 21st century.

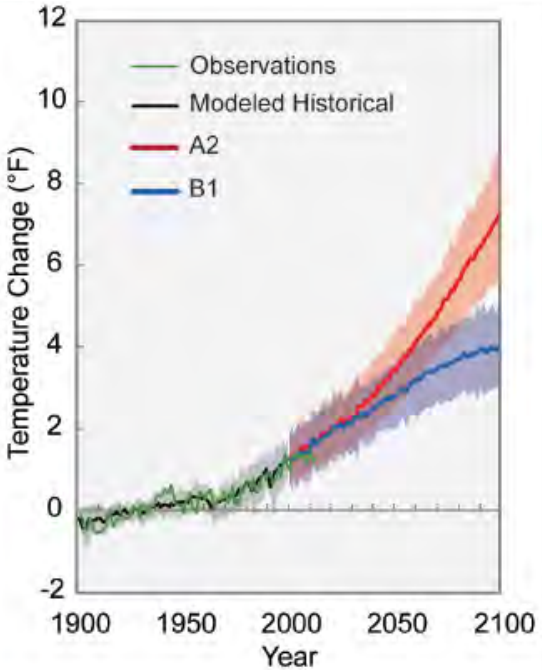

Figure 1.1. Global warming estimates based on two modeling projections.

Source: U.S. Global Change Research Program. 2014. "National Climate Assessment", Accessed: October 23, 2014. http://nca2014.globalchange.gov/

Climate change is affecting the environment at such a breakneck speed that 2014 was the hottest year on record. For instance, it was recently reported by that of the of, "The 10 warmest years since records began in the 19th century have all been since 1997...[and]…While the ranking of individual years can be affected by chaotic weather patterns, the long-term trends are attributable to drivers of climate change that

[5] "*VICE on HBO Season 2: Greenland Is Melting & Bonded Labor (Episode 2)",* Dr. Gavin Schmidt, YouTube video, 13:20, televised by Vice News on Jan. 9, 2015, https://www.youtube.com/watch?v=7Yq-sfWSWLg

[6] 2014 National Climate Assessment, Hawai'i and U.S. Affiliated Islands, 542 - 544.

right now are dominated by human emissions of greenhouse gases…[and that]…Emissions were still rising 'so we may anticipate further record highs in the years to come'."[7] Due to rising global temperatures, warmer climates create higher demand for energy use to cool buildings, people and equipment. Thus a direct correlation is emerging that can be drawn between a building's energy use and its cooling demands.

As seen in figure 1.2, the demand for cooling buildings have risen and will continue to rise as the energy needed for heating will continue to decline due to rising temperatures. The reductions in heating are a result of other available forms of energy that could be used for heating: bio-fuels, natural gas, heating oil, electricity from the grid and passive or solar thermal heating. This now puts the majority of a buildings energy demand on the electrical/utility grid, primarily needed for space cooling, i.e. air conditioning, as a result various energy outputs, lighting, computers, appliances and etc., which produce heat and increase cooling use and costs.[8]

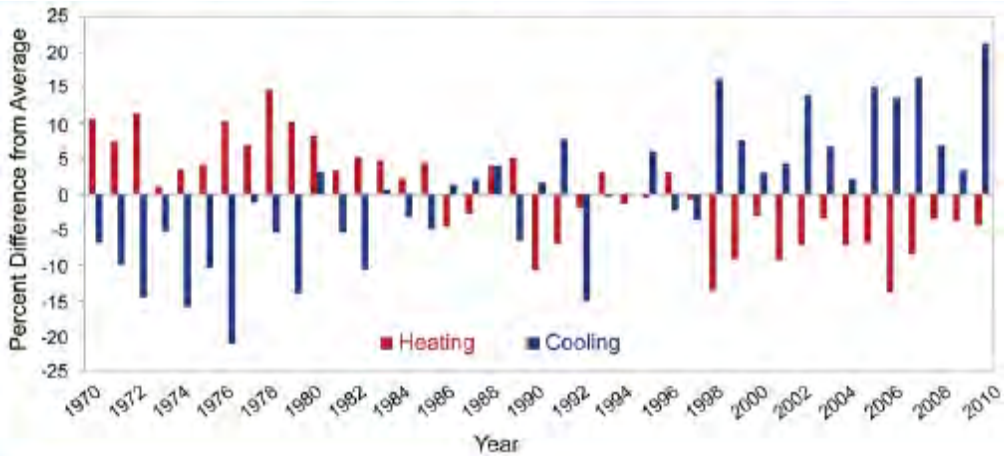

Figure 1.2. Increase in cooling demand and decrease in heating demand
Source: U.S. Global Change Research Program. 2014. "National Climate Assessment", Accessed: October 23, 2014. http://nca2014.globalchange.gov/

This issue is particular to tropical climates, as it is relatively hot and humid and experiences mild fluctuations in its diurnal temperatures on a yearly basis. Therefore, energy demands during the day and sometimes at night (especially near the equator) is directed towards air conditioning and instruments for space cooling.

[7] "Last Year Was Earth's Hottest On Record, U.S. Scientists Say," Reuters, accessed January 16, 2015, http://in.reuters.com/article/2015/01/16/earth-climate-idINL1N0UV17420150116.
[8] 2014 National Climate Assessment, Energy pdf. 116. (et al.)

One of the main culprits that is compounding this issue and adding to increases in climate change is the urban heat island effect. This phenomenon is due to the sub-climate(s) created by urbanization, which creates hotter environments, in comparison to neighboring rural or suburban areas because of a lack in the physical build up of green spaces. Because of its concrete build up, urban areas experience significantly higher solar isolation and longer heat gain due to this effect (fig. 1.3).

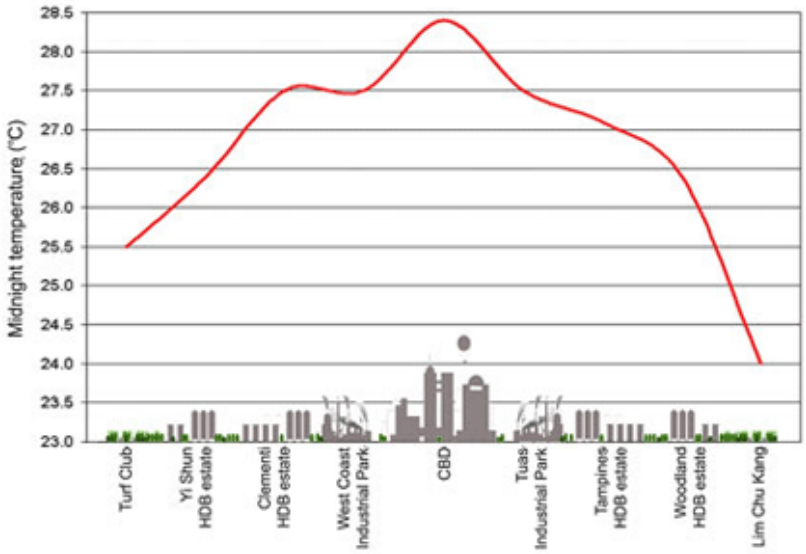

Figure 1.3. Profile of the Urban Heat Island effect in Singapore

Source: NUS School of Design & Environment
Accessed: November 10, 2014. http://www.sde.nus.edu.sg/rsh/SDE_rsh_highlights_B01.html

For instance, according to the U.S. Environment Protection Agency it states that:

> "The annual mean air temperature of a city with 1 million people or more can be 1.8 – 5.4°F (1 – 3°C) warmer than its surroundings. In the evening, the difference can be as high as 22°F (12°C)…[this]…can affect communities by increasing summertime peak energy demand, air conditioning costs, air pollution and greenhouse gas emissions, heat-related illness and mortality, and water quality."[9]

All of this stems from an expanded urban density factor via population increase and migration. Creating designing solutions for building's to mitigate or even recycle this heat saturation effect are paramount in the battle against climate change and resource conservation.

[9] "Heat Island Effect," last modified July 31, 2014, http://www.epa.gov/heatisland/.

II. Urban Density

Accelerated climate change and bio-diversity loss is through population increase, human activity and infrastructural development. These are major factors in the consumption of our finite natural resources and its associated greenhouse emissions (GHG); i.e. fossil fuels. This activity is spread globally but concentrated in cities. As mentioned in the recent Intergovernmental Panel on Climate Change (IPPC) report, *Climate Change 2014: Impacts, Adaptation, and Vulnerability*, it states that:

> "Urban areas hold more than half the world's population and most of its built assets and economic activities. A high proportion of the population and economic activities at risk from climate change are in urban areas, and a high proportion of global greenhouse gas emissions are generated by urban-based activities and residents."[10]

These conditions of urban vulnerability can be further compounded by its geographical placement. The IPCC report goes on to highlight that, "Rapid urbanization and growth of large cities in low- and middle-income countries have been accompanied by expansion of highly vulnerable urban communities living in informal settlements, many of which are on land exposed to extreme weather…"[11] Adapting the urban infrastructure to address such realities and secure such informal settlements will be to attempt to balance its ecology with its physical and economic development. This symbiosis will be focused primarily in city centers, as land scarcity and conditions of vertical density becomes the new normal.

This is defining the importance that cities will play in shaping the 21st century and the effects it will have on all aspects within the environment. Going vertical though urban density presents the most immediate tangible option placed before us as the world gets smaller and land becomes scarcer. Currently, about 3.6 billion, or 52% of the world's population, reside in urban areas.[12] This number in relation to urbanity will only increase. As noted in the book *Vertical Density 2: The Need for Tall Buildings in the City,* it is stated that, "…in the last century the great capitals of the world have increased 10 times its population, and by 2050, it is expected that 75% of the world's population will live in cities…and in this paradigm shift, where ecological footprint and growth should be compatible, the vertical option has no opponent."[13]

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[10] "Climate Change 2014: Impacts, Adaptation, and Vulnerability," last modified March 31, 2014, 10. http://ipcc-wg2.gov/AR5/.
[11] Intergovernmental Panel on Climate Change, *Climate Change 2014: Impacts, Adaptation, and Vulnerability*, 10.
[12] Shobhakar Dhakal, "Sustainable Cities: In Rapidly Urbanizing and Carbon Constrained World" Asian Institute of Technology (PowerPoint presentation given for Planning 625 UH Manoa, Honolulu, Hawaii, Find Date), UN DESA 2012 Statistic, Slide 4.
[13] Wei Lai Jian Zhu Za Zhi She, *Vertical Density 2: The Need for Tall Buildings in the City* (Dalian: Dalian Li Gong Da Xue Chu Ban She, 2012), 10-11.

In the United States we have to consider the importance of this 2050 mark and how it will affect the built environment. It is estimated that by 2050 the U.S. population will balloon from its current 318 million to 400 + million. This currently makes the U.S. the 3rd most populous country trailing behind India (1.23 Billion) and China (1.35 Billion).[14] The consequences of this growth and its environmental effects on people are starting to show. As documented in the book *Hot, Flat and Crowded,* Author Thomas Friedman documents China's changing climate and resulting air pollution effects it is having on the population, by stating, "In Beijing alone, 70 to 80 percent of all deadly cancers cases are related to the environment…[and because of this]…Lung cancer has emerged as the No. 1 cause of death."[15]

Adapting to the forecast of accelerated population growth and its effects on urban density, human health, migration and adaptation to global consumption, GHG and economic effects, through the adoption of renewable energy technologies is no easy task. This is of paramount importance in creating a built environment that is in symbiosis with the ecosystem that created it and the human condition that has come to define it.

III. The Grid

The immediate culprit of climate change and urban density is the built environment and what we do to power it. Currently, the primary amount of energy we use globally is due to buildings and the carbon they emit as well as the resources they consume. This has created an infrastructure that is technologically behind that of most other energy efficient technologies.

Here in the United States, buildings currently account for 39% of all CO_2 emissions and 7.7% of all global emissions.[16] In addition to this, the United States Energy Information Agency estimates that, "…homes and commercial buildings use 71% of the electricity in the U.S.; [and] this number will rise to 75% by 2025."[17] Adapting our built environment to address these energy increases is extremely important in how buildings perform in the future and how they will affect the lives and operations of those involved.

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[14] "The World Factbook - Country Comparison:: Population," Central Intelligence Agency, accessed Aug. 24, 2014, https://www.cia.gov/library/publications/the-world-factbook/rankorder/2119rank.html.

[15] Thomas L. Friedman, *Hot, Flat, and Crowded: Why We Need A Green Revolution and How It Can Renew America* (New York: Farrar, Straus and Giroux, 2008), 348.

[16] Adler, Anderson, *Green building project planning & cost estimating*, 124.

[17] Smith and Gill, *Towards Zero Carbon: The Chicago Central Area DeCarbonization Plan*, 10, 89.

Adding to a building's energy use and its cooling costs, there is a tremendous amount of rejected heat and electrical transmission losses, which could otherwise be used as productive energy, occurring through the utility grid. In the book *Green Building: Project Planning & Cost Estimating,* the author discusses the basis of this issue through the second law of thermodynamics in that "…whenever energy is converted from one form to another, some fraction is irretrievability lost as heat."[18]

The author does so to point out the deficiencies of the utility grid and its main function as being that of "source power"; aka the centralized utility grid (fig. 1.4). The author further states that "To generate electricity for building consumption, about twice as much energy is wasted as rejected heat at the power plant, and losses also occur in transmitting and distributing the electricity over power lines."[19]

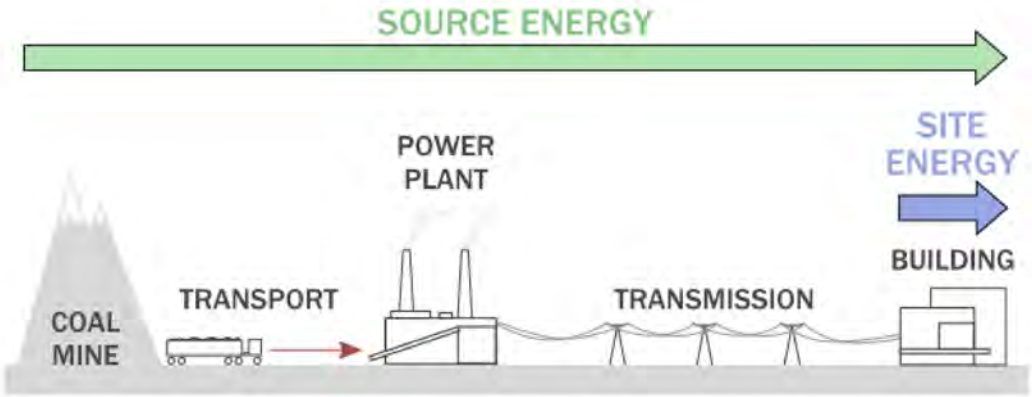

Figure 1.4. Source vs. Site Energy
Source: archtoolbox
Accessed: September 21, 2014. http://www.archtoolbox.com/sustainability/site-vs-source-energy.html

This supports the need for adapting a buildings capacity to electrically interact with one another by developing interconnected networks, smart grids and a decentralized grid for gains in energy efficiency within site based energy applications. The urban topography of the future must be able to transmit energy within close proximity to be able to avoid utility energy losses due to its centralized nature. This loss in productive energy and the economic implications it has on the ratepayer has even raised concern amongst utilities companies and their investors (fig. 1.5). In a study done by the Edison Electric Institute, *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electrical Business*, the utilities report

[18] Adler, *Green building*, 123.
[19] Ibid.

highlights the economic threats posed by renewable energy technologies to its monopolistic business model.

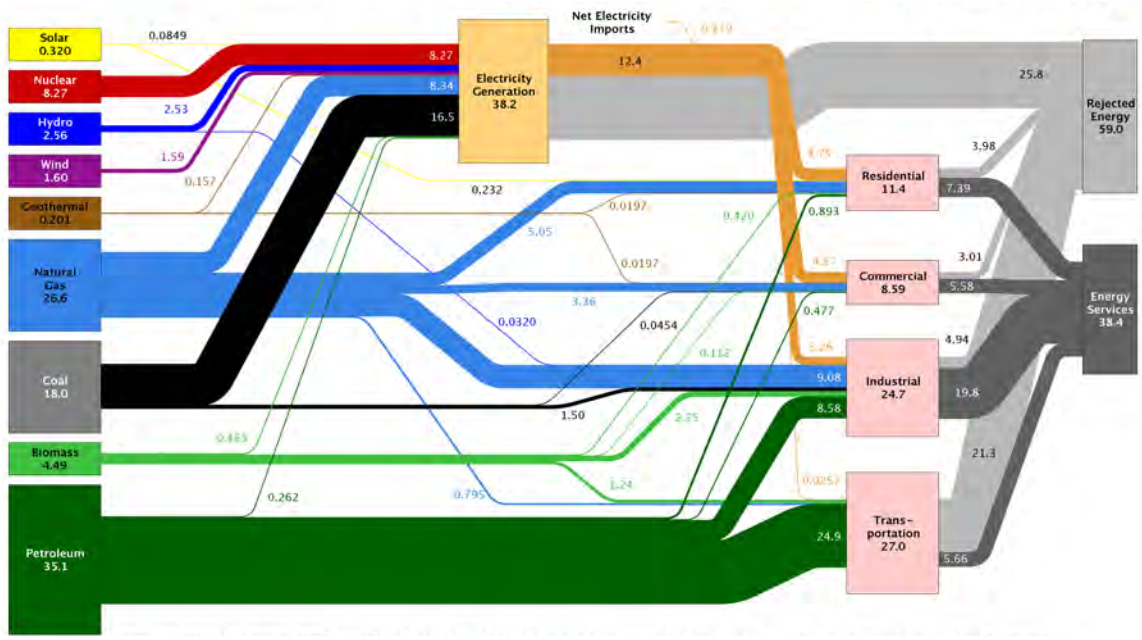

Figure 1.5. U.S. Energy Use in 2013 = 97.4 Quads or 285 Million GWH

Source: Lawrence Livermore National Laboratory
Accessed: January 15, 2015. https://www.llnl.gov/news/americans-using-more-energy-according-lawrence-livermore-analysis

The report focuses on the renewable energy market(s) through the terms of Distributed Energy Resources (DER), i.e. renewables, and Demand side Management Technologies (DSM), i.e. financial incentive given to the ratepayer from the utilities company to reduce energy consumption. The report describes these "disruptive technologies" as consisting of "…photovoltaics, battery storage, fuel cells, geothermal energy systems, wind, micro turbines, and electric vehicle (EV) enhanced storage…", further adding that, "…As the cost curve for these technologies improves, they could directly threaten the centralized utility model."[20] Furthermore, the list of a "convergence of factors" that challenges the utilities' business model is described as:

[20] Peter Kind, "Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electrical Business," *Edison Electric Institute* (2013): 3, accessed September 20, 2014, http://www.eei.org/ourissues/finance/documents/disruptivechallenges.pdf

> "…falling costs of distributed generation and other distributed energy resources…an enhanced focus on development of new DER technologies; increasing customer, regulatory, and political interest in demand side management technologies…government programs to incentivize selected technologies; the declining price of natural gas; slowing economic growth trends; and rising electricity prices in certain areas of the country."[21]

In terms of the retail electricity, renewables are no longer an existential threat but now a tangible reality towards decentralizing the consolidated utility grid and cities' dependence on source power. Additional current factors to consider are the Power Purchase Agreement (PPA), Feed-in-Tariff (FIT) or Net Energy Metering (NEM) for grid tied systems as regulated through the Utilities companies. These are the current modifiers that govern PV's ability to function; so long as they are PV systems tied to the grid.

As adoption of renewables become cost competitive and viably beneficial, those not included in the "Distributed Energy Resources", meaning your average rate payer, will have to foot the bill for maintaining the existing utility grid in the economic magnitude of "…20% or more increase in rates."[22] This is encouraging utility companies to "normalize this competitive threat", as it offers the ratepayer to not the only ecological and technological upgrade by going solar but now the economics as well.

These applications require a faster and larger adoption rate of the technology and modernization of the current utility grid to fully exploit the economic factors through cost competitiveness, higher efficiencies and humanistic appeal. These actions will slow the demand for fossil fuel use for building energy as the price of fossil fuels exponential rises and put the economic burden on the backs of those not yet able to going solar. This could create a critical mass factor wherein people, and even developers, are now given competitive options in how to electrically live their life.

Additionally, there are also national and regional security concerns, existential threats and rolling blackouts that can occur due to the major vulnerability of the Grid, its transformers and substations. It was recently report that the U.S. utility grid is struck by cyber and or physical attacks once every four days. If achieved on a mass scale an attack of the centralized utility grid could leave possibly millions in the dark. Major power outages could affect human productivity and lives as mentioned in the USA Today's piece *Bracing for a big power grid attack: 'One is too many'*, that "A

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[21] Kind, Peter, 2013. *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electrical Business*, Edison Electric Institute, January 2013. http://www.eei.org/ourissues/finance/documents/disruptivechallenges.pdf (accessed September 20, 2014), pg. 1.
[22] Ibid. pg. 5.

widespread outage lasting even a few days could disable devices ranging from ATMs to cellphones to traffic lights, and could threaten lives if heating, air conditioning and health care systems exhaust their backup power supplies.[23]

Transitioning off of source power to site power presents a major argument in the opportunity costs in developing renewables to enhance high performance and sustainability within buildings and in areas of interconnected urban density and for energy security. By improving upon the design within our urban topography and making small yet beneficial gains in energy technology, BIPV promises to have a large impact on electrical energy networking and beneficially affecting the triple convergence factors above.

The issues of climate change, urban density and the inefficiencies of the utility grid has created a sense of urgency on the part of the building community and society to infuse technological change and increase efficiencies in building's and their components. These affect the tropics on a specific level that is both visual, sensorial and affecting the ecosystem unlike anything seen before it.

1.2. The Tropics

The changing of the climate varies regionally, yet impacts globally. Contrary to the public conception that the first area to be decimated by the initial effects of climate change will be the polar ice caps, the region which will first experience the large scale effects of climate change on its economy, species, and culture will be that of the Tropics (23.43° N & S Latitudes). This is because unlike temperate climates, the tropics experiences subtle yearly fluctuations in its diurnal behavior and temperature conditions (hot, humid and wet).

The tropics do not have yearly seasonal variations such as in temperate climates and therefore are extremely sensitive to small changes within its ecosystem and because of this it faces a major vulnerability in adapting to flooding via seawater inundation and high temperature swings which affects human health, ecological diversity and productivity. Therefore, being the first area to impact, the tropics must be the first region to adapt the efficiencies of initiating a BIPV methodology. Recent data on tropical vulnerability was published in the study, *The Projected Timing of Climate Departure From Recent Variability"*, by Professor Camilo Mora of the University of

[23] Steve Reilly, "Bracing for a Big Power Grid Attack: 'One is Too Many,'" USA Today, March 24, 2015.

Hawai'i at Monoa. In it Professor Mora highlights climate change and how the initial effects of it are to be seen in the tropics.

As you can see in the modeled projections of figure 1.5, temperatures in the tropics will excel higher and earlier than other latitudes. The key components in determining these results were calculating "evaporation, precipitation and ocean surface temperature and ph [balance]." Focusing on these key areas, the study determined the dire news that, "Tropical species are unaccustomed to climate variability and are therefore more vulnerable to relatively small changes…[adding that]…The tropics hold the world's greatest diversity of marine and terrestrial species and will experience unprecedented climates some 10 years earlier than anywhere else on Earth."[24]

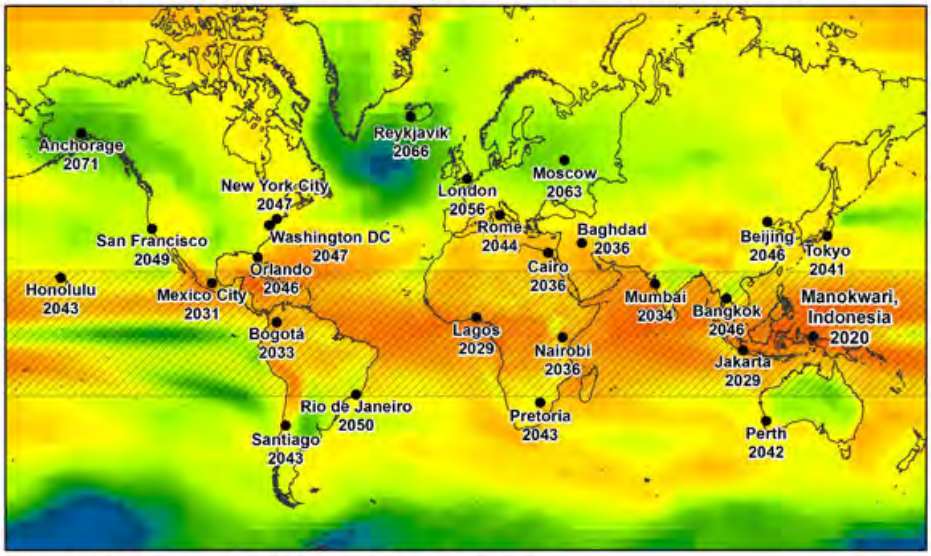

Figure 1.6. Global and tropical future temperature changes

Source: University of Hawai'i at Mānoa
Accessed: September 8, 2014. http://www.hawaii.edu/news/2013/10/09/study-in-nature-reveals-urgent-new-time-frame-for-climate-change/

In Camilo's study, it highlights the comparisons with how we experience our environment and how it is changing at break neck speed. For instance report stated that, "…within [the last] 35 years, even the lowest monthly dips in temperatures will be hotter than we've experienced in the past 150 years…The tropics will be the first to exceed the limits of historical extremes and experience an unabated heat wave that threatens biodiversity and heavily populated countries with the fewest resources to

[24] "Study in Nature Reveals Urgent New Time Frame for Climate Change," last modified October 9, 2013, http://www.hawaii.edu/news/2013/10/09/study-in-nature-reveals-urgent-new-time-frame-for-climate-change/

adapt."[25] Adapting, mitigating and creating solutions towards trying to turn the tide of this alarming information is the only thing we as a species have control over. This adaptation to combat bio-diversity loss could come best with an alternative energy rooted in BIPV.

Tropics will play a big part in major capital and population growth of the 21st century whose regional economies are rapidly emerging. About 40% of land on the Earth's surface is located within the tropics, half the world's animal species are said to reside here and the tropics hold about one third of the world's population; who live under conditions of economic destitution.[26] The tropics lack in modern infrastructure, rely heavily on tourism-based economies, dependence on outside resources and suffer from a lack of diversified employment.

With the possible decimation of one of the earth's most diverse ecosystem through climate change, its emerging economies and expanding population are under threat. The entire globe would be susceptible to ecological monoculture with the loss of its most diverse region. This could threaten the adaptation and mitigation process of anthropomorphic, flora and fauna migrating away from the tropics to evade the results that climate change has created.

Saving the tropics from impending climate change and bio-diversity loss is extremely important in how the 21st century will be shaped, defined and what it will do to future generations having to adjust to these new norms. Redesigning and redirecting technology away from its electrical dependence on forms of fossil fuels, source energy and its greenhouse gas emissions, could help repair the entire globe if approached through innovations in human capital, societal thinking and technological energy and building applications. BIPV applied to the tropics is a small cog but could have large-scale effects if initiated in an energy efficient, cost competitive and culturally applicable manner.

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[25] Mora C. et al., "The Projected Timing of Climate Departure From Recent Variability," *Nature* 502 (2013): 183-187.
[26] Alanna Stang and Christopher Hawthorne, *The Green House: New Directions in Sustainable Architecture*, (New York: Princeton Architectural Press, 2005), 160.

1.2.1. Hawai'i as a Model

Being the gateway between the East and West, Hawai'i views this energy issue through a lens of physical and economic isolation (fig. 1.7). Other tropical regions also share all this, however Hawai'i has been known to provide ideal conditions of unique diversity for relying solely on a sustainable energy model (hydro, solar, wind, biofuels, geothermal, etc.), through exploiting environmental factors. Historically Hawai'i has been sustainable from the beginning.

Figure 1.7. Hawai'i, U.S. (21.3° N, 157.8° W)

Being the most isolated archipelago in the world, it has facilitated an ecological filter, which has created a local flora and fauna that has adapted in order to thrive and avoid famine and extinction. This has produced some of the worlds most diverse and endemic species and has attracted the world over. Before the oil age of the 19th century Hawai'i's electricity and its energy came from locally sourced organic resources in the form of biomass and "bagasse," which is sugar waste.[27] Yet today the state of Hawai'i imports 71% of its energy in the form of petroleum vs. the mainland

[27] Craig Howes and Jon Kamakawiwo'ole Osorio, *The Value of Hawai'i Knowing the Past, Shaping the Future,* (Honolulu: University of Hawai'i Press, 2010), 179.

U.S. average that only consists of only 1%.[28] This has had a deep economic effect in the fact that 10% of Hawai'i's Gross State Product (GSP) is spent on purchasing foreign oil and coal.[29] As you can also see in figure 1.8, second to Hawai'i's oil addiction for electricity is coal at 15%. Trailing at third is wind power at 4%.

This is a start in the right direction for renewables but Solar is at 0% in total energy aggregate. This electrical production in renewables is not enough to counter the total state energy demand and global energy fluctuations and possible oil embargos, as a result of instability in the Middle East, or even Asia, which poses further economic and security threats to the Hawaiian economy, society and ecosystem.

In Hawai'i, we are affected by not only the energy scarcity but also the results of impending climate change. As seen in figure 1.9, CO_2 emissions are contributing to ocean acidification that will lead to increased coral bleaching which will decimate the oceanic ecosystem. This ecological crisis has massive economic implications seeing how 26% of the state of Hawai'i economy is wholly dependent on tourism. In addition, as stated in the *2014 National Climate Assessment* report, based on seawater rise alone "the loss of Waikiki Beach alone could lead to an annual loss of $2 Billion in visitor expenditures."[30]

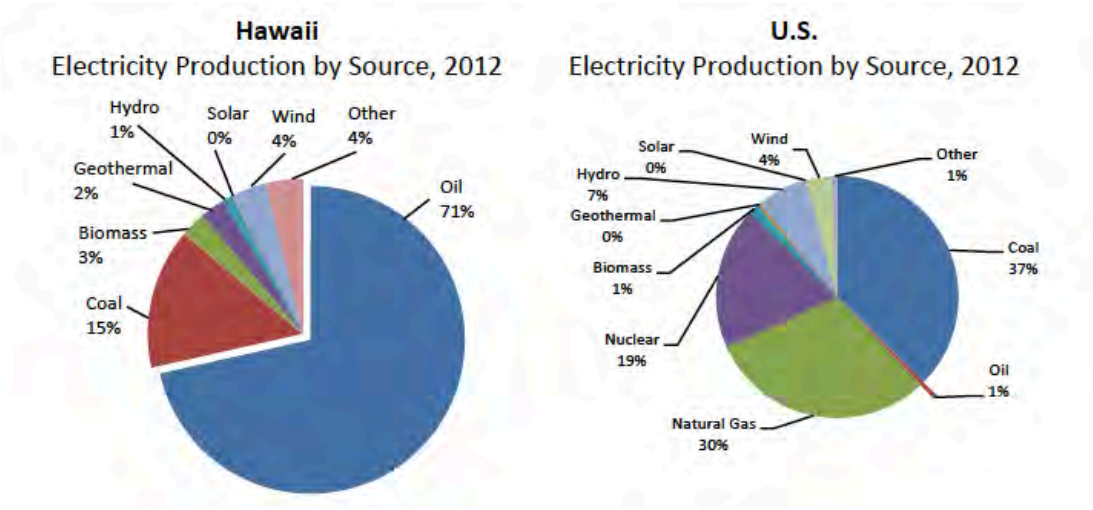

Figure 1.8. Hawai'i vs. U.S. energy production[31]

Sources: Hawai'i Energy Facts and Figures May 2014
Accessed: November 1, 2014. http://energy.hawaii.gov/wp-content/uploads/2011/08/HI-Energy-FactsFigures_May2014_2r.pdf

[28] "Hawaii Energy Statistics," last modified November 2014, http://energy.hawaii.gov/resources/dashboard-statistics.
[29] Howes and Osorio, *The Value of Hawai'i*, 179.
[30] "2014 National Climate Assessment, Hawai'i and U.S. Affiliated Islands," U.S. Global Change Research Program, 542, 543 & 544. http://nca2014.globalchange.gov/.
[31] Source: State of Hawai'i Dept. of Business, Economic Development and Tourism, Hawai'i Energy Facts & Figures, May 2014, 2.

Climate change is very apparent in the Hawaiian archipelago. The island chain is venerable and at risk of losing its ecological diversity as well as its cultural identity and way of life. This attention has been put on Hawai'i as its geography and ecology are to be threatened by climate change in the immediate and long-range future based on the vulnerabilities of seawater and temperature rise and its erosion on shorelines.

Politically this has been known and policy to combat this climate change is slowly but steadily in the works. In 2008, The Hawai'i Clean Energy Initiative (HCEI) was created to acknowledge these energy and climate change problems and provides for action in modernizing its infrastructure to reach 70% of energy needs from sustainable energy sources by 2030 (40% Renewables & 30% Energy Efficiency). If this policy target is accomplished it could set precedence as an island model that could be applied throughout the tropics and those that deal with resource isolation and "captive market" conditions. However, this is only a political wish list with no repercussions if fully executed.

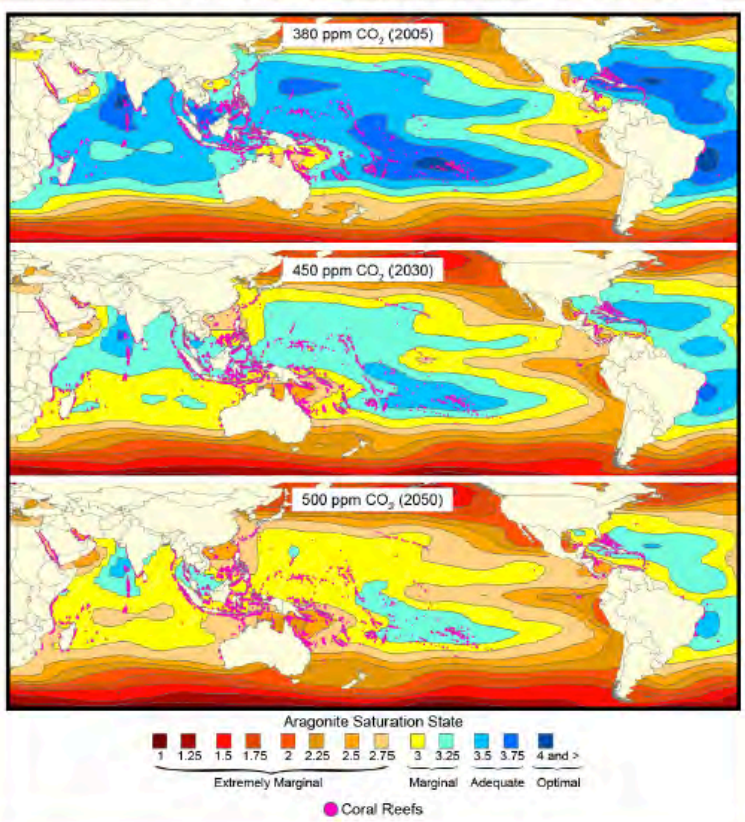

Figure 1.9. Effects of CO_2 emissions on oceanic coral populations.

Source: Reef Resilience

Accessed: October 11, 2015. http://www.reefresilience.org/coral-reefs/stressors/ocean-acidification/

As stated in the *Memorandum of Understanding between The State of Hawai'i and The U.S. Department of Energy*, it identified these two parties as being in agreement that the HCEI "…may be terminated through written notice of the Parties at any time…[or]…Be constructed to be either fiscal or funds obligations…[or]...Create a legal obligation of the Parties…"[32] This is a major issue in having commitment by state and federal governments in outlining in an act for energy targets needed for Hawai'i to go energy independent and eliminate its dependence on fossil fuels.

The dense urban city center of O'ahu, fig. 1.10., is the immediate area to which major adjustments could be made to work with its environment and culture as opposed to against it; which seems to be the local narrative. Both culture and ecology can be balanced through the notion of self-sufficiency, which is dependent on the idea that future technologies and gains in energy efficiencies will provide an energy supply solution. The cultural connector is the advances and gains needed within the populous to bring about change and what can be aligned within the values of Hawaiian culture.

As explained by, Henry Curtis in *The Value of Hawai'i*, "When energy-efficient and renewable energy systems are installed together, the former lowers economic costs and the latter decreases dependence on foreign fossil fuel. Thus they have a positive synergistic effect."[33] This what is needed in Hawai'i, as it could function as a conduit for renewables in a world that becomes far more dependent on cities and the energy needed to power them. As the power demand rises, developing an urban model that optimizes values within energy efficient means of design and renewability are important to our cultural and national identity for innovation and in finding methods to balance the energy equation on all local levels.

Because of its island conditions and base point in the Pacific, Hawai'i is has emerged as most isolated and diverse place in the world; based on its endemic species and ethnic demographics. This island isolation has created a melting pot of thriving racial diversity unseen in most places by the fact that "Hawaii has the highest racial minority population of any state in the union…[standing at]…75 percent…"[34] Engrained in the Hawaiian culture is a respect for the land "Aina" and its resources. If established, a model of sustainability that fosters renewable energy autonomy could set precedence in the tropics and throughout the world.

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[32] National Renewable Energy Laboratory (U.S.), *HCEI Road Map - Memorandum of Understanding Between The State of Hawai'i and The U.S. Department of Energy* (Golden: National Renewable Energy Laboratory, 2011), 3-4.
[33] Howes and Osorio, *The Value of Hawai'i,* 185.
[34] "Hawaii Is Diverse, But Far From A Racial Paradise," narrated by Liane Hansen, Weekend Edition, *NPR*, November 15, 2009, http://www.npr.org/templates/story/story.php?storyId=120431126.

Figure 1.10. Honolulu, Hawai'i (21.4° N, 157.9° W)

Source: Google Maps
Accessed: March 21, 2014. https://www.google.com/maps/place/Honolulu,+HI/@21.4043027,-157.914969,68382m/data=!3m1!1e3!4m2!3m1!1s0x7c00183b8cc3464d:0x4b28f55ff3a7976c Oahu

Oahu Demographics

Classification: Ocean Island Climate[35]
Total land Area (Oahu): 596.7 sq. mi
Population (Oahu): 976,372
Density (Oahu): 632/km^2
Total GDP (HI): $62 Billion
GDP per capita: $48,000 (Honolulu County)
Annual Avg. Temperature: 69.6° - 84.6° F
Annual Avg. Relative Humidity: 68.5%
Annual Avg. Precipitation: 17.1 in
Avg. Solar Irradiance: 5.43 kWh/m^2/day
Optimal Solar Panel Angle: 69° (based on yearly avg.)

[35] David Oakley, *Tropical Houses; A Guide to Their Design* (London: Batsford, 1961).

In relation to the quandary of urban density, which of these energy efficient and or renewable technologies' stands out as being a possible competing interest to the current form of fossil fuel energy within the Hawaiian region? Here is a break down of some of the existing technologies and what their role could be in powering Hawai'i's future:

I. Methods and Renewable Technologies:

A. Energy Efficiency
B. Wind Power
C. Wave Energy
D. Biofuels
E. Geothermal
F. Concentrated Solar Power
G. Photovoltaics

A. Energy Efficiency

Greater energy efficiency seems to be the immediate solution and tangible response to the issue of natural resource consumption, exponential energy demand, climate change and greenhouse gas emissions. Energy efficiency should also be the driver when designing any building in regard to the specifications of its components, products and its holistic design elements within the built environment. Energy efficiency is a factor in determining whether using fossil fuels or renewables in maximizing the $/performance ratio.

Energy Efficiency measurements are seen as trying to enhance a buildings energy cost savings abilities and is typically a voluntary endeavor based on cost and time constraints. There are programs and industry standards that are shaping and establishing performance benchmarks which both address energy and the environment the most common one is Energy Star®. Developed in the U.S. in 1996, the Department of Energy (D.O.E) and the Environmental Protection Agency (EPA), it was established "to promote energy efficiency for individual products, in recognition that increased energy efficiency reduces carbon dioxide emissions."[36]

This rating system seems to be the most popular trend in buildings to able to help architects and engineers build more energy efficiency structures, which are backed by an industry consensus. Similar to this, you have the U.S. Green Building Councils Leadership in Energy and Environmental Design (LEED) program. LEED states that it is "a green building certification program that recognizes best-in-class

[36] Adler, *Green Building,* 248.

building strategies and practices…[and in order]…To receive LEED certification, building projects satisfy prerequisites and earn points to achieve different levels of certification. Prerequisites and credits differ for each rating system, and teams choose the best fit for their project."[37]

The LEED rating system is certified, silver, gold and platinum; in that hierarchy. This is a good start in the right direction and affects both the market place of the built environment and a building's performance but also that of the end user and the industries of the architects, designers and engineers whose goal is to maximize building performance potential and profitability. These rating systems will continue to improve, as LEED is still in its evolution process and still has a host of problems.

Industry rating systems shape how building codes are developed and interpreted. These ideals should always be in a developer's mind. However, the underlying issue of energy efficiency is that you still have to use fossil fuels to generate power. Not all system designs are 100% free of fossil fuel use. That will change in future though once renewable technologies can compete on a $/kWh basis with traditional fossil fuels and changes are made to their embodied energy factor and their material makeup.

B. Wind Power

At 4% of total electricity production in Hawai'i, the use of horizontal axis wind turbines has come to define the Hawaiian landscape of the O'ahu's North Shore. The company First Wind, constructed two wind farms, in Kahuku and the other in Kawailoa, which have a combined total power capacity of 99 MW. At full potential this has been able to supply power to 7,700 homes.[38] This has come as an economic benefit in diversifying Oahu's utility grid and lowering energy costs overall and in more isolated parts of the island. However it has also come at a price of cultural conflict with what the 420' turbines, which is 9' shorter than the tallest building in the state, are doing to the Aina (land), in terms of visual aesthetics and its appearance of man conquering nature. There are also concerns about the environmental impacts at the base of the turbine and the kill rate of its local birds.

Technical issues arise based on the issue that wind power is constricted and seems to be exhausted on the island of O'ahu. This is due to land scarcity and the geography needed to garnish dependable energy from regions that are constantly

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[37] "LEED," U.S. Green Building Council, Accessed September 4, 2014, http://www.usgbc.org/leed.
[38] "*Clean Energy. Made Here,"* last modified August 27, 2014, http://www.firstwind.com/.

windy. There is also the fact that the wind isn't constantly blowing. This has forced First Wind to diversify its energy capabilities and lead them to now invest in solar farms; of which they were just awarded through a Power Purchase Agreement (PPA) with Hawai'i Electric Company (HECO) of 200 + MW of solar power.[39] There are also issues as to the total cost of the wind power system. It is said that the lithium-ion battery storage system, to harness and distribution the generated wind energy, is more expensive than the wind turbines themselves.

The main issue that has arisen from wind being a major power provider on the island of O'ahu is the issues of interisland dependency. This would mean that if Wind Power was expanded to neighboring islands, O'ahu would have to rely on the islands of Lana'i and Moloka'i for exporting wind energy. They would have to export the wind power to O'ahu through an underwater electrical sea cable that could cost "a billion dollars" (in 2010 a dollar amount) and increase overall utility rates. It is also said that, "none of the electrical power generated from the proposed windmill project[s] will serve the homes on these two islands."[40]

This brings into the picture issues of contention in trying to work with and convince local communities outside of Oahu (the area that needs the most power) of adopting wind power when they themselves do not benefit from its implementation neither economically, visually nor culturally. Regardless of these constraints wind power is a major contender in the area of renewables, now in places outside of Oahu, and how it will shape the Hawaiian grid.

C. Wave Energy

It was estimated by the Electrical Power Research Institute (EPRI), a utility researched, non-profit organization, that each of the eight Hawaiian islands could generate all of its electrical needs through using wave power technology.[41] This technology is known as "Blow-Hole Wave Energy System." This technology is based on turbines strategically placed offshore to generate renewable energy. Benefits arise from that fact that it only needs a six-inch swell to generate electricity.

As described by University of Hawai'i Professor Henry Curtis in the book *The Value of Hawai'i*, the technology works is through "A two-way air turbine [which] spins in the same direction as the goes in and out, generating electricity….[by]…Having the

[39] Ibid.
[40] Howes,and Osorio, *The Value of Hawai'i,* 216.
[41] Howes,and Osorio, *The Value of Hawai'i,* 182.

spinning device rotating in the same direction regardless of which way the air is moving significantly increases the efficiency of the generator."[42]

However, it could potentially create aesthetics and cultural issues similar to wind power in that it is a physical structure that rises "…about thirty feet above sea level."[43] There is currently one in operation of off the North Shore of Maui. However other issues that can arise from this is system:

- Expensive to build
- Very location specific
- Non-continuous, storage or grid-backup required
- Locations are often remote
- Barrages may restrict access to open water
- Can change tidal level of surrounding area
- Impact on fish, marine mammals and birds
- Disrupts regular tidal cycles
- Decreases salinity in tidal basins
- Captures dirt, waste and pollution near the coast
- Reduces kinetic energy in the ocean[44]

In regards to this design research project, the technology of wave energy does not seem to be a feasible option in retrofitting a building unless you were doing wharf-side architecture design in an area of high wave patterns; which is not the case.

D. Biofuels

In the 19th century biofuels were the staple for energy electricity in Hawai'i. This was due to the abundance the sugar and pineapple plantations which produced bio-waste and other agro-waste that agricultural businesses were in surplus of during that time. However, with the dawn of the oil age of the 20th century, biofuels have been fighting to regain their place in diversifying the islands energy options. Biofuels are starting to regain composure and their viability as a renewable energy option.

This is because of places like Brazil and the U.S., which when combined produces 83.5% of the world's ethanol biofuels, are leading the way and innovating to replace fossil fuels with biofuels.[45] Seeing how Hawai'i shares a similar latitude and climate with Brazil, biofuels seems like a natural option for renewable energy technologies.

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[42] Ibid.
[43] Ibid.
[44] Tidal Power: Pros and Cons," last modified June 1, 2012, http://www.triplepundit.com/2012/06/tidal-power-pros-cons/.
[45] "World Fuel Ethanol Production," last modified 2015, http://ethanolrfa.org/pages/World-Fuel-Ethanol-Production.

However, issues of implementation on an industrial scale are important to list:

- Uncertainty as to which crop and what island region its conditions will provide a solution.
- Landowners unwilling to dedicate their land to biofuels.
- The biofuel refineries and infrastructure used to convert biofuel crops are not available.
- The water, land and labor issues have not yet determined.[46]

Other issues from the production of biofuels are in areas like that of South East Asia wherein Indonesia and Malaysia have "slash and burn" techniques of clearing the rainforest for Palm oil production which then needs to be refined in Singapore and in the Amazonian rainforest, which is decimating the local flora and fauna and accelerating and contributing to the overall climate change issue.[47] These events were evident in my travels to Singapore where the product of this energy method is immense air pollution, continuous haze during in the burning season and negative effects on human health.

E. Geothermal

Geothermal in similar to wind power in that it sounds like a good idea in supplying renewable energy to the utility grid within the Hawaiian Islands. There is currently a geothermal power plant in the big island of Hawai'i that has been in operation since 1992 called the Puna Geothermal Venture (PGV). It has a power capacity of 38 MW.[48] It follows a similar path of wind power in that if the state could establish an underwater sea cable it could deliver power from the big island of Hawai'i then to Maui then Oahu. With this an established model of state wide renewable energy infrastructure could be set in place. This has been in conception since the 1980's when geothermal like wind was looked at to power the state.[49]

With the volcanic activity that Mauna Kea has displayed for over 30 + years, the potential for a new energy source emerges. The success in geothermal is, unlike wind power, lies in the fact that there is no visual hindrance with obtaining a renewable power supply. Geothermal operations could be contained on site with little effect to outside districts. Being able to convince the local community to deal with exporting power and paying taxes that are not going to benefit them directly is a hard sell. Another issue that exists is one of cultural significance relating to volcanoes. The belief that deity Madame Pele, the Goddess of Volcanoes, should not be tampered with or

[46] Howes and Osorio, *Value of Hawaii,* 181.
[47] Ibid.
[48] "Puna," Ormat Technologies Inc., last modified 2015, http://www.ormat.com/case-studies/puna-geothermal-venture-hawaii.
[49] Howes and Osorio, *The Value of Hawai'i,* 180.

disturbed, is a well known theme that Native Hawaiians have been known to protest against the PGV.

Geothermal's green credentials are under attack because some environmental concerns it has raised within the Puna community. As mentioned in the article *Hawaii Residents Raise Serious Concerns about PGV, Geothermal Energy's Clean Energy Credentials,* it was stated that the local community had concerns with the geothermal company Ormat Technologies and the results of its operations leading to:

> "Open venting of geothermal gases and liquids rife with toxic chemicals and heavy metals, poor environmental monitoring, control and reporting, corporate lies, lax oversight and a particularly troubling, even seemingly nonchalant disregard for residents' repeated requests to local government and state authorities to investigate their concerns and claims command attention and raise very serious environmental health and safety questions regarding geothermal energy's credentials as a 'clean, green' energy source."[50]

Even though this presents grave concerns on geothermal viability as a renewable power source within the Hawai'i, if these concerns and problems could be resolved, geothermal energy could offer an alternative to the fossil fuels that the state currently uses to power its infrastructure.

F. Concentrated Solar Power

Currently, the most powerful and efficient form of solar power comes from Concentrated Solar Power (CSP). It has its roots in the days of the Romans and Renaissance times of trying to use mirrors to channel and harness the suns energy; and it's extremely effective. It is based on thermally heating water to power a turbine by focusing the power intensity of the sun light through mirrors, which track the sun throughout the day and consists of no semiconducting materials. It has an efficiency rating of 31%, with a laboratory research testing and result of 44.4%.[51] It could possibly be the renewable utility grid of the future once energy storage and long-range electrical transmission is perfected.

The shining example of this is the Ivanpah Solar Power Facility in the Mojave Desert in California. Finished in late 2013, it is the largest solar-thermal plant in the world. It consists of three solar-thermal towers and it generates a maximum capacity

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[50] "Hawaii Residents Raise Serious Concerns About PGV, Geothermal Energy's Clean Energy Credentials," last modified April 28, 2012, http://cleantechnica.com/2012/04/28/hawaii-residents-raise-serious-concerns-about-pgv-geothermal-energys-clean-energy-credentials/.

[51] "NREL Best Research Cell Efficiency," last modified August 29, 2013, http://energyinformative.org/nrel-efficiency-record-two-junction-solar-cell.

factor 392 megawatts. It was report that this is enough "to power 140,000 homes and eliminates carbon dioxide emissions equivalent to 72,000 vehicles a year."[52]

However efficient this utility solar power is, the scale and size of land it needs would clash with Hawai'i's isolated and land scarce conditions. In addition, it is better suited for desert locations and it cannot be integrated into the built environment. Further issues arise in the fact that and is posing unintended ecological consequences on local fauna.

Evidence of this is the fact that the Ivanpah Facility is projecting solar radiation so powerful that it is killing about 28,000 birds per year which are being ignited mid air trying to eat the bugs that are attracted to the light being produced by the mirrors. It is even said that "birds [are] dying at a rate of one bird every two minutes. The burned-up birds are being dubbed "streamers," after the poof of smoke produced by the igniting birds."[53]

This is green technology having unintended consequences on the very ecology and environment that it is promoting on protecting. You can see the future issues that might arise from this but in regards to this design research project you cannot integrate this technology into a building even on an industrial scale.

G. Photovoltaics

Sales and installations in Photovoltaic modules, aka Solar panels, have boomed in the residential and commercial sectors. This is providing a substantial price drop in photovoltaic (PV) materials & production costs, advancements in efficiency output and an increase in the availability of tax incentives. This evolution and increased material supply has created a technological convergence within PV, which is aiding to infrastructural upgrades within the built environment throughout Hawai'i, and the contiguous U.S.

This will make PV an economic competitor with traditional fossil fuels when it reaches grid parity – the price point at which solar energy becomes economically competitive with the wholesale energy market – which is estimated to stand at $0.06 per kilowatt-hour vs. the current Hawaiian $0.36 per kilowatt-hour.[54] As you can see there still is a long way to get to this point, remember though that Hawaii has the highest $/KwH in the U.S., but it is possible seeing the use of finite fossil fuels

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[52] "New Solar Plants are Incinerating Birds," last modified August 18, 2014, http://www.weather.com/news/solar-plants-birds-20140818.
[53] Ibid.
[54] "Electric Power Monthly," data for November 2014, http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a

continuing to rise in price as the cost of renewables continue to drop; which has happened on all fronts.

With regards to this design research project, specifically looking at the archipelago of Hawai‘i as the applicable region with which to identify and target the correct renewable energy technology to be integrated within its buildings, none of the above mentioned renewable technologies seem to have the ability of building integration like that of Photovoltaics (PV). Methods and Renewable Technologies sections B – F are viable options in modernizing the utility grid and delivering renewable energy to a system that desperately needs it. However, these options are non-integrable at any direct level into a building. The application of energy efficiency and Photovoltaics into the buildings envelope is possible.

The solution to this could be the merger between Energy Efficiency and Photovoltaics. With the advent of Building Integrated Photovoltaics – photovoltaic materials used to replace conventional building materials – it can help with the transition towards sustainable energy autonomy. This shapes the way we use and conceptualize the utility grid and architecture. By activating the power supply within the building envelope that emphasizes site energy, BIPV can provide a more innovative sustainable energy strategy, explore new forms within the spatial aesthetics of the urban fabric and act as a new multifunctional and performative building material to be utilized in the tropical regions to solve a multiple of energy issues.

Conclusion:

Based on these methods and renewable energy technologies, Hawai‘i and global progress in sustainable power applications are being achieved and will set the standard(s) for the 21st century. In the converging arena of climate change, urban density and population rise, what will be the technology, applications or solutions to solve these issues? Will there be a dominant format or single method, similar to how oil staked its claim, of renewable energy that will emerge? This emerging technology might not be the total solution but a contributing factor of the overall solution. BIPV is cog to this overall solution. Whether it can be “the” emerging factor of renewable energy usage remains to be seen. However, BIPV’s larger potential in the energy picture stands as very promising in future of looking at building’s as conduits of electrical power and resourceful energy harvesters encapsulated in architecture. This is the diversity that BIPV brings to the built environment and architecture as a whole.

CHAPTER 2:
Building Integrated Photovoltaics

2.1. Architectural Interoperability

Building Integrated Photovoltaics (BIPV) can be designed and placed in new, as well as, existing structures. Currently, throughout the solar and building industry, BIPV is considered an architectural niche and design intended for new building projects. This is due to BIPV products' and its availability happening only in boutique markets. A demand for modular BIPV products and systems are acknowledged in the architectural industry, but a turnkey solution, system or methodology has yet to come to fruition for such a demand. However, what is guiding this demand is in BIPV's true potential, which lies in offering features of architectural "interoperability" or "the ability of a system to work with or use the parts or equipment of another system."[55]

This concept and application of interoperability has its roots in information technology, but is not restricted to this field. An example would be a USB storage device, which could be considered interoperable object as it is universal to any computer hardware system but also holds software that can be used in several interfaces or other peripheral technologies.[56] The idea to "inter-operate" is analogous to combining and or streamlining complex data, materials and services. This integration allows for systems to communicate better as cross compatibility increases efficiency and adaptability. This interchangeable feature in BIPV creates both a new building aesthetic and possibilities in utilizing site power through renewable energy technology; i.e. architectural solar panel integration.

The concept of BIPV's interoperability in its achievement of architectural hybridity- when systems of sustainable technology are merged with that of traditional building components: roofs, walls, shading devices, skylights, glass or etc. This allows BIPV to generation power and fuse seamlessly within the building envelope.

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[55] Merriam-Webster.com, s.v. "interoperability," accessed January 3, 2015, http://www.merriam-webster.com/dictionary/interoperability.

[56] "What is Interoperability?," NCOIC, accessed January 16, 2015, http://www.ncoic.org/what-is-interoperability

Increased interior thermal performance and daylighting, which yields greater positive effects on the end user's comfort level and increased human productivity, can be byproduct of BIPV. A BIPV design strategy provides for fewer building materials used with the added benefits of harvesting renewable energy, solar control, glare reduction, protection from weather elements and passive shading. BIPV replaces conventional building materials, which lower building material costs, minimizes construction time and added labor, and reduces energy waste. BIPV serves multiple roles (cladding, shading device and etc.) and therefore eliminates the need for these as separate elements (Fig. 2.1).

BIPV reduces operation and maintenance (O&M) costs due to PV's nature as a fixed in place element, as opposed to ground mounted sun tracking PV technology, which is very costly and incurs more O&M costs. As mentioned in, *The Building Side of Building Integrated Photovoltaics*, Architect Jesse Henson explains succinctly this interoperable concept that underlies BIPV by stating:

> "If you compare the cost and installation time for a BIPV skylight…with the same quantity of skylight glass and a separate conventional PV system, the BIPV skylight has a lower total cost. Further, the BIPV skylight should have less environmental impact since fewer materials are used to achieve the same result: power generation, building enclosure and natural daylighting."[57]

Implementing these smart building techniques in the initial construction phase creates the benefits of energy generation, energy and fiscal savings. The BIPV system pays for itself, up until the initial investment is recouped, then generates positive economic savings for the life of the system.

Due to the climate change and its energy implications, society is demanding more from their buildings in terms of energy use, aesthetic representation, technological performance and "plug and play" amenities. BIPV provides all these elements plus it reduces utility costs through on-site renewable energy generation with the goal of maintaining a certain energy use standard of living. This concept of interoperability requires industry acceptance over time.

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[57] *"The Building Side of Building Integrated Photovoltaics",* 1.

Figure 2.1. Example of BIPV building material replacement

Source: Brooks and Scarpa Architecture
Accessed: November 15, 2014. http://www.brooksscarpa.com/projects/green.dot

BIPV energy conservation of cooling or heating demands equates into fiscal savings through reducing on-site energy consumption otherwise obtained from utility grid sources. This allows the total electrical loads to be utilized through re-networking its power delivery system, which now focuses on independent power acquisition primary occurring within its surrounding environment. Energy creation and loss dynamics become more efficient when BIPV focuses on independence from the grid via emphasizing methods of site energy utilization.

However, there exist major barriers to entry of BIPV which hinder its broad base adoption and use:

- The fractured relationship that exist between the solar, architectural, engineering and construction industries (Fig. 2.2).
- There is not a consolidated energy metric. Contractors configure $/ft^2 vs. Solar Installers which are $/Watt. These two things need to integrate with one another to rethink 21st century architecture.
- High $/watt/installation costs vs. its associated $/performance costs.
- Compliance of BIPV products with legal building requirements.[58]
- High initial costs: BIPV projects typically have a 10% premium, or more, which adds $0.15-0.22/watt installed.[59]
- Utilities companies' monopoly on large-scale power creation to energy distribution.
- Requires 3rd Party approval, application and inspection fees.
- Battery technology is not technologically advanced enough to utilize solar power into mid-to-long term energy storage and distribution and its cost remain relatively high.
- Specific simulation, component libraries and design software programs for Building-Integrated Photovoltaics (BIPV) products and materials do not exist, or do so in expensive beta testing phase.
- Lack of consumer knowledge or education about BIPV.
- BIPV is a nascent industry, which means it's typically a custom job. This highlights the business need to develop modular forms of implementation, installation and turnkey production.

The above-mentioned are factors to consider in reaching a new concept of BIPV interoperability. To be able to arrive at such a solution the Architect, as master builder, must push the envelope in the way we conceptualize buildings, human function and energy use. A conceptual approach invites architects, civil engineers and builders to understand BIPV interoperability.

One focus necessary to be examined by all must include the saving's in time management and economic gain that can be obtained with BIPV. One new method of doing this is in fusing the metric of $/ft^2 and $/Watt, thereby integrating the sustainable incentives of $/ft^2/Watt or "$/ft^2/kW together.

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[58] BIPV projects have to be UL approved separately which can significantly slow down a project, which incurs a longer duration of labor and high construction costs.

[59] Ted James, Goodrich, Woodhouse, et al., "Building-Integrated Photovoltaics (BIPV) In the Residential Sector: An Analysis Of Installed Rooftop System Prices," 8 http://purl.fdlp.gov/GPO/gpo16397..

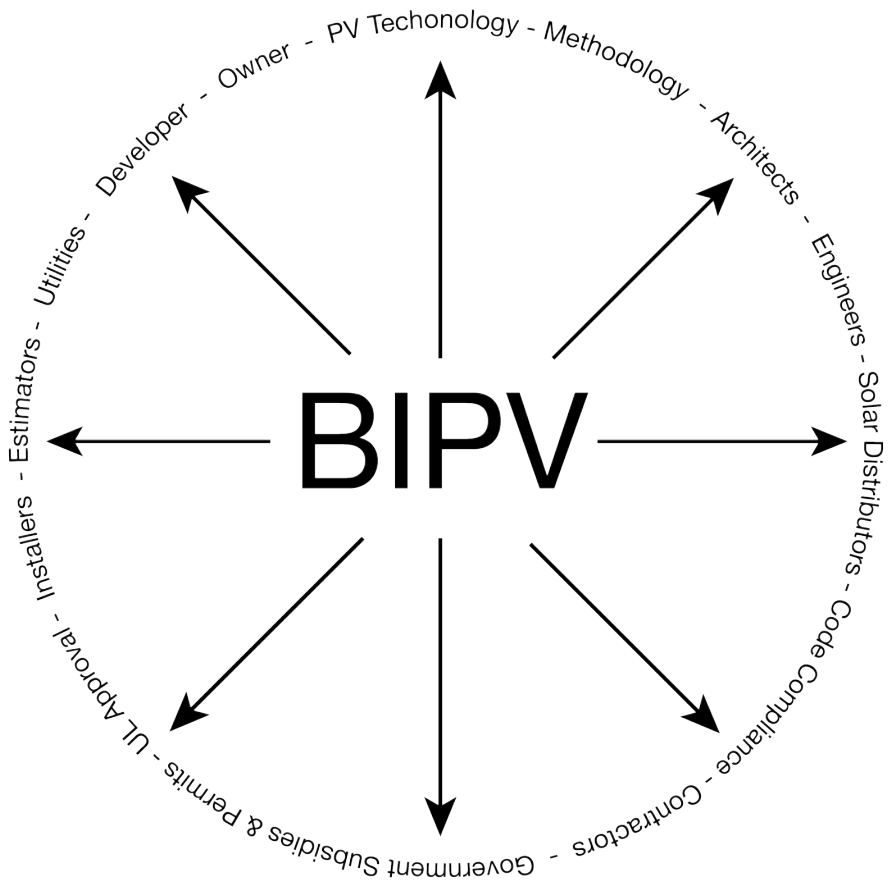

Figure 2.2: Fractured BIPV development chain

If we incentivized the cost of construction with cost of energy savings, both in embodied energy and electricity savings, into one metric, major capital could be created, time could be efficiency utilized and ecological and social benefits could be created. This is no easy task as not only defining a "$/ft^2/Watt or "$/ft^2/kWh" metric but also instituting it on a broader scale could add complexity to future building technologies, codes, requirements, specifications and building methods. This can be seen in programs like U.S.' Leadership in Energy & Environmental Design (LEED), U.K's Building Research Establishment Environmental Assessment Methodology (BREEM) or Singapore's Green Mark program. As much as they want to make buildings more efficient and economically and ecologically viable, they add much complexity to the system as a whole.

A principle goal within BIPV is in streamlining this complexity through establishing a building template based on the interoperability of electrically

regenerative building materials and surfaces. Conceptually and intrinsically, what this does is utilize the dual benefits of active and passive energy acquisition and savings, which provides sustainable Return on Investment (ROI), energy efficiency, architectural energy autonomy and environmentally sound practices.

For this to occur there needs to be a construction and building material incentive where BIPV guides the process of creating a "$/ft^2/Watt or kWh" metric. This equation communicates how we should build based on the bigger picture of how we consume, waste and utilize electrical energy. This equation has been a conceptual obstruction within BIPV's wider industry adoption, squared against BIPV being at its industrial infancy.

Yet, if the infrastructure of a BIPV industry were to be moderately in existence a BIPV movement and standardization of BIPV and its interoperability could be accepted by the building industry. This future projection was the basis of a study done by the National Renewable Energy Laboratory (NREL) in Golden Colorado, where it found that, "…of the more than 5,000 commercially available modules, less than 5% were listed as BIPV."[60] This has compounded BIPV's relative obscurity. The lack of consumer adoption driven by the market place was noted by NREL in *Building-Integrated Photovoltaics (BIPV) in the Residential Sector: An Analysis of Installed Rooftop System Prices:*

> "For more than 30 years, there have been strong efforts to accelerate the deployment of solar-electric systems by developing photovoltaic (PV) products that are fully integrated with building materials. Despite these efforts and high stakeholder interest in building-integrated PV (BIPV), the deployment of PV systems that are partially or fully integrated with building materials is low compared with rack-mounted PV systems, accounting for about 1% of the installed capacity of distributed PV systems worldwide..."[61]

2.1.1. Technological Costs of BIPV

Low cost/highly efficient BIPV modules are not yet available which precludes their widespread industry acceptance. The overall consensus among architects, engineers, contractors and PV insiders is that BIPV has not flourished

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[60] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, *Building-Integrated Photovoltaics (BIPV) in the Residential Sector: An Analysis Of Installed Rooftop System Prices,* by Ted James, Alan Goodrich, Michael Woodhouse, Robert Margolis, and Sean Ong, Technical Report November 2011, National Renewable Energy Laboratory (Golden, Colorado, 2011), http://purl.fdlp.gov/GPO/gpo16397.

[61] Ibid.

because its price/performance variable is not yet competitive with conventional rooftop PV systems. One of the technical disadvantages currently playing out in BIPV is the limited energy storage due to expensive battery technology.

Battery technology is a major component that is material to BIPV's success. Battery storage is a major factor to BIPV offering a competitive alternative to grid technology. Currently, battery storage falls behind BIPV technology and drags the potential of BIPV's cost effectiveness. PV technology needs to reduce cost and enhance in energy performance to compete with grid technology.

So what are the costs of a PV module vs. the total installed cost of a PV system? As seen below in figure 2.3, the total cost of a PV system is examined. The total cost of a solar panel system may vary, yet a reliable metric used is $/Watt, when establishing the total installed cost. As you can see the total systems cost is about two-thirds (2/3) more expensive than that of $/Watt of its main component: the PV module. Lowering PV module cost will make total costs lower. Yet, operational costs, Balance of System (BOS) and Permits, Fees and inspections expenses need to be reduced in order to lower the total cost of a solar panel system. For this project I was quoted at $4.85/Watt for the total installed costs. Based on this we can assume that the panels will only cost $1.45/Watt.

As PV technology experiences more widespread global use, lower $/Watt per PV module costs are achieved. This also lowers the overall installed cost of a PV system. As mentioned in *Detail* magazine's BIPV issue *Photovoltaics A-Z*, it states that, "There is an unwritten rule in the PV sector: With every doubling of output from installations worldwide, module prices will fall by around 20%. Recently this has been the case every two years, resulting in costs falling annually by 10%."[62] This comes as a benefit to BIPV at a time when fossil fuels are finite and incur high environmental, social and economical costs, PV is continuing in a reduced price curve that will assist in BIPV conceptual and actual acceptance in the building industry.

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[62] Roland Krippner, "Solar Technology in Building Envelopes," *Detail*, July 2012.

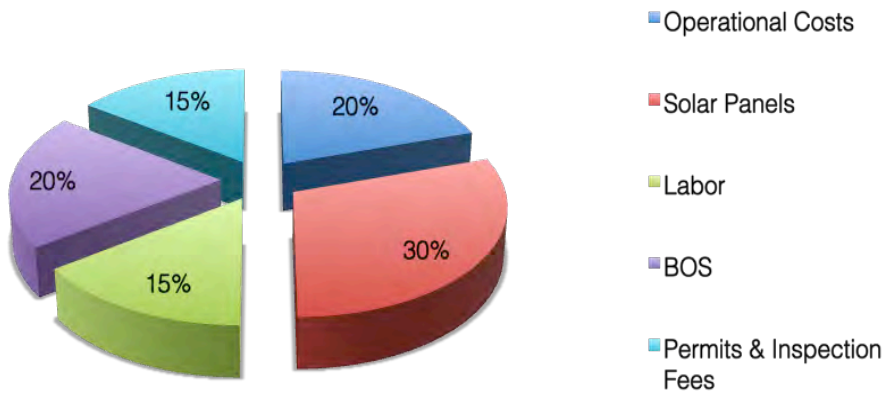

Figure 2.3: Total cost of solar panel system[63]

When evaluating energy and costs functions, a good energy metric to use is the Levelized Cost of Energy (LCOE). What the LCOE does is compares conventional energy, i.e. fossil fuels, with that of renewable energy. This industry metric known is defined by the U.S. Energy Information Administration as being a:

> "…convenient summary measure of the overall competiveness of different generating technologies….Key inputs to calculating LCOE include capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant…"[64]

The current limiting factor for PV, and BIPV, is the price of energy and where energy needs to be to reach grid parity. To find this we need to hit a price point below that of the cheapest forms of conventional energy: coal and petroleum. Currently, the LCOE for Coal is $108.50/MWh vs. $151.50/MWh for PV. As you can see PV has a price gap of about $43.00 that needs to be closed before grid party can be achieved.

When you compare both of these prices next to Battery Technology, its cost is even higher standing at $294.5/MWh.65 The renewable energy/technology price gap is a ways off from being economically competitive

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[63] Energy Informative, How Much Do Solar Panels Cost, Accessed: February 2,2015. http://energyinformative.org/solar-panels-cost/

[64] U.S. Energy Information Administration, "AEO2014 Early Release Overview," Analysis and Projections, http://www.eia.gov/forecasts/aeo/er/index.cfm.

[65] ""Lazard's Levelized Cost of Energy Analysis – Version 8.0," last modified September 2014, http://www.lazard.com/PDF/Levelized%20Cost%20of%20Energy%20-%20Version%208.0.pdf., pg. 2. *Numbers of comparison were derived from taking the mean of Coal, Solar PV – Rooftop C & I and Battery Storage.

with conventional forms of energy. However, it can be expected that this gap will be closed as it is mentioned in the *EIA Annual Energy Outlook 2014*, that:

> "For technologies such as solar and wind generation that have no fuel costs and relatively small variable O&M costs, LCOE changes in rough proportion to the estimated capital cost of generation capacity. For technologies with significant fuel cost, both fuel cost and overnight cost estimates significantly affect LCOE."

This assumes that fuel costs rise as a continuing factor, which will also raise the cost of conventional forms of energy. Renewable energy, on the other side of the argument, is able to bring down the overall technology, hence it becomes more cost competitive. The above LCOE estimates consider only the technologies at an unsubsidized market price rate. In Hawai'i, the state and federal subsidies for PV equate to 65%. From this it can be assumed that the new LCOE for solar went from $151.50/MWh down to $98.40/MWh. This allows renewable energy, and BIPV as a whole, to become a competing factor for sustainable energy integration and utilization.

Asides from the lowering cost of PV technology what remains as an additional hindrance is that most BIPV exist in the form of rack mounted PV products which are "re-appropriated" onto the building design. This current and popular use represents an application of Building Applied Photovoltaics (BAPV), and not a full integration of parts and systems. The BAPV aspect is detrimental to both the qualitative and quantitative aspects of BIPV as new method of construction, interoperable object and philosophy.

The lack of BIPV products is the quandary that architects and designers are currently facing. As mentioned in the *Photovoltaics in an Architectural Context*, "When it comes to costs, maximizing revenues and implementation/technical requirements, the architect often has no convincing argument for combining the architectural and aesthetic qualities with the possibilities offered by PV systems."[66] This is a sentiment that I hear constantly amongst practicing architects, however I challenge this notion as the evidence above proves contrary. The elements that are needed for BIPV's success can occur it just depends on when, how and in what form.

BIPV adds value to a structure through offering architects and builders advanced concepts in 21st century design by creating on-site activated building

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[66] Henk Kaan and Tjerk Reijenga, "Photovoltaics in an Architectural Context," *Progress in Photovoltaics: Research and Applications 12,* no.6 (2004): 396.

surfaces that are electrical conduits for a renewable power supply which doubles as traditional passive building elements. There is even greater potential of future urban smart grids and power sharing among city centers and buildings using BIPV and its interoperable features. BIPV offers a new vision.

2.1.2. Photovoltaic Material Science

Photovoltaics (PV) is the process of generating a direct current (DC) of electricity via the conversion of solar radiation through semiconducting materials, typically silicon (Si), to create the "photovoltaic effect". This effect is a two-step process consisting of the absorption of the light, in the visible and some of the infrared range of the electromagnetic spectrum, and the distribution of its energy charge through a semi-conducting substrate, aka solar cell.[67] The book *Photovoltaics in the Urban Environment: Lessons Learnt from Large-Scale Projects*, best summarizes this scientific process:

> "In most solar cells the selective interface (junction) is formed by stacking two different semiconductor layers…(so-called 'p' and 'n' type). This junction can be formed by adding different types of impurities (dopants) to the layers on both sides of the semiconductor. The key feature of a semiconductor junction is that it has a built in electric field, which pushes/pulls electrons to one side and holes to the other side. When the two sides of the junction are connected and an electrical circuit is formed a current can flow (i.e. electrons can flow from one side of the device to the other)."[68]

By the sun charging solar cells to photoexcitation, (Fig. 2.4), the energy charge delivers an electrical transfer that then goes through wires stringed together which form a PV Module, a.k.a., a Solar Panel. It is then fitted with electrical junctions and encased in laminated plastic or glass. The solar panels are then linked together by way of electrical connections and wires that are collectively known as a "PV Array" (Fig. 2.5). Furthermore, the metric used to measure the power transfer of solar radiation is called "solar insolation." It is defined as "measure[ment] of solar radiation energy received on a given surface area in a given time…[and is]…It is commonly expressed as average

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[67] Bruno Gaiddon, Henk Kaan, and Donna Munro, *Photovoltaics In the Urban Environment: Lessons Learnt From Large-Scale Projects* (London: Earthscan, 2009), XX, accessed 11/24/14, http://public.eblib.com/choice/publicfullrecord.aspx?p=471073.

[68] Ibid., 146.

irradiance in watts per square meter (W/m^2) or kilowatt-hours per square meter per day (kWh/m^2/day)…"[69]

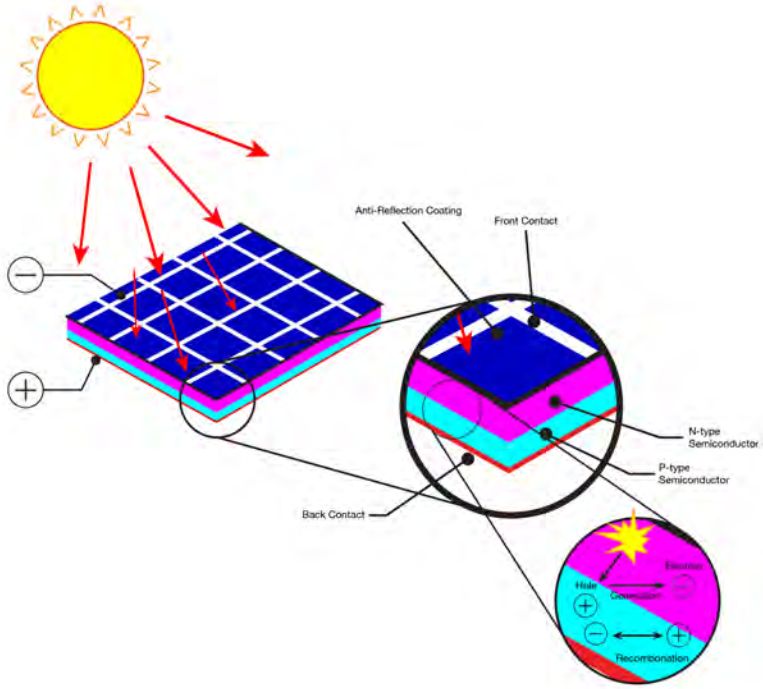

Figure 2.4: Photovoltaic process

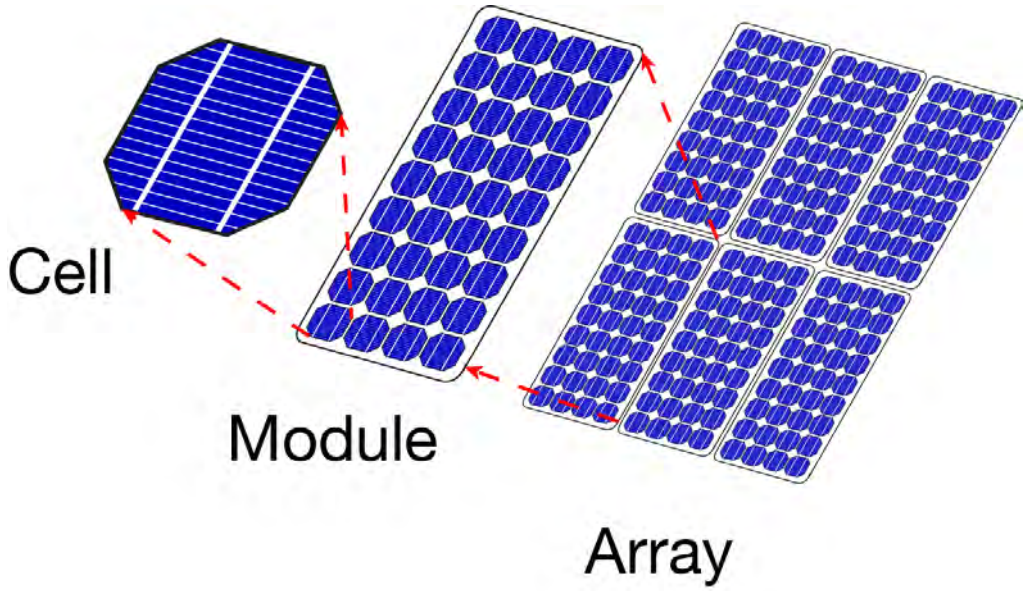

Figure 2.5: Photovoltaic unit to whole assembly

[69] "Solar Insolation," last modified January 15, 2012, http://solarinsolation.org/.

Electricity travels through an inverter which transfers the DC power into an Alternating Current (AC) power, where it is then calibrated for correct voltage and frequency and distributes reliable power throughout the entire building and out onto the utility grid. The Balance of System (BOS) is comprised of the whole system, cells, modules and arrays, in addition to its components: wiring, mounting racks, inverters, maximum power point tracking (MPPT), connections to the grid and battery storage for off the grid installations.

The industry standard used in evaluating a photovoltaic systems performance and output is the power conversion efficiency or "efficiency rating," which is the amount of incident photon power that can be converted into power. The main advantage of using PV is that it has an abundant power source - the Sun, which on a hot day, gives off 317 BTU/SF/Hour (1,000 watts per m^2)[70].

PV systems are solid-state devices that have no moving parts, are fixed in place, act as a protective weather barrier and generate no sound. PV is an ideal source of power in remote and off-the-grid locations because of its on-site generation of energy; which does not lose efficiency output because it does not have to be distributed over long-range transmission lines.

It is said by the U.S. Energy Information Administration that the national average of electricity transmission and distribution losses are six percent (6%).[71] This number is amazing when you think about the fact that in 2013 the U.S. generated over 38.2 Quads of electrical energy.[72] This amounts to over 11,203,953,889 MWh of energy. If you consider the above 6% transmission and distribution losses in electricity, this equates to over 672,237,233 MWh of losses in electricity or $80,688,467,960.[73]

Monocrystalline Panels: c-Si

Most of the PV panels being used today are Mono-crystalline silicon solar panel (c-Si). These are the majority of solar panels that you see on roofs and are

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[70] Adler, *Green Building*, 122.

[71] U.S. Energy Information Administration, "How Much Electricity is Lost in Transmission and Distribution in the United States?," Frequently Asked Questions, http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3.

[72] Lawrence Livermore National Laboratory and the Department of Energy, "Estimated U.S. Energy Use in 2013: ~97.4 Quads," Flowcharts, https://flowcharts.llnl.gov/content/energy/energy_archive/energy_flow_2013/2013USEnergy.png.

[73] Numbers generated assuming 2011 U.S. average of $0.12/kWh. This also means that these numbers could be even could be even higher seeing how they are based on previous data and a U.S. "average" of 6% in losses. http://www.npr.org/blogs/money/2011/10/27/141766341/the-price-of-electricity-in-your-state

sold globally. They have the highest efficiency rating of any PV panel on the market averaging 15-18%, but some are said to be as high as 22%.[74]
There are also multi-crystalline, aka poly-crystalline (poly-Si), solar cells that used to be popular for BIPV applications because of its blue crystal like granular sparkle, which is called the "metal flake effect." This is phenomenon occurs because, unlike a solid plane of silicon, the poly-Si has a molecular silicone structure of multiple and fragmented crystals. Poly-crystalline has the advantage of being more aesthetically dynamic and increases a designer's palette of colors. It is cheaper than c-Si, however this is due its lower efficiency rating which stands at a high of approximately 15%.

Thin-Film Elements: a-Si, CdTe or CIGS

Second generation Photovoltaic technology is achieved through Thin-Film PV. The oldest to newest elements are: Amorphous Silicon (a-Si), Cadmium telluride (CdTe), Copper indium gallium selenide (CIGS). As PV panels, CIGS seems to be the most promising and actually increases in efficiency in the first six months after installation. The advantages to thin-film are its relatively low costs of production and a reduced mass factor - up to 90% lighter in some cases.[75] It can be rolled out onto sheets and its flexibility allows shaping to linear and or non-linear forms of architecture. This allows architects to experiment with thin-film as a renewable energy building material that offers greater adaption.

Other benefits arise from CIGS's temperature adaptability and utilization of ambient or indirect lighting. In terms of ambient lighting thin-film converts light into useable energy, as opposed to c-Si's ability to only convert direct lighting. As temperatures rise on the panels, the thin-film actually increase electrical output and does not degrade like c-Si. CIGS's disadvantage compared to Mono-Crystalline is that it does not have a competitive $/efficiency rating. The c-Si PV is an accepted product that has a track record going back to 1953. Many solar panel companies shy away from selling thin-film and prefer c-Si, designating longer warranties, contractor recognition and application into buildings. However, this is starting to change as Thin-Film, and CIGS specifically, are more viable and less costly.

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[74] James Montgomery, "SunPower Tops in Mono C-Si Cell Efficiency," *Renewable Energy World,* March 29, 2012, http://www.renewableenergyworld.com/rea/news/article/2012/03/sunpower-tops-in-mono-c-si-solar-cell-efficiency.
[75] Simon Roberts and Nicolo Guariento, *Building Integrated Photovoltaics a Handbook* (Berlin: de Gruyter, 2009), 9.

Below is a table of comparison of the thin-films above. Market penetration and growth are occurring and efficiency gains are being achieved. However, the overarching question remains: When is one of these three technologies going to be able to compete in the market with the dominant c-Si technology on the basis of lower price per higher module efficiency? This has yet to be seen but with the $/efficiency making gains yearly and its applicability and adaptability beyond mere architecture, it is only a matter of time that thin-film becomes the dominate factor.

Table 1: Best performing Thin-Film modules on the market[76]

Type	a-Si	CdTe	CIGS
Best research-cell efficiency	13.40%	19.00%	20.40%
Best solar module efficiency	8.10%	14.40%	14.50%
Thin-Film Market Share	32.00%	43.00%	25.00%
Advantages	Mature technology, Excellent	Low cost manufacturing.	High efficiency Glass or flexible substrates.
Disadvantages	Low efficiency, High cost equipment.	Medium efficiency, Rigid glass substrates, Cadmium is highly toxic	Market share expected to grow. Requires less cadmium than CdTe solar cells.
Major manufacturers	Sharp	First Solar	Solar Frontier

[76] Data based on information from: http://energyinformative.org/best-thin-film-solar-panels-amorphous-cadmium-telluride-cigs/. Last updated September 24, 2014 by Mathias Aarre Maehlum. Accessed 12/15/14.

Hybrids: Gen 1 + Gen 2

There are hybrid modules emerging in both generation #1 PV and #2 Thin-Film PV called "HIT" or Heterojunction with Intrinsic Thin layer(s). This function is achieved by combining c-Si with a-Si materials. It is said that "The back face of HIT Double solar panels generates electricity from ambient light reflected off surrounding surfaces, and combines with power from the front face of the panel…this results in up to 30% higher power generation (more kWh) per square foot."[77]

3rd Generation PV: DSC or OPV

The 3rd generation of PV technology is based in Dye-Sensitized Solar Cell (DSC) and Organic Photovoltaics (OPV). They are a semiconducting thin-film technology that consolidates the best of both generation #1 (efficiency & durability) and #2 (low production costs, low mass & flexibility) but are generated out of more sustainable and cost effective materials. Currently, 3rd generation PV materials are transparent and semi-transparent, flexible and can easily integrate into glass. They come in a variety of colors, can be rolled out on sheets, generate a electrical charge in cloudy conditions, work in interior lit spaces, and theoretically receives an added charge from the UV part of the electromagnetic spectrum.[78]

Commonly known as DSC, Dye-Sensitized Solar Cell(s), it is composed of Titanium Dioxide (TiO_2) covered in cost effective dye molecules to absorb the sunlight. It converts energy through the conduction of platinum, which generates an electric charge, similar to the process of photosynthesis via charging electrolytes within its semiconducting material. With Gen.#3 power efficiency is achieved through its molecular construction, which is different from both crystalline (Gen.#1) and thin-film's (Gen.#2) p-n junction, whose solar cell is "theoretically" constricted to the Shockley–Queisser limit of a maximum efficiency potential of 33.7%[79]. Its efficiency is an average 5%, however it is said that it reached rating high of 15%.[80]

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[77] "Bifacial Photovoltaic Module," SANYO Energy U.S.A. Corp, last modified September 1, 2008, https://www.hepn.com/assets/files/renewables/rushshelby_sanyo.pdf.

[78] "PV cell for invisible spectrum only", Stack Exchange: Physics, accessed February 5, 2015, http://physics.stackexchange.com/questions/31215/pv-cell-for-invisible-spectrum-only.

[79] William Shockley and Hans J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells," *Journal of Applied Physics 32,* no. 3 (1961): 510-519.

[80] "Dye-sensitized solar cells achieve record efficiency of 15%"

Photovoltaic Boundaries & Gans

It was just reported that the University of New South Wales was able to develop and test, in outdoor conditions, a solar cell that achieved an efficiency rating of over 40%. The amazing part about this was that the PV system able to surpass the Shockley–Queisser limit with using only commercial solar cells. [81] The manufacturing of solar cells and photovoltaic arrays has expanded dramatically in recent years to create a photovoltaic industry, which has high appeal through generating electricity from sunlight, silently, with no maintenance, no pollution and no depletion of materials.

None of these achievements have produced an industry, method or product predicated upon and building surface material replacement with solar energy features that can truly be considered a BIPV skin. This is partially predicated on the lack of BIPV knowledge and acceptance as an industry standard.

All these technologies, (fig. 2.6), were created from a growing demand for clean sources of energy, by a heightened awareness of impending climate change, and a drive to develop a more efficient competing power source to challenge the finite and polluting nature of fossil fuels.

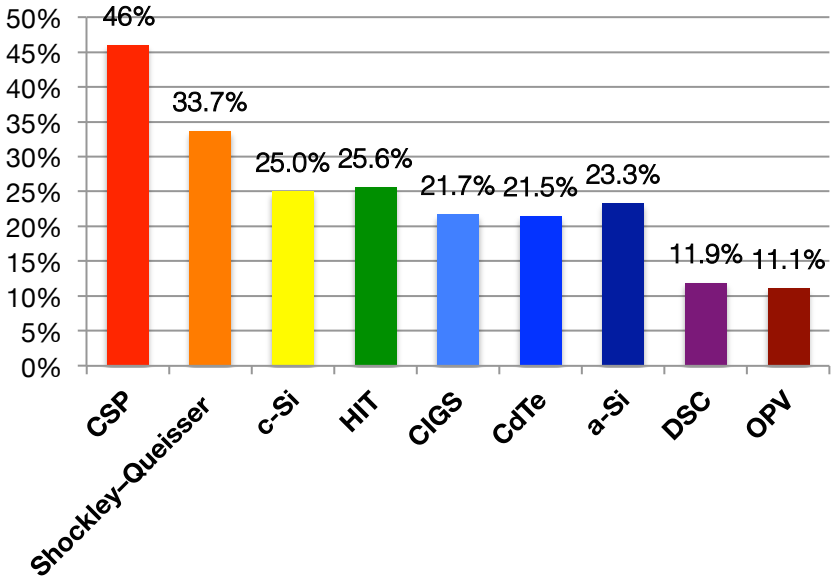

Figure 2.6. Best research solar cell efficiency[82]

[81] "UNSW Researchers Set World Record In Solar Energy Efficiency," UNSW Australia, accessed December 15, 2014, http://newsroom.unsw.edu.au/news/science-technology/unsw-researchers-set-world-record-solar-energy-efficiency.
[82] Numbers generated from "NREL Best Research-Cell Efficiencies". http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

2.1.3. History of BIPV

The French physicist, Alexandre-Edmond Becquerel (1820-1891), created the Becquerel effect, later known as the "photovoltaic effect." In 1839, Becquerel placed two semi-conductors of silver chloride coated platinum electrodes together and immersed them in a nitric acid electrolyte solution and exposed it to light, to produce a current of electricity.[83] Since then the semiconductor has been the prime component of photovoltaic technology.

It was not until 1953, at the Bell laboratories, scientists Daryl Chapin, Calvin Fuller and Gerald Pearson discovered the modern silicon (Si) solar cell. Experimenting with impurities that changed silicon, from a poor to superior electrical conductor, the scientists used a piece of silicon with a small amount of gallium dipped a hot lithium tub and exposed it under a lamp, to render a negative charge out of the silicon material and created a silicon wafer with a conversion efficiency of 6%.[84] Thus the solar cell was born. Solar cells were first used to power satellites.

In the early 1970's, Dr. Elliot Berman engineered a cheaper solar cell by introducing silicon of poorer grade quality and materials, thereby reducing the price of a solar cell from $100 to $20 per watt.[85] This allowed the PV material to shows its economic viability and power capacity potential. This started an industry development of photovoltaic production, testing and material science research.

The Carlisle House, built in 1979, was the very first BIPV "Net-Zero" house - which is a structure that generates as much energy as it consumes over the course of a year – to be constructed (fig. 2.7).[86] Since then it has set precedence as what BIPV looked like and how it functioned.

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[83] "History of Computers and Computing, birth of the modern computer, bases of digital computers, transistors"

[84] U.S. Department of Energy, Office of Science and Technical Information, *The Silicon Solar Cell Turns 50*, by John Perlin, National Renewable Energy Laboratory (Golden, Colorado, 2004), http://www.osti.gov/servlets/purl/15009471-Jg9qgS/native/.

[85] Mario Pagliaro, Giovanni Palmisano and Rosaria Ciriminna, *Flexible Solar Cells,* (Weinheim: Wiley-VCH, 2008), 46-47.

[86] "*The Building Side of Building Integrated Photovoltaics*"

Figure 2.7: The Carlisle house c. 1979

Source: Solar Pro
Accessed: June 15, 2014. http://solarprofessional.com/articles/products-equipment/modules/the-building-side-of-building-integrated-photovoltaics

The term BIPV came into use in the early-1990's, through a pilot program conducted by the Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) called "PV: Bonus". As mentioned in the paper *BIPV: High on the Agenda for Survival* by Professor Susan Roaf, it describes the BIPV program as being:

> "…focused upon developing products, called Building Integrated Photovoltaics (BIPV) that can be readily attached to buildings, and provide for a higher level of use of solar technologies by making their integration into the building structure easy to achieve and capable of being considered routine."[87]

One of the most revolutionary concepts that supports future adoption of BIPV as a key sustainable method to construction, is a concept of applying the theory of photosynthesis to building applications. As mentioned in *Biomimicry in Architecture*:

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[87] Susan Roaf, "BIPV: High on the Agenda for Survival", Low Carbon Cities Initiative, (paper presented at the 14th Sede Boqer Symposium on Solar Electricity Production, February 19-20, 2007), 155.

> "Photovoltaics offer the potential for the skins of buildings to become much closer in function to the photosynthetic surfaces of plants – harvesting energy from the sun so that human-made structures could shift from being static consumers of energy to net producers of useful resources."[88]

This is challenging the common conception of what BIPV is capable of. Especially when BIPV starts to shift from the roof and onto the façade thereby engaging the public interest and pushing the boundaries of what is 21st century sustainable architecture can be (Fig 2.8).

Figure 2.8. Architect Martin Ferrero's BIPV facades

Source: Archinect
Accessed: August 21, 2014. http://archinect.com/blog/42664453/the-new-solar-architecture

[88] Michael Pawlyn, *Biomimicry in Architecture* (London: Riba Publishing, 2011), 98.

2.2. BIPV's role in Hawai'i

There exist major opportunities in exploring the potential advantages, power savings and conceptual solutions of adopting BIPV in Hawai'i. Being the most isolated archipelago in the world, Hawai'i is in dire need of adopting renewable forms of energy to be able to sustain its culture, economy and ecological way of life. This parallels Hawai'i's cultural thinking due to its history, demand for energy, and drive for self-sufficiency.

Hawai'i historically was very self-sufficient. As mentioned in the book *The Value of Hawai'i: Knowing the Past, Shaping the Future*, Professor Henry Curtis states that "In the late nineteenth century, Hawai'i energy and electricity systems were based on locally available resources, including biomass, bagasse (sugar waste), and hydropower."[89] Hawai'i was sustainable at that time because it had to be due to its isolated and captive market conditions. In the 20th century, Hawai'i became dependent on fossil fuels for its electricity needs. Currently Hawai'i the highest electricity rates in the nation, which stands at a mean between residential and commercial sectors, of ¢36.43/kWh.[90] In 2012, Hawai'i spent 10.8% of its yearly GDP on energy costs.[91]

Energy use and cost baffles many observers and visitors to Hawai'i because of the uniqueness of the Hawaiian archipelago and its potential as a testing bed for renewable energy based on solar, wave and wind energy. As stated in *Green Building: Project Planning and Cost Estimating*, that "Some buildings can get a significant portion of their needs from cost effective projects, and in a few places where energy is expensive, such as Hawai'i, could even get 100% of their energy from cost-effective, on-site solar projects."[92]

BIPV's ability to focus as "on-site" power, this could also offset costs needed for upgrading the antiquated infrastructure that plagues Hawai'i's electrical energy progress.

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[89] Howes and Osorio, *The Value of Hawai'i,* 179.

[90] U.S. Energy Information Administration, "Electric Power Monthly," Data for November 2014, http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a.

[91] Hawaii State Energy Office, "Hawaii Energy Statistics," Hawaii Energy Facts and Figures, November 2014 Edition, http://energy.hawaii.gov/resources/dashboard-statistics.

[92] Adler, Anderson, et al. Green building project planning & cost estimating, 124.

Urban commonality of Honolulu:

1. High-density living.
2. High cost of building/living.
3. High humidity and temperatures.

The above-mentioned three variables adversely affect human performance and true economic efficiency. Air conditioning and energy technology application is important shaping human behavior, thermal comfort, and economic efficiency. Climate change is relevant factor in energy use and in idyllic Hawai‘i (21.3° N, 157.7° W), with its climatic conditions and geographical features which offers these renewable forms of energy on all the islands via the high solar insolation which Hawai‘i averages of about 5.96 kWh/m2/day; which is the highest average in the nation.[93]

This is almost double the rate of available solar resources when compared to Germany, who is the world leader in solar power and in May of 2014 it was reported that 74% of its total power needs were achieved through renewable energy; a majority being wind and solar.[94] Furthermore, their solar insolation potential is far less than Hawai’i’, averaging a solar irradiance of only 3.18 kWh/m2/day[95]. If you were able to take the darkest place in Hawai‘i, it would still be lighter than the lightest place in Germany (Fig.2.9). This puts Hawai‘i on the map for its ideal conditions in PV adoption and investment of these technologies, as well as its research and design processes.

Yet, Hawaiian Electric Industries (HEI)/Hawaiian Electric Company (HECO) here in Oahu, has stagnated the push for renewable energy development and policy change. HEI currently control 95% of the electrical industry in the state of Hawai‘i.[96]

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93 “Solar Insolation,” last modified January 15, 2012, http://solarinsolation.org/.
94 Kiley Kroh, “74% Generation - Germany’s Record Renewables Day,” Business Spectator, May 15, 2014, http://www.businessspectator.com.au/article/2014/5/15/wind-power/74-generation-%E2%80%93-germanys-record-renewables-day.
95 3.18 kWh/m2/day is based on visual assumption of Germany averaging a mean of 1162.5 kWh/m2/year.
96 “Power Facts,” HECO, last modified September 2002, http://www.heco.com/vcmcontent/FileScan/PDFConvert/PowerFacts.pdf.

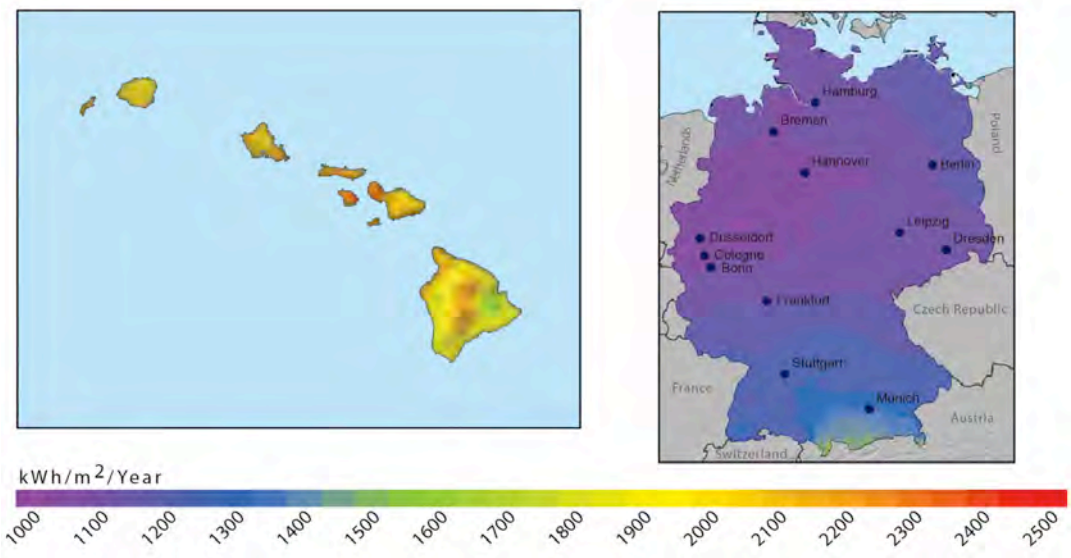

Figure 2.9. Comparison of Hawai'i vs. Germany yearly solar insolation

Source: NREL
Accessed: January 12, 2015. http://mediamatters.org/research/2013/01/24/myths-and-facts-about-solar-energy/192364

As mentioned in *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electrical Business*, it states that, "While the immediate threat from solar PV is location dependent, if the cost curve of PV continues to bend and electricity rates continues to increase, it will open up the opportunity for PV to viably expand into more regions of the country."[97] Hawai'i is primed for such a change in PV energy expansion.

In the book *The Value of Hawai'i*: *knowing the past, shaping the future* Professor Henry Curtis sums up perfectly why a method such as BIPV can make it Hawai'i in that:

> "Hawai'i must develop a decentralized, distributed, community supported approach to sustainability. Energy is the cornerstone of sustainability. Hawai'i has every natural resource to create our own energy, and an abundance of human resources and technological know how to design innovative systems. Hawai'i…can become the world's laboratory for energy innovation."[98]

In terms of its cultural implications I believe Tropical BIPV adoption falls in line with the values held by Native Hawaiian and their sustenance practices of living off of the "Aina" (Land) and its Ahupua'a land divisional system that is

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[97] Kind, Peter, 2013. *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electrical Business*, Edison Electric Institute, January 2013. http://www.eei.org/ourissues/finance/documents/disruptivechallenges.pdf (accessed September 20, 2014), pg. 5.
[98] Howes and Osorio, *The Value of Hawai'i,*186.

engrained into the cultural even after a post-Western contact. Being the most isolated archipelago in the world means you either work with what resources you have or depend upon outside sources of energy, food and economics.

The unique circumstance of Hawai'i is it has fostered a cultural identity tied into sustainability. As mentioned by Professor Davianna McGregor of UH Manoa Ethnic Studies Department, she states that

> "…living on the lands of Hawai'i engages us in a relationship of stewardship that connects us to those who lived on the lands before us…Each part of our islands requires stewardship unique to its natural resources and cultural history. We need to embrace a sustainable approach to our lives and livelihoods to offset and reverse the dramatic transformation of the natural and cultural landscapes of urbanized O'ahu."[99]

2.2.1. Hawai'i's Role as East-West Gateway

The broader importance Hawaii will play in the East-West relations of the 21st century will be pivotal. When considering Hawai'i and its surrounding geography of the Pacific, it is surrounded by the world's largest ocean covering roughly a 1/3 of the planet and is extremely crucial to the world's shipping industry, which creates access to many emerging economies in the East opening to the West, human sustenance and global survival.[100] Different from the tropics but still contain within it, the Pacific has a higher concentrations of human activity due to the fact that it holds 60% of the world's population and presents continual issues of venerability towards international conflict (fig. 2.10).[101]

This allows Hawai'i to act as a conduit towards East-West relations, politics, economic development and military defense. Besides business interests, this was one of the main drivers of why the Hawaiian Kingdom was overthrown by the U.S. government in 1893; basically it was known as a strategic position in the middle of the Pacific and continues to play this important role even today.

In the Asia-Pacific region, China and territorial disputes have brought about renewed focus both politically, economically and militarily as the

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[99] Ibid., 212.
[100] Paul D.N. Hebert, "Pacific Ocean," Last modified May 13, 2013, http://www.eoearth.org/view/article/155111/.
[101] "*The Future of Amphibious Warfare; War Games"*, YouTube video, 13:10, televised by Vice News on Sept. 2, 2014, https://www.youtube.com/watch?v=P5f-Bt3DXfU&list= UUZaT_X_mc0BIdjXOlfhqWQ&src_vid =bYG1qccSUAw&feature=iv&annotation_id=annotation_4190727581

Association of South East Asian Nations (ASEAN) are aligning themselves with Western allied powers, based on Chinese aggression over territorial island disputes with Japan and the Philippines. A potential conflict could spark a resource war with the China cutting off oil from the Asian rim. China has already surpassed its energy use tapping neighboring countries for its coal and oil dependence as it attempts to exponentially expands its economy. This will lead to a tipping point for worldwide resource demand, thereby eliminating supply to Hawaii and the United States.

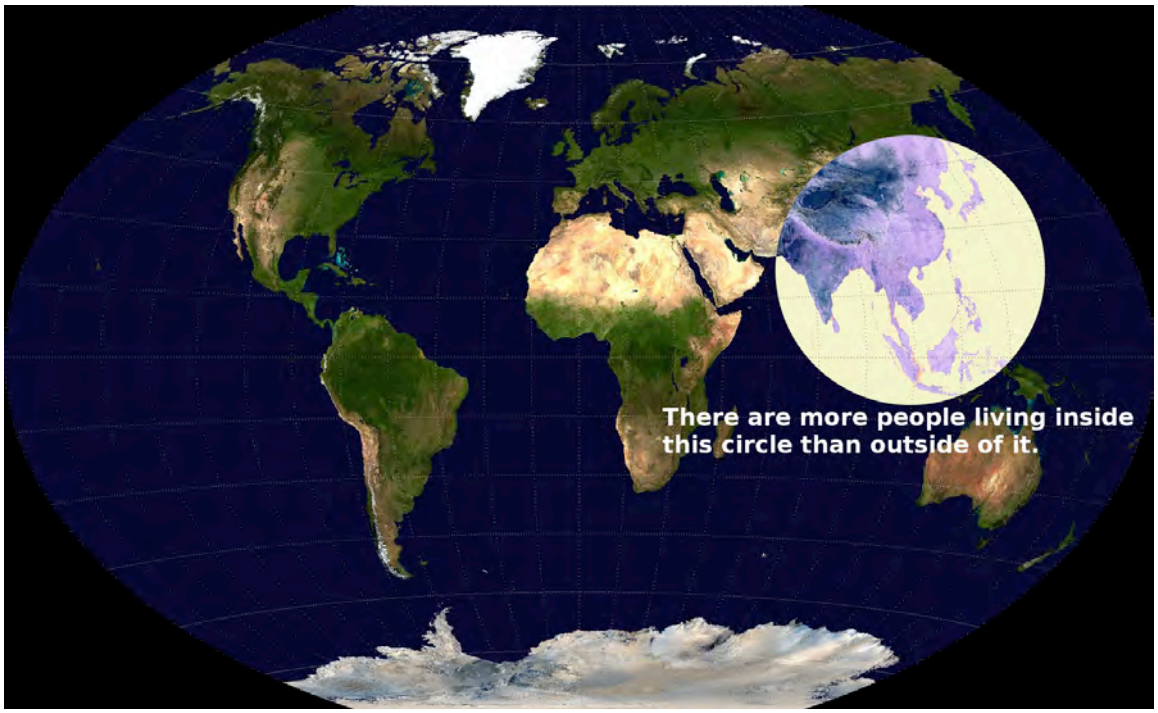

Figure 2.10: Hawai'i as East-West gateway

Source: Reddit
Accessed: February 18, 2015. http://i.imgur.com/CK6aONG.jpg

As mentioned in *Green Building Project Planning & Cost Estimating* goes on to support solar adoption in that that, "…Global conflicts over energy supplies are certain if we acknowledge that energy supplies are crucial for a nations interest and will be secured by military force. As an equitable resource available to all, the increased use of solar energy lessens global conflicts over energy resources."[102] Continuing the pursuit of domination over countries that

[102] Adler, Anderson, et al. *Green building project planning & cost estimating*, 125.

experience the paradox of the "resources curse", will only produce more of the same: death, religious extremism, social unrest and global GHG emission.

A new paradigm shift is occurring amongst governments and the general public towards considerations of ecological renewability, net-zero architecture and "cradle to cradle" design - which is described as "a holistic economic, industrial and social framework that seeks to create systems that are not only efficient but also essentially waste free."[103] PV helps achieve these aims through its free and abundant power source: the Sun.

BIPV offers interoperability of high-performance architecture, sustainable energy generation and aesthetic appeal. Its technological costs are becoming competitive with fossil fuels as grid parity is become a reality. PV technology merged into building envelopes provide excellent promise and hope to a greater future as BIPV truly integrates into our daily lives.

In short, Steven Strong, best explains BIPV's true potential:

> "BIPV has become one of the most powerful visual manifestations of green design…While there are literally hundreds of options to improve a building's performance and reduce its environmental footprint, most are invisible when you are done. BIPV is unique in its visibility. Innovative architects are now adding BIPV to their design pallet and the creative process. With continued progress in component and systems development, BIPV is destined to become ubiquitous in the built environment."[104]

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[103] L. Hunter Lovins, " Rethinking Production," in *State of the World 2008*, ed. Linda Starke (New York: W.W. Norton & Company, 2008), 38–40.

[104] Jesse Wolf Corsi Henson, "The Building Side of Building Integrated Photovoltaics," *SolarPro*, Issue 3.1, December/January 2010, http://solarprofessional.com/articles/products-equipment/modules/the-building-side-of-building-integrated-photovoltaics.

CHAPTER 3:
BIPV Case Studies

3.1. Temperate BIPV Case Studies

The case studies below are representative of the temperate region (23.27°N, 66.33°N & 23.27°S, 66.33°S). As this is not our relative tropical geography here in Hawai'i it stands as a basis of innovative design to optimize BIPV as a building skin and viable architectural option worldwide.

3.1.1. CIS Tower: Cassette System

The CIS tower built in 1963 in Manchester, England, was once the tallest building in Europe - standing at 400' - and established the identity of the Co-operative Insurance Company through its iconic size and stature. In 2006 it was retrofitted with a ventilated cladding system that integrates PV technology. Since then it has set precedence in sustainable commercial buildings by having the largest solar façade in Europe.[105]

Once a façade of 14 million shimmering mosaic tiles (Fig. 3.1), the building envelope of the CIS Tower badly needed a cladding renovation after the tiles on the façade of the building became visually weathered and posed health and safety hazards from lose tiles falling off the structure. This was caused by a lack of expansion joints, tension stresses in the grout and cement failure.[106]

A solution to this issue was to create a building skin that modernized its crumbling building envelope by adding performance weather-barriers, and in creating on-site energy production and use reductions through PV technology. This move also reflected the company's corporate image of social responsibility, community involvement, and their vision of ethical and ecological responsible business practices.

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[105] "CIS Tower Manchester," Energy Planning Knowledge Base, Accessed October 21, 2013.
[106] Roberts and Guariento, *Building Integrated Photovoltaics,* 76.

Figure 3.1. Before & after PV retrofit

Source: the guardian & Newform Energy
Accessed: Feburary 16, 2014. http://www.theguardian.com/uk/blog/2009/sep/10/the-northerner-manchester-ugly-gems & http://products.newformenergy.ie/photovoltaic.php

Latitude & Longitude: 53.4° N, 2.2° W
Location: Manchester, U.K.
Typology: Office Building
Average Horizontal Irradiation: 2.53 kWh/m^2/day
PV Surface Area: 42,754 ft^2
PV System Compacity: 391 kW
PV system output: 183,000 kWh/yr
PV Technology: Polycrystalline Silicon (poly-Si)
Date of completion: 2006[107]

In the book, *Building Integrated Photovoltaics: A Handbook*, listed are three options taken by the design team in evaluating the CIS Tower's mosaic façade and executing a design solution:

1. Replace with new mosaics throughout, installing these with stress/expansion joints. The replacement material would be similar to the original so the appearance would have been impacted only by the introduction of the new joints. However, removing all the old tiles would be lengthy, noisy and costly.
2. Remove all the mosaics and paint or render the bare surface. Although the lowest cost option, this would have met serious problems with the Grade II, of historic preservation, listing on

[107] All Information based on *Building Integrated Photovoltaics: A Handbook* (pg.76)

the exterior, since it would have fundamentally and negatively impacted the appearance of the building.

3. Overclad to retain the mosaics while awaiting developments in technology for fixing mosaics to concrete. This approach offered a high degree of certainty as a solution since existing mosaic finish could remain conserved beneath the cladding. The appearance would be different but there was an opportunity to achieve a high quality and lasting aesthetic result. Also there would be the opportunity to design in provision for future maintenance.[108]

It was decided that implementing option #3 through a viable BIPV cladding strategy was the most cost effective way that did not violate the building codes associated with national historic conservation laws; the cost came out to at a total price of £5.5 Million. Followed were practices by architects to design within the code limitations of the program, as the CIS tower was, "…categorized as Grade II listed ('a building of special architectural or historical interest' within England and Wales)."[109] The groundbreaking aspects about this project were its retrofitting methodology.

By adopting a technologically active surface, the project was successful as it reestablished the structure's architectural character, while optimizing its energy performance and spatial potential through integrated PV into its building envelope (fig 3.1). This updated the building's internal energy infrastructure through a cost strategy aimed at "…design[ing] a weatherproof cladding solution by integrating photovoltaic's around the tower's structure…[thereby]… offsetting building material cost[s] of replacing the traditional mosaic tiles."[110]

A cladding system was the appropriate design based on creating a "skin" to the existing building. In the initial integration phase the building was draped with, "…a metal mesh for retention…[then]…Aluminum mullions ran the full height of the tower and were fixed to the concrete structure by brackets. Seven photovoltaic modules were joined vertically together by aluminum framing members to form each cassette."[111]

Further innovations were "PV cassettes," which slipped into connected slots that were bolted into the wall, which spanned one level to the next. Designs also incorporated mullions, which included "local maintenance cradle" points,

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[108] Ibid., 78.
[109] Ibid., 76.
[110] "CIS Tower Manchester," Energy Planning Knowledge Base, Accessed October 21, 2013, http://casestudies.pepesec.eu/archives/67.
[111] Roberts and Guariento, *Building Integrated Photovoltaics,* 80.

where workers could latch into the façade for future replacing, cleaning and or servicing the PV modules (Fig. 3.2).[112]

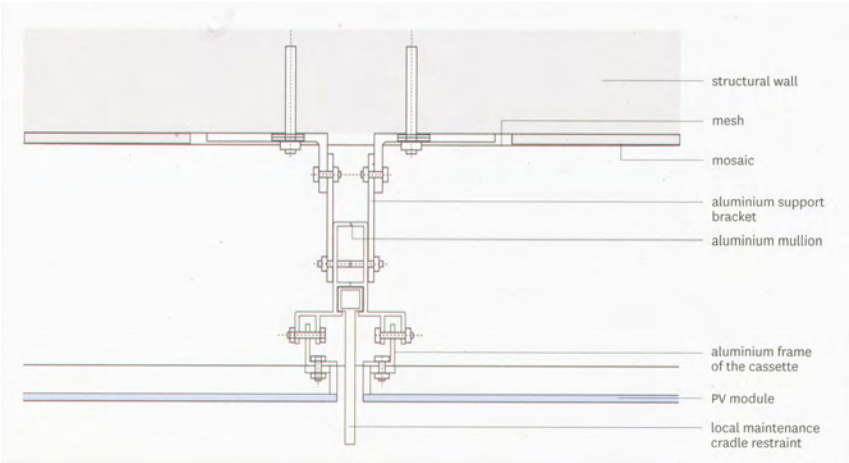

Fig. 3.2. Construction of PV cassette system
Source: *Building Integrated Photovoltaics: A Handbook*, pg. 80.

The aspect of targeting efficient installation, maintenance and economies of scale further streamlined the process. By using 7,244 PV modules, at 80 watt per panel, the architects optimized its total energy capabilities by strategically orienting 6,265 function PV modules for optimum energy efficiency, while placing 979 "dummy modules" - low priced non-functional PV panels purely for aesthetic purposes – in areas that experienced shading to offset PV costs.[113]

The result is now a building that is aesthetically uniform and contemporary yet historically familiar with the performance benefits of generating 183 MWh of renewable energy per year; which has the energy capabilities of powering up to 75 homes and reduces emission by 78 tons of CO_2 per year (Fig. 3.3).[114]

The project created a new aesthetic for an implied façade glazing through the use of poly-crystalline PV modules as well as solving design constraints such as creating airspace between 3 layers of building materials: the mosaic wall, aluminum attachment system and the PV modules. The layers were spaced from one another for purpose of allowing convection to cool the back of

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[112] Ibid, 80.
[113] "CIS Tower Manchester," Energy Planning Knowledge Base, Accessed October 21, 2013, http://casestudies.pepesec.eu/archives/67.
[114] Ibid.

the PV modules, which in turn stabilizes and optimizes the panel's efficiency and adds a barrier against solar heat gain.

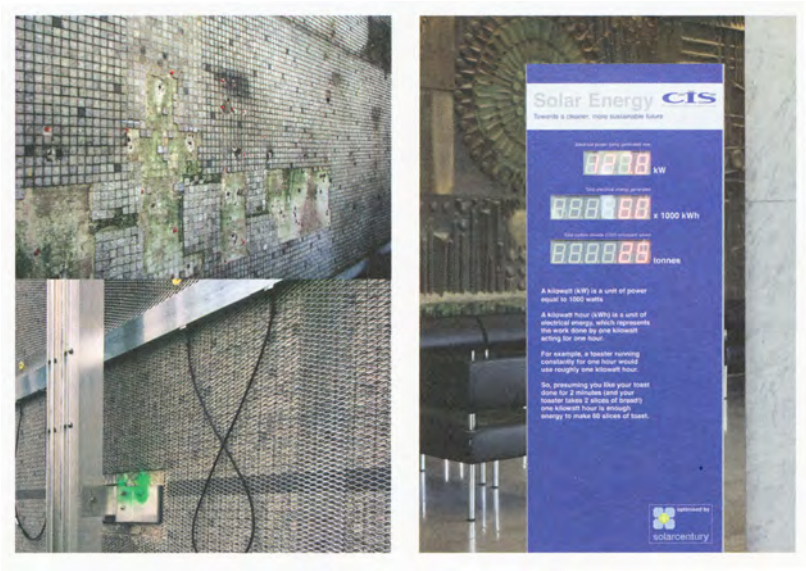

Fig. 3.3. Retrofit for PV integration & Electronic Display of PV kWh/CO_2
Source: *Building Integrated Photovoltaics: A Handbook*, pg. 81.

Aesthetic and functional innovations are also present in the new CIS tower. The pre-2006 renovation of the tower was just a service shaft, however it is now an implied façade which looks qualitatively better than before, updates its image with one that is visually activated with marked ecological credentials; i.e., BIPV. The new face humanizes the entire structure through its implied use of that being an office tower when really it's just a shaft. This could be considered a "Trompe-L'oeil" or "Trick of the Eye," which can augment an architect's design statement. By integrating the renewable energy harvesting capabilities of PV into an existing structure, it further simplifies the conservation efforts as a cost alternative of having to investing the material, labor and fiscal intensive processes of constructing a whole new building.

Through the process of BIPV integration, the retrofit has unified two seemingly unrelated buildings and has created a complementary relationship of holistic symbiosis exemplified by a large-scale renewable energy generation (Fig. 3.4). The CIS Tower serves as a model that not only could be applicable worldwide, but could specifically benefit Honolulu's dense urban topography, and its need for energy efficient and aesthetically innovative building stock.

Fig. 3.4. CIS Tower, Manchester, U.K.
Source: Wikipedia
http://en.wikipedia.org/wiki/The_Co-operative_Group#/media/File:CIS_Tower_and_One_Angel_Square.jpg

3.1.2. Northumbria University: Façade Retrofit

The Sports and Psychology Building at the Northumbria University in Newcastle, UK, is a case study in retrofit adaptation that supports design application with BIPV façade integration. More than 20 years old, the Northumbria Building started out as a refurbishment, a.k.a., retrofit, of a 1960's rainscreen cladding system and applied PV as a cladding design alternative. Acceptance of PV use as a building material was spurred by a 1991 report by the UK Government touting the benefits of BIPV as a viable cladding alternative for broad based commercial application. Spurred local, private and government sponsors offering fiscal assistance and funds from the European Community Thermie Grant secured this design goal.[115]

[115] Roberts and Guariento, *Building Integrated Photovoltaics,*164.

The building's original concrete weather cladding (fig. 3.5) consisted of a "mosaic finish [which] was suffering from carbonation, reinforcement corrosion and mosaic detachment. "[116] Because of this the entire façade cladding and its window frames were damaged beyond repair and had to be removed.

Fig. 3.5. Before BIPV Façade Retrofitting
Source: *Building Integrated Photovoltaics: A Handbook* pg. 165

Latitude & Longitude: 54.9° N, 1.6° W
Location: Newcastle, U.K.
Typology: Psychology and Sports Sciences Center
Average Horizontal Irradiation: 2.6 kWh/(m2 × day)
PV Surface Area: 4628 ft^2
PV System Compacity: 40 kW
PV system output: 25,000 kWh/yr
PV Technology: Monocrystalline Silicon (c-Si)
Date of completion: 1994[117]

[116] Ibid.
[117] Information based on Building Integrated Photovoltaics: A Handbook (pg.164)

The step in the project was in determining the site's optimization for proper PV application. Five stories high and rectangular in its form, the building is elongated on a North to South axis, with its width to the East and West. This offers optimal PV solar exposure to the South, which the building was previously designed for capturing passive solar light and heat. Draped on the South façade, the PV Panels are in oriented in portrait position and tilted at an angle of 25° (Fig. 3.6). The quantitative results from this were that it created the right perpendicular angle for increased solar collection via PV cell efficiency. This strategy has allowed the façade to now generate over 25,000 kWh/year and covers 30% of the buildings electrical loads.

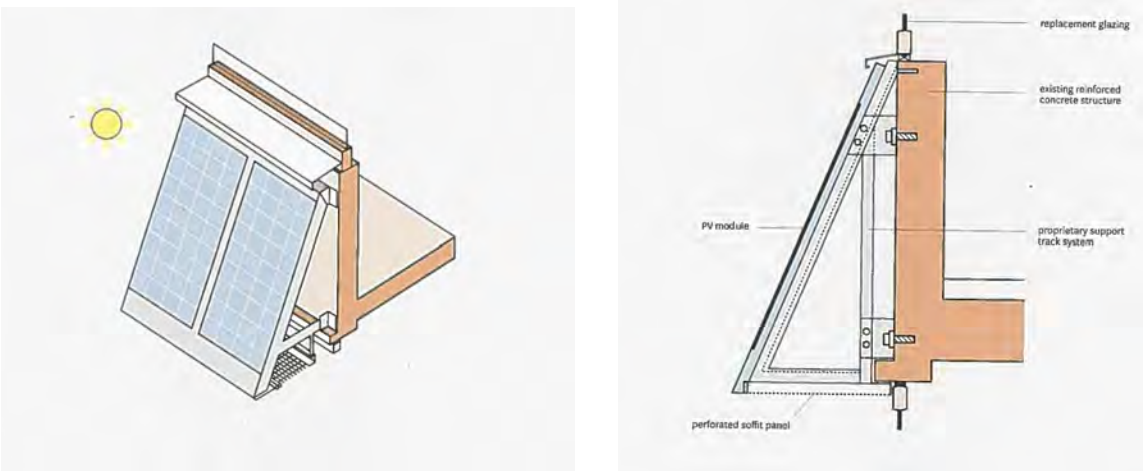

Fig. 3.6. BIPV shading device angled of 25° & BIPV section

Source: *Building Integrated Photovoltaics: A Handbook* pg. 167

Added benefits of passive hybridity occur through cladding doubling as an overhanging shading device at the top of the window (Fig. 3.7). This helps regulate internal temperature gain or loss by shading in the hot summer – based on high sun angles – and lettings the sun enter into the interior, through low sun angles, in the cold winters.[118]

[118]Ibid, 165.

Fig. 3.7. BIPV Exterior of the Northumbria, Newcastle, U.K.
Source: Skyscrapercity,com
http://www.skyscrapercity.com/showthread.php?t=449892&page=10&langid=6

The building materials consisted of a total of 4,628 ft^2 of PV and 3,875 ft^2 of new window glass were installed.[119] The project used standard size PV panels as a modular form of integration to traditional cladding systems. These were done in five PV sections per cladding unit for every four set of windows. These were fabricated off site for economic and modular design efficiency. After the sections were completed and brought to the site, they are installed using "hook-system" on the PV sections to be matched with an aluminum proprietary support track system built into the façade and sill of the building envelope. This readies the streamlined installation and integration the PV sections into its building skin for active renewable energy generation and passive shading implementation (fig. 3.7).[120]

The inclined angle of the PV units allowed for open space at the soffit to interact with natural ventilation and convection. This reduced the operating temperature of the PV cells thereby increasing electrical performance, durability and extended the life of the panel. Other functions this space innovated on were in its BOS and ease of maintenance of the PV units through its accessibility. This allow for service to occur per individual unit as not to disrupt the surrounding

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[119] Kristine Smith, "Northumbria Is Solar Panel Test Ground," Construction News, January 19, 1995, http://www.cnplus.co.uk/news/northumbria-is-solar-panel-test-ground/953402.article.
[120] Roberts and Guariento, *Building Integrated Photovoltaics*, 166.

power generation of the entire PV system. This was achieved by the designers, in which they were able to fit into the open spaces, "…wiring trunking, junction boxes and monitoring equipment."[121]

Highlighted is the PV's integrated aesthetic relationship as a new building material. The result is a seamless merger within the rhythm and form of the window façade. Architectural beauty is enhanced, building systems are upgraded and energy efficiency is achieved.

3.1.3. Caltrans Building: PV Louvers + Double Skin Façade

Innovating design through the use of louvers can augment a BIPV façade. Based on energy harvesting and conservation, as exemplified by the Caltrans Building (2005) in Los Angeles, CA, by the Architect Tom Mayne and his architectural firm Morphosis, created this hybrid structure whose dynamic double skin façade acts as a physical buffer that insolates, ventilates, and repurposes solar and thermal radiation.

Costing $165 million dollars and approximately 13 stories high at 756,000 ft^2, Mayne's design includes a "scrim wall," which is made out of perforated aluminum panels, which creates an effect that the outer building shell is opaque during the day but transparent by night (fig. 3.8). It has expanded upon the innovations of integrated building skins systems with the addition creating is one of the largest BIPV walls on the west coast of the U.S.[122]

The Caltrans project won Tom Mayne the Pritzker Prize in 2005, not just on it's stunning and futuristic looks, but also from the sustainable functions achieved. The porous layers of the double skin façade allow natural ventilation to diffuse into the interior through its pneumatic window system, western and eastern scrim wall(s) as thermal flues and the thermodynamics of its PV louver system. In between its perforation, PV is tilted at a 50° angle with a vertical spacing of 5 ft. between each array which is linked to the exterior double skin façade (Fig. 3.9). This PV skin is juxtaposed to an interior matrix of pixelated glazing on the southern fenestration. The exterior skin also allows these

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[121] Ibid.
[122] "Caltrans District 7 Headquarters," Clark Construction Group, LLC, last modified 2014, http://www.clarkconstruction.com/our-work/projects/caltrans-district-7-headquarters.

automated metallic screens, when aligned together, to double as larger shading devices.[123]

Fig. 3.8 Caltrans Building, Los Angeles, C.A.

Source: Clark Construction
Accessed: November 24, 2013. https://www.clarkconstruction.com/our-work/projects/caltrans-district-7-headquarters

Latitude & Longitude: 34° N, 118° W
Location: Los Angeles, CA
Typology: Government Building
Average Horizontal Irradiation: 4.9 kWh/m^2/day[124]
PV Surface Area: 14,000 ft^2
PV system Compacity: 92 kW
PV Technology: Monocrystalline Silicon (c-Si)
Date of completion: 2005

[123] http://www.arup.com/_assets/_download/download388.pdf, 4
[124] "Solar Radiation Data," Global Village Institute for Appropriate Technology, *http://www.i4at.org/lib2/solarrad.htm*.

Fig. 3.9. BIPV Louvers in Caltran's Façade

Source: Morphopedia
Accessed: November 23, 2013. http://morphopedia.com/projects/caltrans-district-7-headquarters

After conducting a case study on the building, the multinational building firm Arup, in its journal, commented on not just the active components of this BIPV system, but on its passive multifunctional nature as well. In addition to its energy saving properties, the south façade behaves similarly to the east and west, reducing the heat load by shading from opaque, monocrystalline BIPV cells, reducing thermal infiltration, and promoting natural ventilation between the two vertical layers of façade.[125]

In determining the right strategy for BIPV optimization, sun path studies were conducted:

- The optimum power output angle of the panels
- Their vertical spacing to prevent self-shading
- The optimum cell density in the panels to achieve the required output and maximize natural light in the offices.
- Their positioning relative to each other in order to balance aesthetic with the occupants line of sight.[126]

In addition, in designing a strategy to up its R-values and increase its thermal barrier, glazing used was that of a "dual-pane, low-E and low solar heat gain coefficient windows." Within the PV façade, Arup has estimated that within a web of an, "…open lattice framework…[it]…supports a vision glass wall

[125] Ibid.
[126] Ibid.

incorporating 14,000 ft^2 array of 859 BIPV panels…contributing 92 kW of peak power."[127] This has contributed to a PV system that generates 5% of the buildings peak loads in the summer time without impending a clear view to the ocean (Fig. 3.10).[128]

Another benefit is in its office building typology, which the entire peak load needed to power this building are during the day when PV is at its most optimal function and user occupy the building. Conceptually, these PV louvers as an external form can bring attention to the way buildings work by making an engaging visual statement.

Fig. 3.10. BIPV Louvers + Double Skin Façade on the South Wall

Source: Clark Construction
Accessed: November 24, 2013. http://www.clarkconstruction.com/our-work/projects/caltrans-district-7-headquarters

This BIPV building typology further transcends the current stereotype that PV is just a rooftop application geared primarily for functional purpose and not

[127] Ibid.
[128] "Caltrans District 7 Headquarters," last modified April 5, 2012, *http://morphopedia.com/projects/caltrans-district-7-headquarters*.

for architectural expression or holistic design integration. This project adapted its building envelope by using a dual (Active + Passive) system. Such a system as this could be the most geographically and culturally applicable design that should be considered in this design research project.

These temperate case studies stand as precedence for architects to employ BIPV for building skin solutions and solidify BIPV as a viable design option. Additionally, it comes as a unique benefit to these buildings that as the sun path is more lateral and direct sunlight interacts at higher rates to the facades' in temperate, than in tropical, climates where the sun path is located towards the zenith and rooftop PV is more optimal.

However, these constraints should not hinder one's architectural motivation to employ BIPV building skins and PV façade devices. As you will see below, these constraints have only embolden architects to think deeper and design more efficiently as the natural resource of the sun provides a plethora to innovate ways to harness its power potential in tropical climates.

3.2. Tropical BIPV Case Studies

The case studies below provide a template on which one could reference an appropriate BIPV design strategy, application and holistic integration in the tropical regions. They provide examples of adaptation in working with less than optimal sun path orientations to achieve efficient power potential and aesthetic PV exploration. As there are no definitive commercial BIPV case studies in Honolulu, Hawai'i, similar tropical regions covered are that of Asia and South East Asia.

I use these as design sources and inspiration because of my Practicum experience spent in Singapore (Fig.3.11) and in traveling to the neighboring countries of Indonesia, Thailand, Cambodia, Philippines, South Korea and Malaysia in 2014. This first section on Tropical BIPV starts out in Singapore based on my familiarity with the region and because it poses design constraints as a hard place to do façade based BIPV design. This is due to its constant cloud cover, haze from Indonesia – who is burning down its forest to clear for production of palm oil – and its latitude which is right on the equator where the sun path is nearest the zenith and more suited for rooftop based PV.

Figure 3.11. Singapore (1.3° N, 103.8°E)

Source: Wikipedia
Accessed: March 30, 2014.
http://en.wikipedia.org/wiki/Geography_of_Singapore#/media/File:SingaporeSatellite1024x710.jpg

Classification: Warm Humid Climate[129]
Total land Area: 275.8 sq. mi
Population: 5.4 Million
Density: 7,540/km^2
Total GDP: $327.5 Billion (USD)
GDP per capita: $61,000 (USD) (3rd Globally)
Annual Avg. Temperature: 77° – 88° F
Annual Avg. Relative Humidity: 84.2%
Annual Avg. Precipitation: 7.66 in
Avg. Solar Irradiance: 3.15 kWh/m^2/day
Optimal Solar Panel Angle: 1.3°

[129] David Oakley, *Tropical Houses; A Guide to Their Design* (London: Batsford, 1961).

3.2.1. Building Constriction Authority: Ubiquitous Integration

Fig. 3.12. Building Construction Authority Academy

Source: Solar Energy Research Institute of Singapore
Accessed March 10, 2014. SERIS: Advanced daylighting and building integrated Photovoltaics in high performance building envelopes in the tropics Zero Energy Building at BCA Academy

Location: Singapore (1.3° N, 103.8°E)
Typology: 3 story retrofitted office building
Date of completion: 2008
Size: 4500 m^2
Firm: NUS, Public and Private Endeavor

The Building Construction Authority (BCA) is managed under the umbrella of the Ministry of National Development and is the center of all things related to construction, the built environment and infrastructure in Singapore. The BCA is part of Singapore's economy and modern identity and is tied to its construction development and growth. It plays a pivotal role and yields considerable power in Singapore's national prosperity and its future. Through the BCA Academy, a showcase for green technology, energy and development,

it is making history and defining the sustainable learning curve in South East Asia.

The academy lies near the nucleus of the Singaporean island and parallel to the upper part of the Kallang River. I had the opportunity of visiting the BCA academy to interview the Senior Executive of the BCA Alice Goh, who is an Engineer and worked on the PV retrofit project in 2007-08. I was given a tour and design explanation of the academy by Ms. Goh (fig. 3.13). She informed me that the BCA Academy is acknowledged as being the "first net-zero energy office building retrofit in Southeast Asia and the tropics" and was awarded a Green Mark Platinum rating, which is the highest rating you can get, in 2009.

When gazing upon the skin of the building I noticed that the whole academy was completely encased or enveloped in PV. I was entranced by its construction and solar shell like form. I was also amazed by the way it was done so seamlessly and blended into the membrane of the building skin as to become the overall anatomy of the structure.

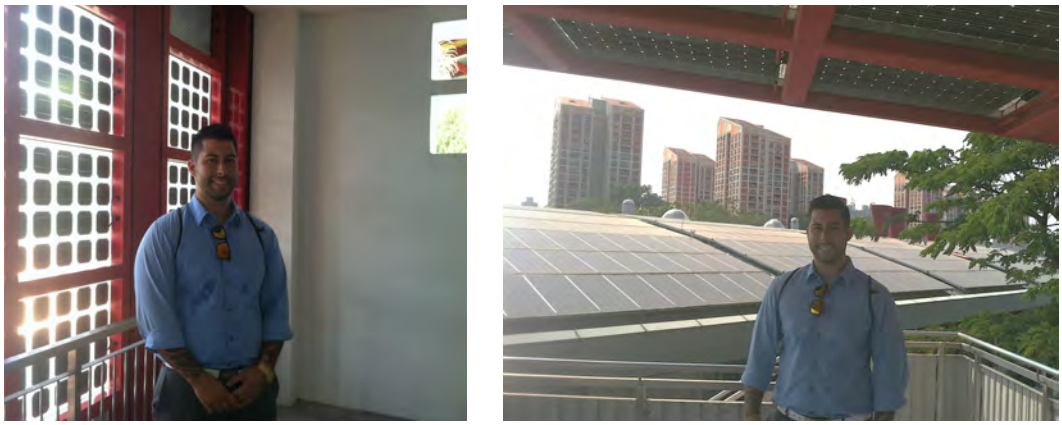

Fig. 3.13: Tour of the BCA Academy

With the building there were major obstacles to overcome, not only as a retrofit - which is very challenging in itself by having to updating an entire building system(s), overall look and thermal and energy performances - but in its regimented design brief. In the brief it was mandated that the total building consumption be reduced by 40%, when compared against a similar office building of typology and size.130 It exceeded this mandate by using PV, which

[130] Wittkopf, Final Report: Advanced daylighting and building integrated Photovoltaics in high performance building envelopes in the tropics. Zero Energy Building at BCA Academy, pg. 2.

established itself as the primary electrical driver of energy delivery, displaying building behaviors in both passive and active applications.

The academy was design to be a Net-Zero building. However, over a commissioning process (ensures all building systems perform and operate as design intended) of 18 months it surpassed this expectation by generating over 299 MWh, whilst only consuming 274 MWh of energy, which gave it an energy surplus of 9%. Currently, it is now venturing into the realms of the energy-plus zone – a building that produces more energy that it consumes - which makes it extremely unique, as there are only a handful of these buildings in existence throughout the world (fig. 3.14).[131]

This energy plus factor was achieved through designing a building envelope that emphasized a photovoltaic integration on all levels to the point of ubiquity. It also used the PV modules to its advantage in the modes of passive application via shading devices, such as the PV louvers, opaque to semi opaque thin-film PV in the fenestration and the carport(s) doubling as PV canopies. The numbers in terms of energy savings due to passive shading devices were not calculated but the active components of PV systems was. The entire system consists of 31 grid-connected arrays, producing a D/C power capacity of 190 kWp, and 7 off grid arrays, producing a D/C power capacity of 2.2 kWp.

The grid-connected system supplies a majority of the power to the buildings overall electrical demand while off the gird systems are of a more integrated nature that is incased in glass using thin-film PV and or combinations of thin-film with Mono-crystalline (c-Si), poly-crystalline (poly-Si) PV, amorphous-Si (a-Si) and or Copper indium gallium selenide, aka CIGS. What this does is to showcase to the public all the available PV technologies that exist in the marketplace and its power potential in Singapore's buildings through utilizing solar energy in both active and passive ways.

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[131] Ibid.

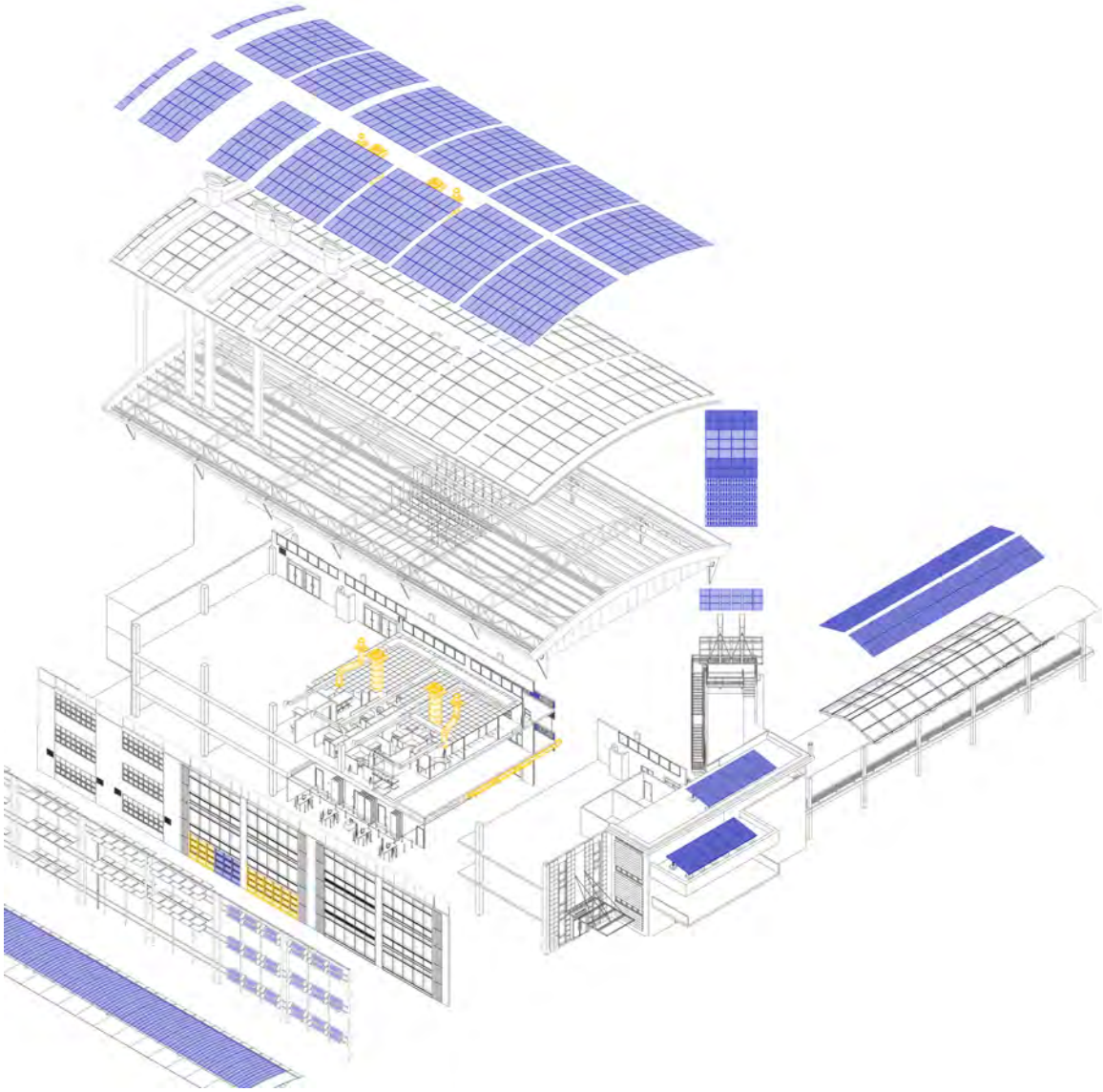

Fig. 3.14. Exploded axonometric view of BCA Academy's BIPV system

Source: Solar Energy Research Institute of Singapore
Accessed March 10, 2014. SERIS: Advanced daylighting and building integrated Photovoltaics in high performance building envelopes in the tropics Zero Energy Building at BCA Academy

PV System:

- 750 poly-Si modules covering 80% of the main curved roof.
- 156 a-Si modules laminated on the roof of the carpark.
- 18 Hybrid (c-Si + a-Si) modules the roof canopy of staircase tower.
  - The east staircase tower displays a variety of PV technologies: 8 units of opaque c-Si wafers, 20 units of both translucent and opaque a-Si and 8 opaque CIGS on top of the roof.[132]

In addition, by having the main grid tied vs. non-grid tied PV systems, they are purposely divided on basis of the form and its overall function. A metric of performance vs. aesthetic and educational design integration plays out visually, allowing a blending and protrusion of the various PV arrays to express themselves and offer building diversity in energy efficiency and high performance technology. You can see the more performative PV adhering to the curved roof with optimally positioned angles which respond to the solar arch throughout the day and has zero shading obtrusions; i.e. shading from surrounding structures (fig. 3.15).

The grid-tied PV being more function than visual does not blend as seamlessly as its lower performing cousin of integrated thin-film PV. However, this c-Si based PV is designed well enough as to hide it bulky features. This offers insight into design innovations that can lead into more acceptance and application among architects and developers, based on how it is able to cater to maximizing both form (aesthetics) and building performance (function). The non-grid tied PV arrays are on the buildings fenestration, curtain walls, canopies, glazing, railings and louvers and play the potential future outlook into how PV can be integrated more ubiquitously into the entire building skin.[133]

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[132] Ibid., 3.
[133] Ibid.

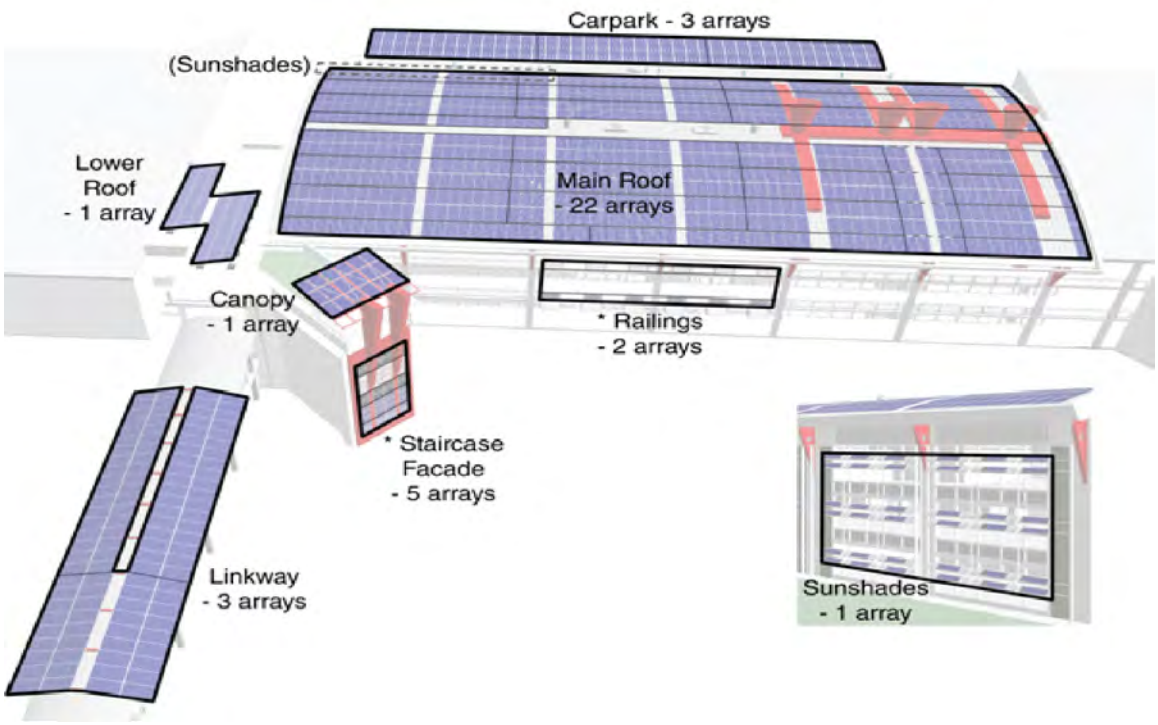

Figure 3.15. BIPV Array Layout

Source: Solar Energy Research Institute of Singapore
Accessed March 10, 2014. SERIS: Advanced daylighting and building integrated Photovoltaics in high performance building envelopes in the tropics Zero Energy Building at BCA Academy

The east staircase is the interactive cathedral of PV technologies based on its window arrangement. This is seen through the dynamic interplay of the way natural light penetrates and interacts with the user in the stairwell. By seeping in through the edges of the PV cells the light then is shaded from the PV cells that makes the stairwell's inner light dance about. As you ascend the staircase to different levels, the modules go from semi-opaque to opaque, thereby maximizing solar gain where most of the PV receives unabridged shading in the morning when the sun rises from the east (fig. 3.16). When you get to the top-viewing platform you realize it's a vertical cascade of technological PV integration that is self-affirming and suggests where construction technology is heading.

The benefit to the overall building is apparent from its sustainable multifunction to its aesthetic. It also highlights PV's ability as a passive shading device and daylight control component. However, in the case of the east stairwell and its non-grid tied PV system, its more looks than performance. As noted by the Senior Executive of the BCA Alice Goh, the BIPV Façade generates

little energy (2.2 kWp), as compared against the optimally oriented rooftop PV (190 kWp), and it's power potential is only at certain times in the morning then tapers off around noon.

Despite this energy constraint I think this PV attachment and or full-scale integration offers new solutions in activating the overall building envelope vs. the static nature of traditional building materials in use today. Some energy is better than no energy at all. By mixing the passive and active components of these PV arrays, the academy is chartering news paths in looking at and utilizing the multifunction and efficient power potential of BIPV in the Tropics.

PV louvers offer an attractive alternative in updating an architectural device that balances both passive and active design features. Having PV laminated onto the louver, or even constructed of PV materials, it can then be tilted at the most precise angles year round to optimize sustainable energy output while also passively shading the interior. The best of both worlds consolidated into one architectural device.

One of the features and concepts that qualitatively differentiated this project from others is in its goal of using PV as a form of visual communication in displaying its multifunctional - both passive and active - interactions and integrations with the overall building envelope. The PV system is balanced as well in the quantitative need for energy measurements by displaying its "analytical performance monitoring" in its main educational showroom on the main floor.

The BCA Academy takes tropical BIPV to new heights by consolidating it in one place. This is done in a manner that is expressive and acts educational tool in visual communication, technological energy efficiency, sustainability and advancements in evolving building materials. For the purpose of this retrofit, this mixture of grid tied vs. non-grid tied PV systems also allowed balance to be struck to be achieved in targeting the bottom line - a definite return on investment (ROI) on the entire PV system - and for what solar panels are generally used for: renewable energy.

Additional benefits where in its aesthetic expression and catharsis that communicates to the practice of architecture and its users, which can deliver solace and environmental comfort. All these factors are a blend of science, art and (sustainable) technology, which is what architecture is all about.

Fig. 3.16. BIPV staircase tower and laminated louver system.

Source: Solar Energy Research Institute of Singapore
Accessed March 10, 2014. SERIS: Advanced daylighting and building integrated Photovoltaics in high performance building envelopes in the tropics Zero Energy Building at BCA Academy

3.2.2. NUS Study: Three Singaporean Case Studies

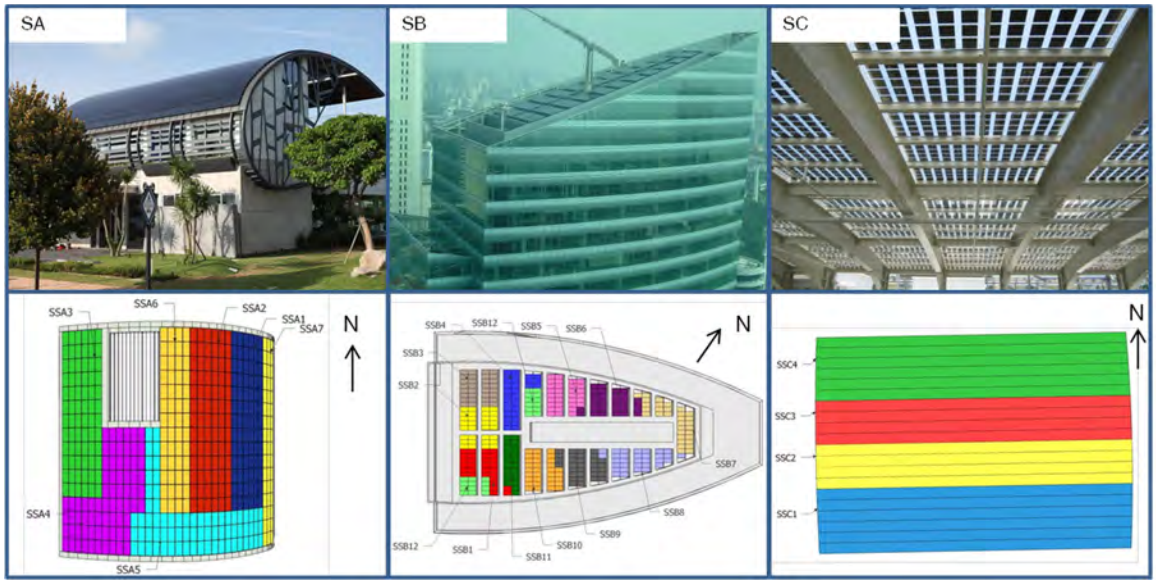

Fig. 3.17. Three tropical BIPV case studies: form vs. performance

Source: SERIS Annual Report 2013
Accessed April 20, 2014. *The Balance Between Aesthetics and Performance in Building-Integrated Photovoltaics in the Tropics*

University: National University of Singapore (NUS)
Research Institute: Solar Energy Research Institute of Singapore (SERIS)
Location: Singapore (1.3° N, 103.8°E)
Typology: Varies
Case Studies: 3

One of the most compelling and convincing Tropical BIPV case studies I came across in Singapore was a paper entitled *The Balance Between Aesthetics and Performance in Building-Integrated Photovoltaics in the Tropics* (fig. 3.17). The Solar Energy Research Institute of Singapore (SERIS), which is the Photovoltaic R&D arm and test bed of the National University of Singapore (NUS), was the entity that commissioned it. It is the authority on all things PV and BIPV related in Singapore and the tropics at large. It also has an R&D divisions in Solar Façade Technology and Solar Building and Solar Thermal Systems, which conducts tests primarily in Singapore to be adapted onto its urban fabric and infrastructure but with the wider goal of further PV and BIPV implementation throughout the tropical region(s) of South East Asia.

What SERIS did was they examined the performance of three different BIPV buildings based on shape, size and power capacity to, "…investigate the behavior of three BIPV systems with PV systems playing an aesthetically appealing role in their architecture, with detailed analysis for a one-year period (June 2012 to May 2013)."[134] This was done so that the researchers could address the validity, due to the growing use of PV amongst architects and engineers, in using BIPV in the tropics, as it was important to "quantify and assess losses due to non-optimal module orientation and tilt as well as shading effects."[135]

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[134] Clarissa Zomer et al., "The Balance Between Aesthetics and Performance in Building-Integrated Photovoltaics in the Tropics," Progress in Photovoltaics: Research and Applications 22, no. 7 (2014): 36.
[135] Ibid.

Three Tropical BIPV systems:

System SA:

- Typology: Residential
- Form: Curved Roof System
- PV Compacity: 48.84 kW_p
- Density: Low Density Surroundings
- PV Orientation: East and West facing
- Modules: Frameless and all Black c-Si

System SB:

- Typology: Commercial
- Form: Linear Roof Tilted 19°
- PV Compacity: 75.03 kW_p
- Density: Dense Urban Surroundings
- PV Orientation: Southwest facing
- Modules: c-Si (heterojunction silicon)

System SC:

- Typology: Residential
- Form: Curved Glass Canopy
- PV Compacity: 42.12 kW_p
- Density: Low Density Surroundings
- PV Orientation: North and South facing
- Modules: poly-Si (custom)

The way they were able to conduct this research through gathering "On-site irradiation and partial shading analyses" and using two measures which made performance comparisons of all three of the BIPV systems. The two measures of electrical output were quantified based on "…the annual yield [kWh/kWp], which relates the energy produced per year to the unit of peak power installed and the performance ratio, or PR [%], which puts the annual yield in perspective to the annual irradiance received in the module plane."

Now what this allows for is the annual yield and PR to act as barometers in evaluating energy losses that occur from shading, modules overheating and any incongruity occurring within the inverters or energy losses.[136] This seems to be one of the more balanced approaches in going about trying to measure

[136] Zomer et el., "The Balance Between…"

performance vs. aesthetics vs. functionality that I have come across in all of my Tropical BIPV research (fig. 3.19).

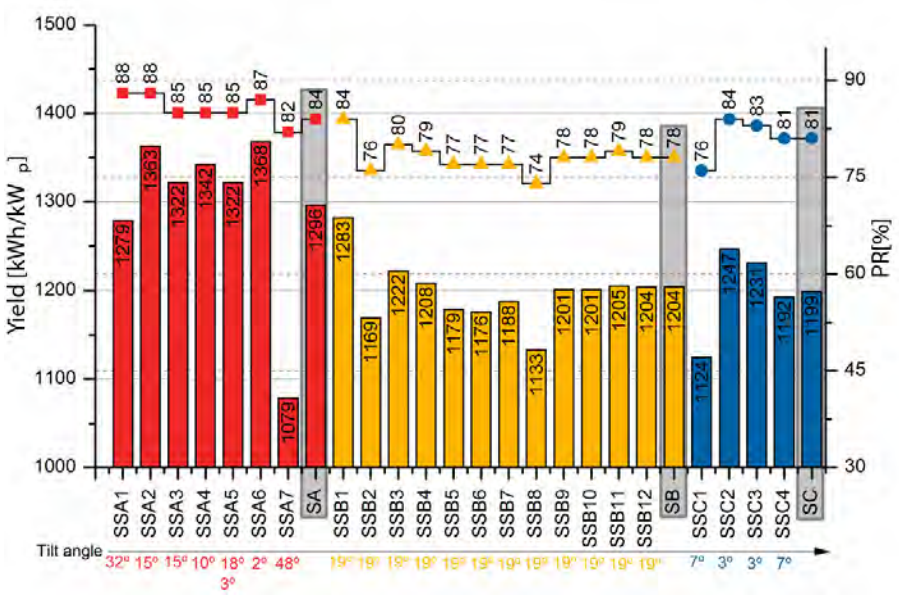

Fig. 3.18. Solar Irradiance data from Systems A, B and C

Source: SERIS Annual Report 2013
Accessed April 20, 2014. *The Balance Between Aesthetics and Performance in Building-Integrated Photovoltaics in the Tropics*

Based on these findings, researchers at SERIS discovered that, "…even with a theoretically non-optimal combination of azimuthal deviation and tilt angle, a PV system can show better performances in yield and performance ratio than other PV systems that are more ideally oriented."[137] Meaning that you can experiment with architectural form and are not confined nor have to compromise aesthetic design intent based on strictly following the orthodox approach most people think of when matching PV to its most optimal latitudinal angle.

[137] Ibid.

Figure 3.19. Tropical BIPV System A

Source: Phoenix Solar Group, SG
Accessed: April 23, 2014. http://www.phoenixsolar-group.com/business/my/en/references.html?location=all&referenceType=b90c904e-eb1d-4c1a-8fb7-64b4cfa74fda&currentPage=2

In system SA, which is the more expressive and of an organic form yet it still produces the most amount of optimal energy based on the performance ratio and energy yield graph (fig. 3.19). This allows architects to express architecture in adapting and integrating PV into the building envelope, as well as, allow the justification of experimental forms, which can also yield optimal energy performance as well. This was the most compelling evidence that supports my research in implementing BIPV envelopes in the tropical urban fabric with the goal of balancing aesthetics and sustainable energy performance.

This idea that PV can open up new avenues in advanced sustainable design and integration was noted in the study, "The acceptance of architects in including PV elements in their projects is growing and the availability of energy efficient, flexible and transparent PV materials is transforming the way architects and building engineers view and use PV modules…such as in curved roofs and on facades."[138]

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[138] Ibid.

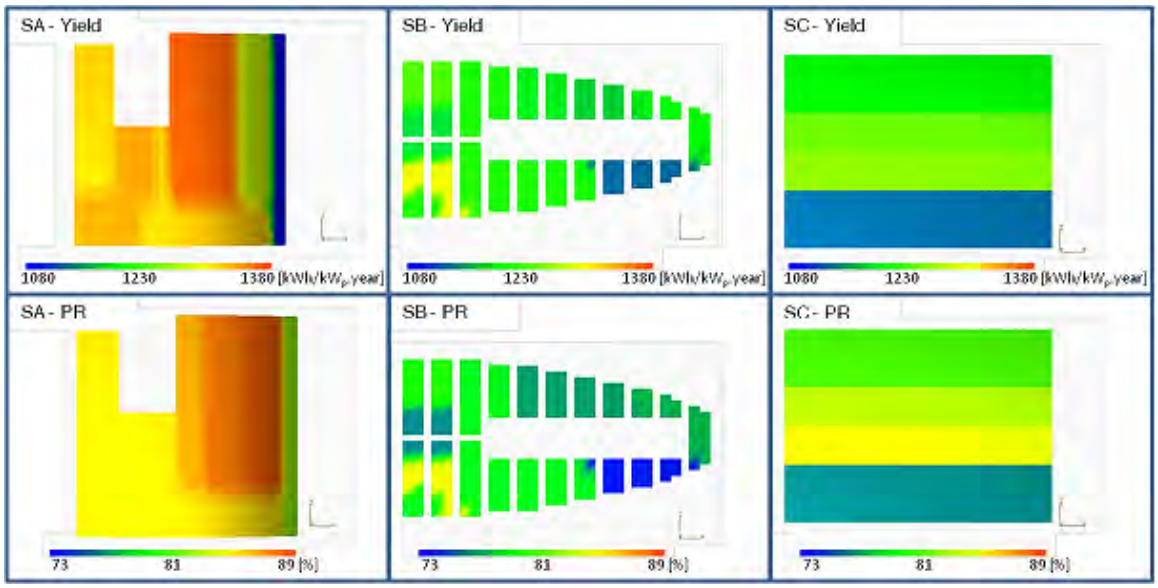

Figure 3.20. Energy performances of Tropical BIPV Systems SA, SB and SC

Source: SERIS Annual Report 2013
Accessed April 20, 2014. *The Balance Between Aesthetics and Performance in Building-Integrated Photovoltaics in the Tropics*

This study goes against conventional thinking in PV implementation. It also challenges the conceptual thinking of engineers, contractors and architects who currently posit that BIPV is a “pie in the sky” idea and entirely non-optimal as compared to the angularly efficient, non-integrated and bulky rooftop solar. The study challenges all previous assumption about tropical BIPV and highlights the opportunities that are arising and the possible tools it is providing to architects as a new building material to pick from (fig. 3.20).

3.2.3. Pearl River Tower: Louvers and Edge Conditions

Fig. 3.21. Pearl River Tower by SOM

Source: SOM

Accessed: March 23, 2014. http://www.som.com/projects/pearl_river_tower

Building: Pearl River Tower
Location: Guangzhou, China (23.1° N, 113.2° E)
Date of completion: 2013
Size: 2.3 Million ft2
Height: 1020 ft.
Firm: SOM

The Pearl River Tower, in Guangzhou, China, sets the standard in 21st century sustainable architecture (fig. 3.21). Geographically it sits where the Tropics meet the Subtropics (23° 27' N) and because of this the atmospheric conditions are hot and humid. Guangzhou is becoming one of the newest boomtowns in China, but because of this the air quality is poor and getting worst. Based on this backdrop the Firm of Skidmore Owings and Merrill (SOM), via Adrian Smith its former head Architect, were able to utilize a triple format through region, size/form and energy necessity into a design consideration which appropriated local attributes and programmatic needs into its advantage and produced one of the tallest and largest eco-friendly buildings in the world.

As measured by a Leadership in Energy and Environmental Design (LEED), the PRT building is said to use 44% less energy than a tower of its size built to the U.S.* Because of this is was awarded the title of LEED Platinum through a design whose target was in reducing overall energy demands, energy recovery and power generation through using state of the art technologies.[139] With the goal being a Net Zero Building – which is a building that produces as much energy as it uses on a yearly basis – the project focused on two main pieces of the an sustainable energy strategy to achieve this goal: it used the latest in high performance building technology via a PV, on its roof and through its Louvers, and Vertical Axis Wind Turbines (VAWT).

Even though SOM didn't reach this goal of creating a Net Zero Building, due to "technical and regulatory challenges," the PRT building was still able to use PV and the VAWT to produce an impressive combined power of over 332 MWh per year. These renewable energy sources assisted the building as an auxiliary power source to offset the overall energy demand of the building. Located on the 25th and 50th floors, the VAWT's are technical marvels in themselves and deserve to be noted in tropical high performance architecture

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* based on the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) standards 90.1-2007.
[139] Gonchar, Architectural Record: The Big Issue, 96.

for its utilization of the "Venturi Effect" – the effect where air pressure is funnel through an aperture which increases thermo dynamic velocity - and its sustainable power supply. However, it is the ubiquitous integration of the PV that is eye catching and spans the majority of the building skin (fig. 3.22).[140]

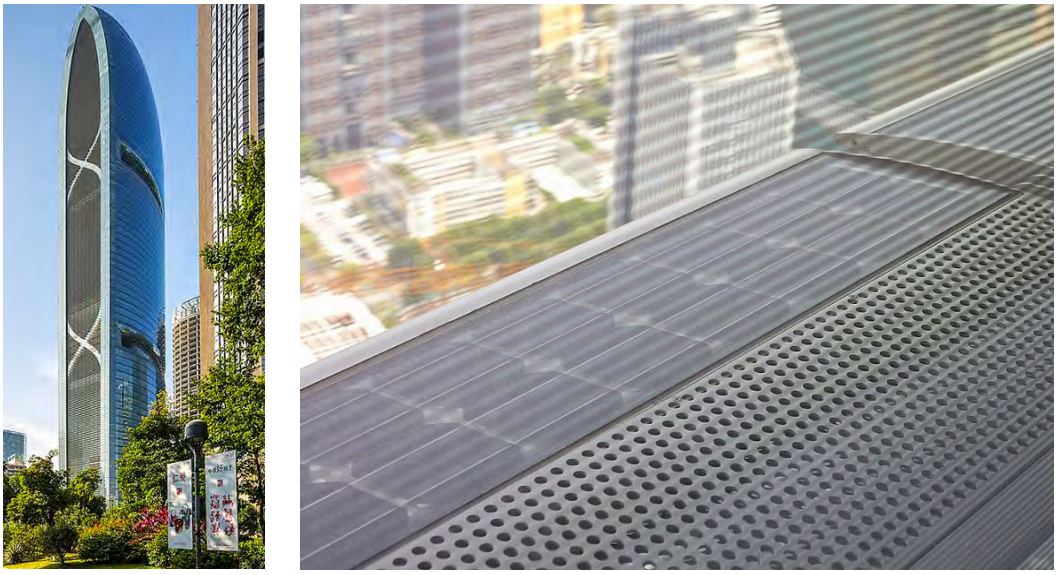

Fig. 3.22. Perspective view and PV louvers of PRT
Source: SOM
Accessed: March 23, 2014. http://www.som.com/projects/pearl_river_tower

Integrating PV seamlessly, the Pearl River Tower utilizes this technology on higher more sophisticated and elegant level. Integrated into its bullet shaped glazed roof and its shading louvers, the building takes advantage of the dictum "Form follows Performance," as Adrian Smith would say. This is achieved by the convexed body, which sits 13.6° off the street grid axis. Generating over 200 Mwh per year, the Photovoltaic additive is unique in that it blends coherently into the overall building skin through the integration of PV in the south facing roof, lower southern entry points of the VAWT's, as well as the louvers on the East and West Facades. The PV louvers are sandwiched between a double skin façade, which includes a venetian blind system that is motorized, via its PV louvers, and tracks the sun's path throughout the day.[141]

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[140] Ibid.
[141] Roger E. Frechette III and Russell Gilchrist, 2008, *Towards Zero Energy: A Case Study of the Pearl River Tower, Guangzhou, China, March 3 - 5, 2008,* Dubai: CTBUH 8th World Congress.

The benefit is that the solar angle and its generated renewable energy are optimized throughout all points of the day and the louver system powers itself. This is noteworthy not just for its active power features in sustainable design but for its passive power savings as well. The passive elements of this design is highlighted by using the PV as a building material for glare reduction, natural lighting control, and additional use as shading device; which louvers are a more dynamic and electrically efficient.

Another interesting additive is that the double skin façade is ventilated. This reduces the PV cells overexposure to thermal heat gain and maintains its efficiency as opposed to most solar modules that are exposed to the elements and sun and have a higher performance and aesthetic degradation factor(s) (fig. 3.23). In addition, the exterior glazing is made of tempered glass that has a low-E film on it to increase its R-Values and facilitate reduce thermal heat gain.[142]

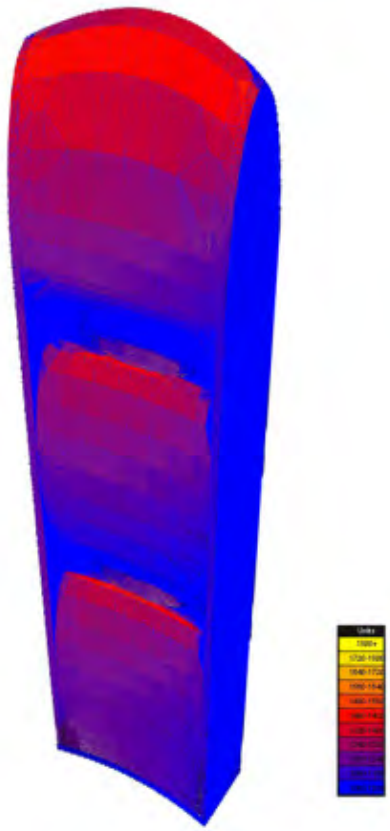

Fig. 3.23. Solar Radiation Mapping of PRT
Source: Remcal Corporation
Accessed: April 1, 2014. http://remcalcorp.blogspot.com/

[142] Ibid.

The PV louvers and its double skin façade can also be easily serviced through the interior, which increases maintenance efficiency dramatically, as opposed to exterior mounted PV modules which requires exposure to safety risks through exterior gondolas and incurs higher labor costs. These factors and the simple fact that the PV louvers are encased in this thermally regulated glass skin, the system of PRT offers an extended product guarantee of the PV cells reliable power potential and longevity. It offers a more optimal ROI because of its durability and longer shelf life due to the thermal protection and nature of the double skinned façade.

BIPV's failure to produce enough efficient power, provide thermal control, and maintenance costs are factors in any building's commissioning process. However, I think the main issues of surrounding urban density is that neighboring buildings tend to grow taller and taller, thereby resulting in a blocking of its daily sun path and shading the PV system(s). But seeing how the owner of the PRT building is the state controlled Guangdong Tobacco Corporation, (China has over 300 million smokers and consume about 1/3 of the world's tobacco) I doubt that the Chinese state sponsored zoning department would allow such a thing to occur.[143]

These 6 case studies, three in temperate and three in tropical climates, add to the body of knowledge in BIPV architecture. This is done by setting precedence in what can be accomplished when BIPV migrates into the façade of buildings to express its dynamic identity and what its power capabilities are. These architectural examples have now established certain BIPV design iterations that will now affect the overall design process moving forward as its method of tectonic construction, aesthetic affirmation and energy transfer have proved themselves viable. Furthermore, the examples presented above are very pivotal as they embody certain universal design concepts in exploiting the energy duality (passive and active) that set BIPV apart from other building methodologies of the 21st century.

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[143] World Health Organization Western Pacific Region, "Tobacco in China," WHO Representative Office China, http://www.wpro.who.int/china/mediacentre/factsheets/tobacco/en/ (accessed May 10, 2014).

CHAPTER 4:
Design Parameters

4.1 Basis of Design

The basis of design is in retrofitting the Pacific Davies building with a BIPV awning system. The structure is located on the block of Bishop St., Alakea St., Merchant St. and Queen St. in the heart of downtown Honolulu's financial district (fig. 4.1). The building was developed by the Theo H. Davies Co. and designed by the Architecture Firm of Au, Cutting, Smith & Smith Associates in 1970. It functions as a commercial typology of various offices.

Figure 4.1. Pacific Davies Center

Source: Pacific Office Properties
Accessed: January 3, 2015. http://www.pacificofficeproperties.com/p_honolulu_2.htm#

The building is further described as:

> "….a 22-story office property with an attached garage and ground floor retail space comprising a full city block in the heart of Honolulu's CBD. The property uniquely offers its tenants the sophistication and high-tech features of a modern Class A office building coupled with design details reminiscent of old Hawai'i. Davies Pacific Center features a beautifully landscaped pedestrian plaza, outdoor patio seating, conference rooms, and a host of other amenities."[144]

Having had Architectural Studio 543 in the 10th story of this building, facing the First Hawaiian Bank building and overlooking I'olani Palace, I am familiar with the Pac Davies Center's interior as well as its exterior layout and experience (fig. 4.2). The atmosphere of the Pac Davies Center is lively and active. The building fosters a professional environment and utilizes its site and surrounding views well. This is exceptional as the Pac Davies Center is located in the most concentrated and densest part of the city.

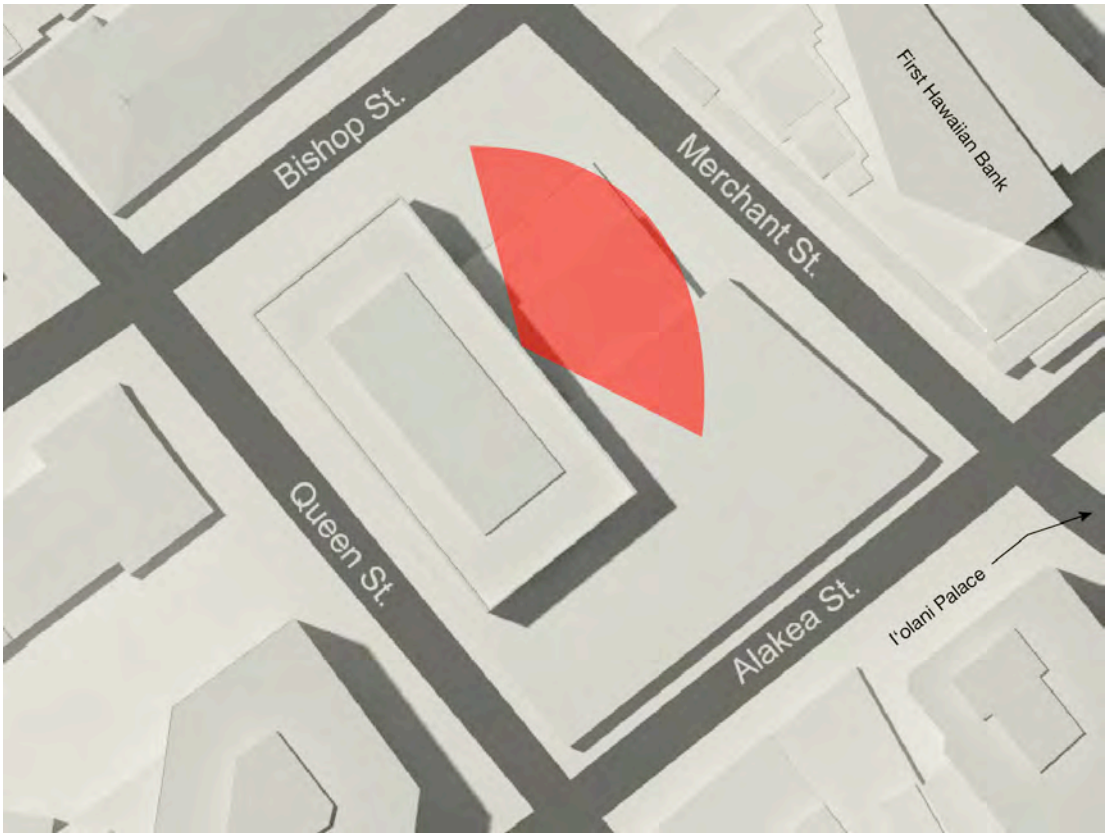

Figure 4.2. 10th Story Arch Studio 543 view

[144] "Pacific Davies Center", Pacific Office Properties, accessed February 2, 2015, http://www.pacificofficeproperties.com/p_honolulu_2.htm#.

The primary reasons why I choose the Pac Davies Center for the D.Arch project is because of my own personal experience with the building and for the fact it offers an ideal application of a BIPV tropical retrofit. This logic resides in the fact that the building has massive potential in energy harvesting through areas of the façade that experience high solar insolating. The issue of peripheral shading constraints created by nearby buildings present additional challenges and opportunities for aesthetic discovery using BIPV in a real world application.

In 5 years the Pac Davies Center will be 50 years old. Seeing how this surpasses the average life-cycle span of a building, only demolition, retrofit or renovation would suffice. [145] I choose retrofit because I believe that the most sustainable building is one in which you reduce a building's embodied energy on all fronts, work with the existing conditions to maximize longevity and minimize resource consumption. Furthermore, a retrofit is a great alternative to having to build a new building, as it doesn't have such a high initial cost compared to the latter, and it updates the building's look but keeps intact certain features of the building that has come to define in its historical identity. Additionally, because of Hawai'i geographical isolation the replacement costs of building materials for a demolition and rebuild would be extremely high.

After accessing these factors the ultimate reason on why the Pac Davies Center became the ideal candidate for design retrofit lies in an examination of its utilities bill, which totaled $2,081,000 over a 1-year span. Retro fitting is cost effective as the money used on the electricity bills could pay for a new PV system that could save on on-site energy use and provide an added economic benefit to the owner by updating its electricity systems. All these issues and opportunities were factored into my final decision for the Pacific Davies Center as the ideal building to do my D.Arch Dissertation on.

I. History

The Theo H. Davies Co. was one of the "Big 5" - C.Brewer & Co., Amfac, Castle & Cooke and Alexander & Baldwin - companies that influenced its history and development of Hawai'i. The company was started by British businessman Theophilus Harris Davies (1833–1898). Today these companies could be considered a modern day oligarchies through their land holdings and

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[145] Jennifer O'Connor, "Survey on actual service lives for North American buildings" (Presented at Woodframe Housing Durability and Disaster Issues conference, Las Vegas, October 2004), http://www.woodworks.org/wp-content/uploads/2012/02/fpi-survey-actual-service-lives.pdf.

agricultural companies in Hawai'i, which influenced the overthrow of the Hawaiian Kingdom in 1893. Today these companies still yield considerable economic and political power throughout Hawai'i.

It is mentioned historically that Theo Davies was actually against the overthrown, which was primarily instigated by Castle & Cooke. He even served as a chaperone for Princess Ka'iulani when she traveled to the U.S. to contest annexation by the American government to President Grover Cleveland.[146] A building's origin or identity sometimes affects people's outlook based on its creator's historical past.

II. Aesthetic Identity

The PDC is in the architectural style of "Brutalism", which was influenced by Le Corbusier's Unité d'habitation (1946-52) in Marseilles, France (Fig. 4.3) and was propagated in waning days of Modernism from 1950 though the mid 1970's. This Brutalist style has been described in *Understanding Architecture: Its Elements, History, and Meaning*, as the "…celebration of rough building materials in deliberately crude construction…"[147] The Pacific Davies Center shares this motif, as it emphasizes the use of poured in place concrete in a rugged course manner which produces a visually heavy and somewhat authoritarian appearance like that of a fortress. The Pacific Davies Center stands as a time capsule to the Utopian concept and ideological "straight jacket" espoused in Modernism.

The stoic force and weight behind this building further promoted a man or corporation of strength and stature. The landscaping, interior environment and transitional parts of the building bound the place together for an affective cohesion of components, which facilitated social interaction. The exterior, in today's context, is hard to relate to. It was uniform, heavy, somewhat stagnate and dated. The building is commanding, but stands awkwardly within the dense urban environment as the two buildings flanking it, the First Hawaiian Bank Building and the Pacific Guardian Building.

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[146] Ralph Kuykendall, The Hawaiian Kingdom 1874-1893: the Kalakaua Dynasty, (Honolulu: University of Hawaii Press, 1967),115.
[147] Leland M. Roth, *Understanding Architecture: Its Elements, History, and Meaning,* (New York: Icon Editions, 1993).Pg. 596.

Figure 4.3. Unité d'habitation in Marseilles, France

Source: Fondation Le Corbusier
Accessed: December 15, 2014. http://www.fondationlecorbusier.fr/corbuweb/morpheus.

These buildings facades' offset the Pac Davies Center's heavy concrete and competes visually in the uses of glass and stainless steel within their building envelope. However, the PDC's rugged skin and or egg crate fenestration produces beautiful shading lines that catch the attention of the viewer. The building still has much life left in it, so there was promise in utilizing the good while designing in front of or around the bad.

On an aesthetic level, a BIPV design retrofit was in order as it gives it both a qualitative (aesthetic) and quantitative (energy performance) reinterpretation. I wanted to do this to be able to enhance its future potential, challenge the notions of what a BIPV retrofit could be and where it could be used. This would also enhance the Pac Davies Center's appeal by being able to physically compete with the surrounding buildings of the downtown financial district while also promoting the current and future goals renewable energy through technological retrofits and architectural upgrades.

III. Façade Based BIPV

It is common knowledge that façade based BIPV performs better in temperate climates (23.5° N. to 66.5° N. & 23.5° S. to 66.5° S. Latitude) as the sun is at more lateral angles, based on the latitudinal sun path, which is lower in

the sky and hits more directly on the facade of buildings. However, in the tropics the roof is the most ideal location for PV application or integration as the sun path is closer to zenith due to the latitude being nearer to the equator.

This design research project looks applying temperate based design methods within tropically based climates. This was analyzed and achieved in 3.2.2. NUS Study of Three Singaporean Case Studies and will be expanded upon in a Hawaiian climate and latitude. This will be done because PV as a technology and BIPV as a design basis are underutilized and demands more expressive and dynamic designs in the façade.

The current PV technology is relegated to being an applied rooftop apparatus where BIPV designs capture a greater utility. Even then, PV is purely a function aesthetic that doesn't appeal to the everyday person. If view from more of a proletariat position, say from the street, say in residential situations, the PV is still a Building Applied Photovoltaics (BAPV) system; as it is crudely rigged to the roof and serves only a functional role in the overall scheme of the building.

Current application of PV is very ugly and not beautiful or unique due to its "attachment" nature. It is not cohesively integrated into the identity of the structure. This creates a mismatch in a functionally visual way, as the system adds visual entropy and clutters balance of the architecture. However, with façade base BIPV it has the dual potential to be expressively beautiful and performatively functional. This changes the way BIPV can be viewed as a façade based practice.

Yet, working with a BIPV retrofit is no easy matter. As mentioned in *Detail* magazine's *Photovoltaics A-Z* issue, it states "When the energy performance of existing buildings is to be improved, the general conditions are far more complex than in new buildings."[148] This is because the creative and physical controls an architect has over a new building vs. a retrofit or renovation is easier to predict as it is design intended using the newest technology and systems and the commissioning process of the new additions or systems are either simulated to prove the design and backed and guaranteed by warrantees. With a retrofit or renovation, the architect has the issues of working with older systems to integrate and mix with their new architectural applications. This requires a higher labor and knowledge cost in applying modifications of BIPV.

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[148] Roland Krippner, "Solar Technology in Building Envelopes," *Detail*, July 2012.

IV. Design Concept

The main driver of this D.Arch dissertation is application of temperate climate façade based designs to tropical latitudes, with the goal of pan-tropical adoption, the current objective is not in reducing the overall cost of BIPV construction. As of now PV technology, and BIPV as a design alternative to energy development, is not yet at the price point, business model or modularization standard, that makes it economically and politically accepted in all forms of construction. The concept will realign and focus on not only what influenced the creation of BIPV, but in cross-application of energy development and traditional architecture.

As mentioned in Chapter 2, BIPV has the future potential to replicate photosynthetic processes to harvest renewable energy to rethink architecture from being consumers of energy to "…net producers of useful resources."[149] However, the current technology does not yet exist to fully replicate the photosynthetic process, with a high enough electrical energy yield, and for a low enough cost, to use for complete building integration. The future of BIPV is evolving, The concept of a future of BIPV lies in its potential to shape the world for a more energy efficient infrastructure and its built environments.

For the purpose of the overall concept of BIPV and what is to be designed is an initial step, will be in trying to achieve on a conceptual level, a design that in some sense points towards a photosynthetic building replication and envisioning a future where building components can double as "photosynthetic surfaces" for increased on-site axillary or total demand power potential. This is the qualitative goal but not the goal of the entire D.Arch dissertation. For that it will be discussed in section 4.3.1. Qualitative Analysis.

4.2 Methodology

The methodology will be in developing design parameters that either balances or scales the benefits of the active and passive functions of the PV awning scheme. In the case of the Pacific Davies Center, I have made the decision to examine the equation in the direction of active PV generation as the dominant format between the two.

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[149] Michael Pawlyn,, *Biomimicry in architecture,* (London: Riba Publishing, 2011), 98.

Reasons for this are:

- The Eggcrate construction of the building envelope acts as a thermal barrier consisting of a window to wall ratio of 45%. This has established a well design building, as it was intended to be, and getting in more light in the interior due the depth of the façade, during certain times of the year, might be more important.
- A major concept of this dissertation is in photosynthetic replication. Therefore an emphasis will be placed more on the PV technology side than on the passive side of the BIPV equation.
- Quantifying the interior light changes and needs, as well as embodied energy, is very difficult and requires longer analysis than this dissertation permits.
- Quantifying the exterior solar insolation is more verifiable and further reinforces BIPV as a viable design intervention.
- For BIPV to become more adopted within the building community, the first promotion comes with discussing the phenomenon of the renewable energy (active) generation as a reliable payback, economic incentive and energy efficiency component.
- Passive benefits are important but architects should already have passive strategies in mind as a deign default.
- The shear price and scale of the energy bills and electricity consumption puts the building's demand side on that of energy harvesting needed to offset consumption in electricity.
- In regards to retrofit vs. new build, a passive system is easier to measure in a new build, with existing computational fluid dynamic, radiation and daylight design simulations, than it is in an existing building because of changes in technology and the age of the building.
- Poor energy performance, lighting and energy uses, are contributing to its overall $2 + million costs.

Because of the above issues with the passive side of the awning system, as it relates to the existing building, I have decided to focus more on the active side of the PV generation in the retrofit scheme. That is not to say that the passive/shading side of the BIPV system doesn't have a role to play within the overall design retrofit goals of this dissertation. It now means that the passive component to the interoperability concept will have to play the subdominant role of a sidekick vs. that of the lead actor of active PV energy harvesting. Both are integral to one another's successes within the threshold of building envelope. However, both cross at the intersection of a specific shared goal: Interoperable energy function (fig. 4.4).

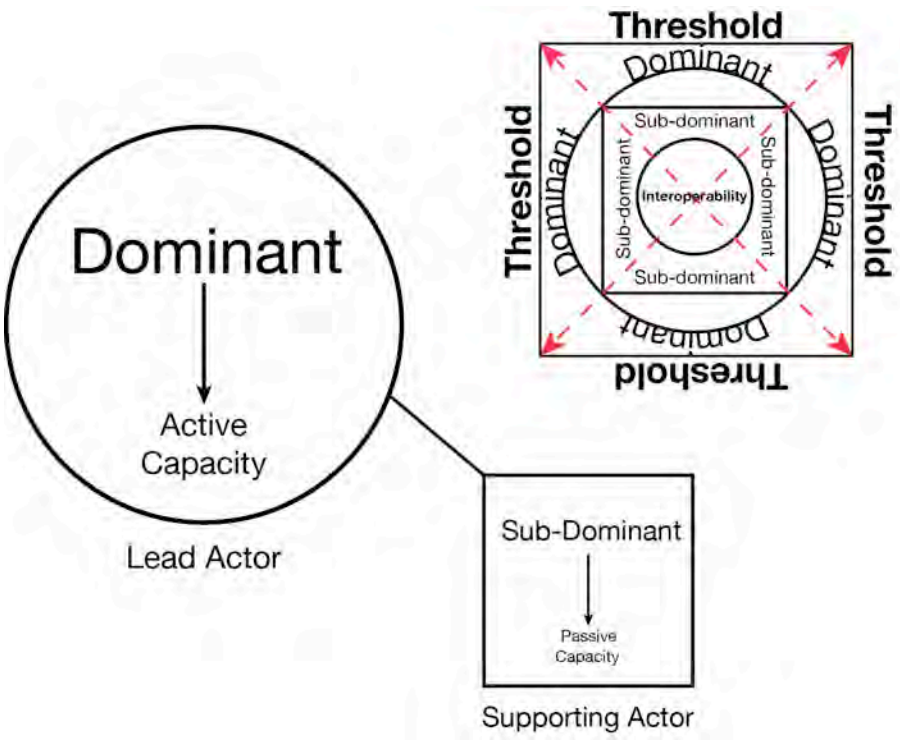

Figure 4.4. Dominant (Active) to Subdominant (Passive) relationship

This diagram is tangible to reality as it is symbolic of the social continuum of dominant to subdominant relationships; specifically as it relates to personality types that are active and passive. This diagram is applicable in deciding which relationship to leverage the majority of the electricity demand. To establish a focused methodology of the BIPV systems, the sections needed for successful architectural design intervention and increased power potential needs to be outlined and defined (fig. 4.5). Below are methodological topics to consider.

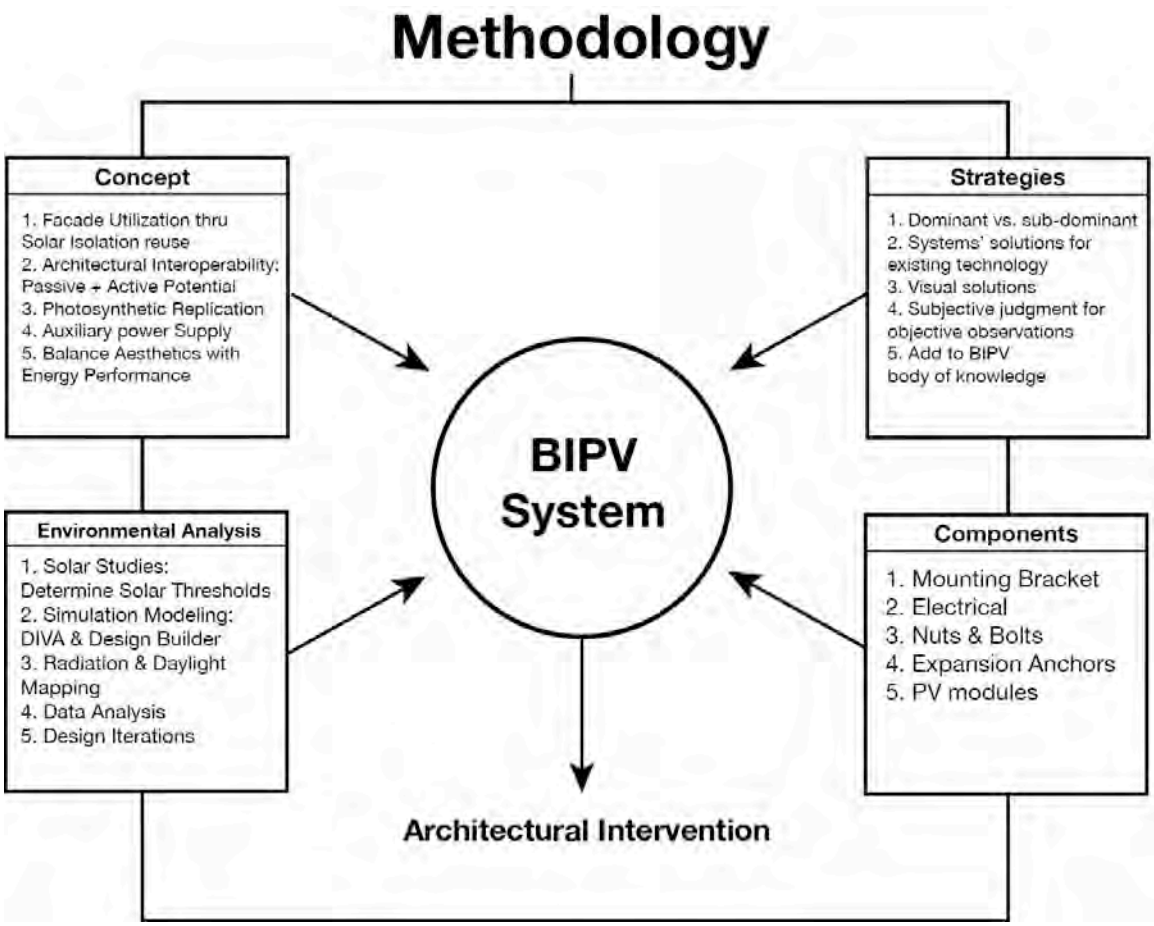

Figure 4.5. Methodology Map

These topics are important as they establish a format of decision-making through out the design considerations. Not all points will be equally balanced to one another. However the goal will be in hitting a majority of the targets for an architectural intervention that produces a well round BIPV solution for the dense urban area of downtown Honolulu. The above concepts are the drivers and goals of the BIPV façade system. Accomplishing them to the fullest is not the purpose of the design research project. What is the purpose is in utilizing both active and passive potentials within the building envelope to push the boundaries on what tropical BIPV adoption can be and how it can be considered a reappropriation of photosynthetic concepts.

The objective of the methodology map above is to outline and target the qualities of the BIPV façade's interoperable features. This duality is in an attempt to balance its aesthetic qualities with that of its performative qualities, which is a reflective value of each other's functions. The current retrofit goal is power

reductions through the BIPV system delivering energy as an auxiliary power supply. To produce a net-zero or energy-plus building that can surpass this retrofit goal is the longer-range picture in the historical arch of BIPV and its broader base potential. This is because currently PV technology and the chosen building and its orientation, net-zero or energy-plus is not possible based solely on BIPV. Functional problems of battery technology and storage capabilities require separate investigation and are not intended for discussion here.

Environmental analysis is used to determine solar insolation, solar thresholds, kW power potential, shading factors and direct energy reuse are based on 10 BIPV awning design iterations. Accordingly, modeling the base line energy use of the Pac Davies Center vs. the 10 design iterations with DIVA and Design Builder energy simulation programs are essential to determine energy production ina BIPV setting. Using these programs to utilize the data from the radiation and daylight mapping will further reinforce and justify placement of the PV array(s) and validate an appropriate retrofit based on a sound BIPV methodology.

The strategy above, which facilitates the flow, and content of this design research project, includes, determining the dominant to subdominant roles of the BIPV system, which has been done above. Determining the visual type and systems solution for how to best utilize the existing technology will help push the BIPV design into the next realm of development. After completing these tasks, a major strategy will be in the choosing one of the 10 BIPV retrofits based on energy output, shading needs against direct solar heat gain and aesthetic preference. This last part is the subjective judgment needed to arrive at an objective solution. This results in achieving efficient BIPV retrofits.

Furthermore, I have to determine and design which mounting bracket, electrical or balance of system (BOS) needed to conduct electricity transfer, nuts, bolts and expansion anchors to be applied and PV modules to choose from. After all this is done, the execution of the project should facilitate itself and my hypothesis based on the above should reveal itself as either true or false.

4.3. Design Considerations

In determining the climatically appropriate BIPV shading device for Honolulu, H.I., the elements of function and appeal are significant factors. Together, these elements provide for an increased energy advantage to any existing building. In estimating the appropriate BIPV awning system, it is the elements of aesthetics, energy performance and economics, that will play pivotal roles in the design considerations (fig 4.5).

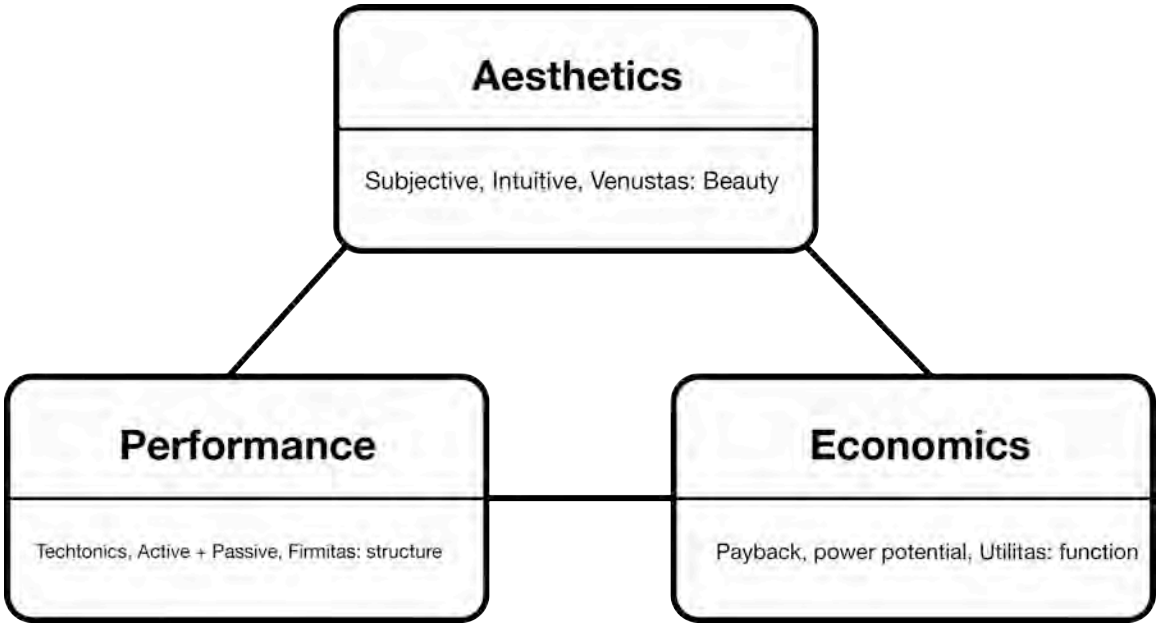

Figure 4.5. Triple design considerations

The essential factors in determining a successfully BIPV awning system, within the building envelope, are as follows: First, one must consider what a building envelope is. In its basic architectural form a building envelope must act as a physical interface between the external and internal environments while mediating heat transfer and minimizing energy use in delivering interior thermal comfort. As an active electrical component, PV can be reduced down to one thing: the generation of energy using solar power.[150]

PV panels can be optimized functionally to the specific Hawaiian latitude of 21.3° N to achieve a reliable electrical output. Application of PV and BIPV to

[150] Roberts and Guariento, *Building Integrated Photovoltaics*, 44.

the tropics raises new challenges, such as relative humidity and elevated heat factors, which affect the overall cell performance of the solar panels.

To understand how the passive side of the BIPV system works, we first must define what "Passive" means in relation to the solar design aspect of this project. Mentioned in the book *Green Building Project Planning & Cost Estimating*, the term passive, in building terms, applies to:

> "…architectural elements, such as windows, insulation, and mass, operate as a system without the need for power input to mechanical equipment. Passive solar designs are categorized as direct gain, sunspaces, or Tromble walls."[151]

In terms of tropical applications, it is stated that by the Solar Energy Research Institute of Singapore, the "Facades account for up to 50% of the thermal load in buildings in the tropics and are related to many occupancy comfort issues, such as glare, thermal comfort and noise transmission."[152] This provides an enormous opportunity in targeting and addressing energy efficiencies and power conservation within building envelopes.
Based on the active and passive design considerations, further determinations of the qualitative and quantitative energy types and the component system itself are needed in estimating the appropriate tropical BIPV awning scheme for the D.Arch project.

4.3.1. Quantitative Analysis

The Pacific Davies Center consists of a total of 348,319 ft^2. However, the façade retrofit will only consist of the analysis of 288,800 ft^2. This aids in a quantifiable target as the main body of the building, and not its total footprint, will be the focus of this D.Arch project. However, overall electrical energy demand of the total footprint will be reduced using a BIPV design intervention spanning the dominant core of the building: 7th-22nd floors (fig.4.6).

This central massing is key in the development of the BIPV system and its performance, as this area, mostly notably the East, South East and South West façades, experience high levels of direct solar insolation. The shear surface area of the spandrels, 33,552 ft2, on the façade provides enough space that

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[151] Adler, *Green building*, 130.
[152] "Annual Report 2013," Solar Energy Research Institute of Singapore, http://www.seris.sg/Seris/Publications/AnnualReport.html.

can be sufficiently utilized with the incoming solar radiation for the energy reuse and harvesting (solar panels) while also establishing a passive energy potential (shading devices). But what are the immediate factors one should evaluate when looking to achieve a successful BIPV design intervention?

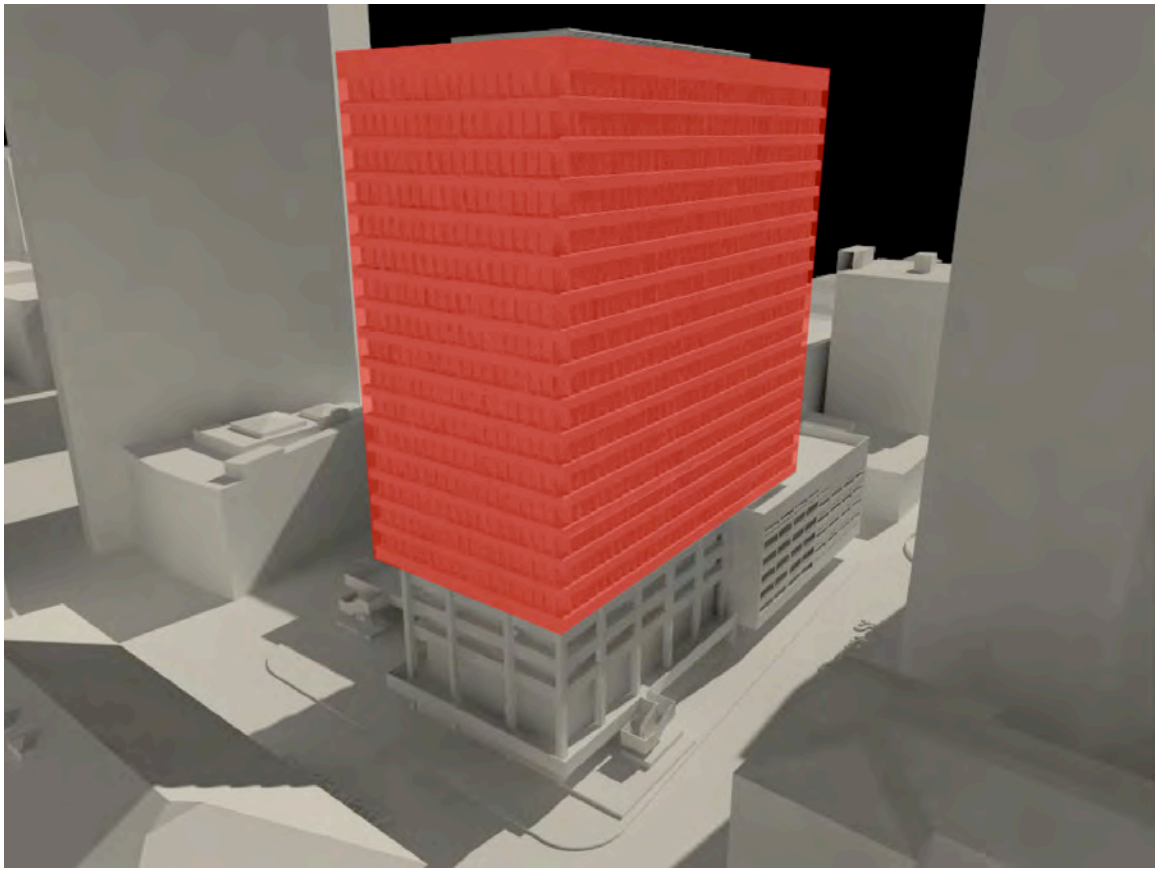

Figure 4.6. Area of BIPV design intervention

Immediate factors to consider:

1. Location, Site and Typology:
    - This is the first step in addressing the conditions of the Hawaiian climate and environmental factors that could affect the design and performance of the BIPV awning.

2. Estimate Orders of Magnitudes:
    - Panel efficiency rating
    - Hours of available peak sun hours: 5.8[153]
    - kWh/year for load demand and solar insolation
    - Performance: Active and Passive

[153] "Solar Map Oahu," Hawaii Energy, http://hawaiienergy.com/images/contractors/OahuSolarMap65f1.pdf

In accessing factor 1, this will be covered in detail in Chapter 5.1.1. This is highly important, as this will affect the design and its lifetime performance, both in the active and passive energies strategies. With factor 2, the panel efficiency rating will range from 13%-21%. This is estimated on the uses of generation #1 c-Si and generation #2 CIGS Thin-Film. The exact module and its efficiency rating will be fully established in Chapter 7, when the components needed for a BIPV awning system will be finalized.

According to the solar map of Oahu below, the downtown region of Honolulu experiences, on average, 5.8 peak sun hours/day (fig. 4.7). Furthermore, as estimated in Chapter 2, the annual solar insolation Hawai'i gets about and 5.96 kWh/ft^2/Day.

The total energy consumption by the Pacific Davies Center is 6,542,000 kWh/year or 17,774 kWh/day (average). Economically this equates to $2,074,058.00/year or 5,433.00/day. As you can see the magnitude of the energy consumption and its translated costs are staggering. As measured and simulated through radiation mapping, the buildings façade experiences a mean solar insolation of 768.5 kWh/m^2/year.

These numbers will be covered more in depth in Chapter 6. These estimations are just to give you a frame of reference in establishing the baseline energy uses of the Pacific Davies Center so that one knows what the project is dealing with and how to design around these energy issues.

As was determined above, the leverage of the passive aspects of the BIPV design will be overruled by the active capabilities of the PV system and its renewable energy performance(s). Figuring out the technical design components, such as a bracket and or PV mounting system, will be pivotal in channeling the associated wiring needed to establish a proper Balance of System (BOS). The solar panels used should be more opaque as it needs as much light absorption to trap and convert solar energy. If designed clearly and simplistically, this will streamline accessibly for future maintenance and operation needed and will consolidate efficiency measures as best as possible for further durability and quality control of the entire BIPV system.

Another design parameter to consider is the nature of the BIPV system itself. Will it be modular to reduce cost and look uniform or will it be customized to create aesthetic expression but with a higher price tag?

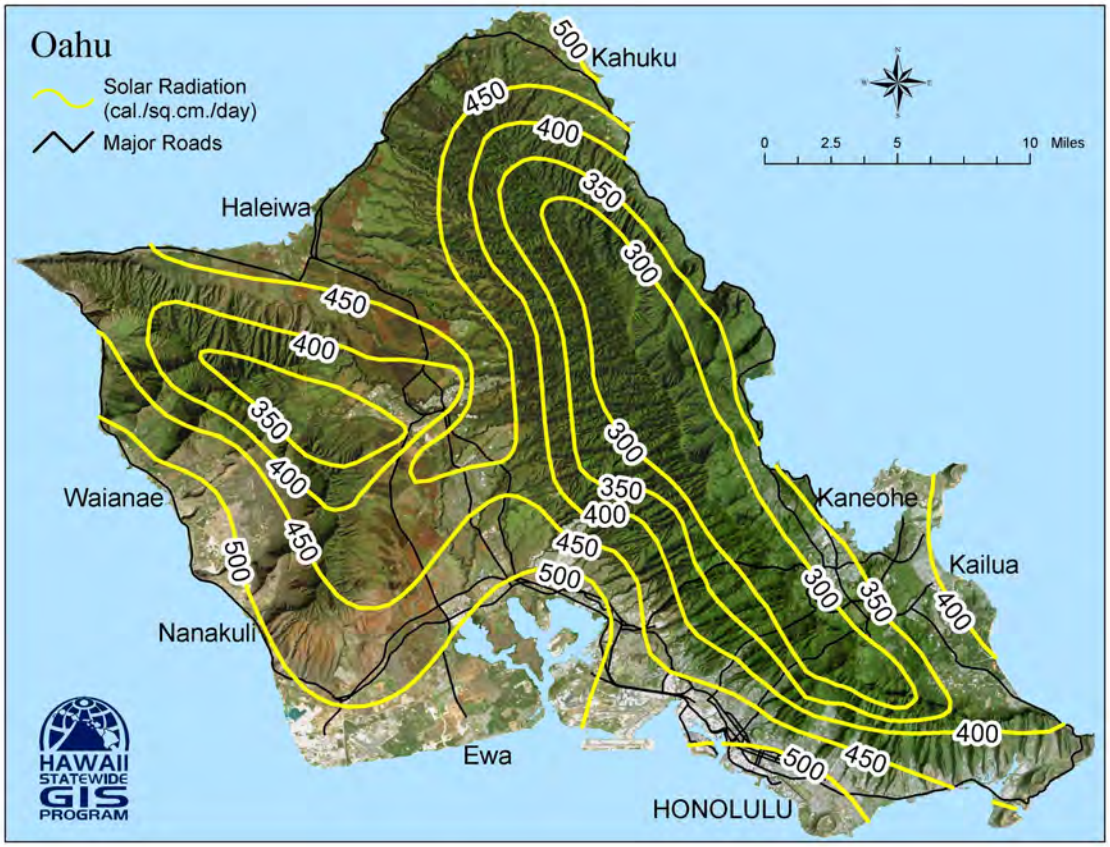

Figure 4.7. Solar Map of Oahu

Source: Hawaii Statewide GIS Program
Accessed: December 13, 2014.
http://hawaiienergy.com/images/contractors/OahuSolarMap65f1.pdf

Modular vs. Custom

1. Modular (Fixed)
2. Hybrid (Adjustable Mounting Brackets)
3. Custom (Sun-Tracking)

Due to the operation and maintenance (O&M) of going custom, sun-tracking system for BIPV and not ground mounted, which raises costs significantly, I believe the system will settle midway between a modular and hybrid BIPV system. Further aspects of quantification involve a variety of design options. In the book *Building Integrated Photovoltaics: A Handbook*, it suggests the specific design considerations of BIPV consisting of:

- Color, image, size
- Weather-tightness
- Wind loading

- Durability and maintenance
- Safety during construction and in use (fire, electrical, stability)
- Cost

The passive component of this BIPV façade could save a considerable amount of energy, offer better human comfort and require less maintenance than its active PV counter part. This is because passive systems are self-regulating systems that function in perpetuity. It is even possible that the final results of this design research paper could lean on the passive side as achieving more energy and fiscal savings than its active counterpart.

The length of Daylighting will be very important in trying to balance out the optimal performance aspects of the PV system, orientation, tilt and etc., while creating a space that improves upon human productivity, psychology and comfort through the phenomenon of natural daylight. This leads into the cause and effect relationship of the cooling and electrical lighting loads, which are set in motion by the ratio of openings (windows) that emit daylight.

In addressing the cooling loads, which are triggered by the building's form and its daylighting factors, the project has the benefit in that it is primarily concerned with the mitigating of heat while also utilizing it as a renewable energy source in the building envelope.

The D.Arch project will need to consider calculating an appropriate "daylight factor" suitable for seasonal shifts in the tropics. This factor deals with overcast conditions and its relation in calculating and designing for the desired interior natural lighting. This can be determined by how high and large windows are in a building envelope contrasted with the floor area of each daylight space.[154]

Cooler temperatures in the interior of the exterior of the office building, affects the thermal envelope. The passive design features could also aid in a combination of energy and wind and shading by mitigating thermal heat gain providing higher solar cell efficiency through on the backside of the PV modules through convection via the cross and stack ventilation on the façade of the building. This benefits the solar cells of the module which can improve electrical performance by reducing PV temperature by up to 50° F.[155] By designing a layer of space we can in effect create natural convection through an ventilated air

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[154] Grondzik, Walter T. 2010. Mechanical and electrical equipment for buildings. Hoboken, N.J.: Wiley, pg. 219.
[155] Gaiddon, Bruno, Henk Kaan, and Donna Munro. 2009. Photovoltaics in the urban environment lessons learnt from large-scale projects. London: Earthscan, 151.

gap, which can reduce performative efficiency losses during high-temperature gains of the PV system by up to 7%.[156]

There is an average payback time it takes for a PV module to recover the embodied energy needed pay for itself (fig. 4.5). However, there is no definitive number of the average payback time it takes to recoup the total installed cost, $/Watt, of a PV system. This is because of the diversity of building stock, which dictates that no two buildings, and their payback periods, are the same. Accordingly, it is hard to find an average payback-whether state wide or nationally. Payback price are dependent on a number of factors:

- Tax subsidies, which varies state to state
- Parts and Labor costs (covered in Chapter 2)
- Utility inspection fees and third party approvals
- kWh size and average output of system
- Building orientation and PV placement
- Regional electricity rates
- Financing of PV system, whether leased or owned

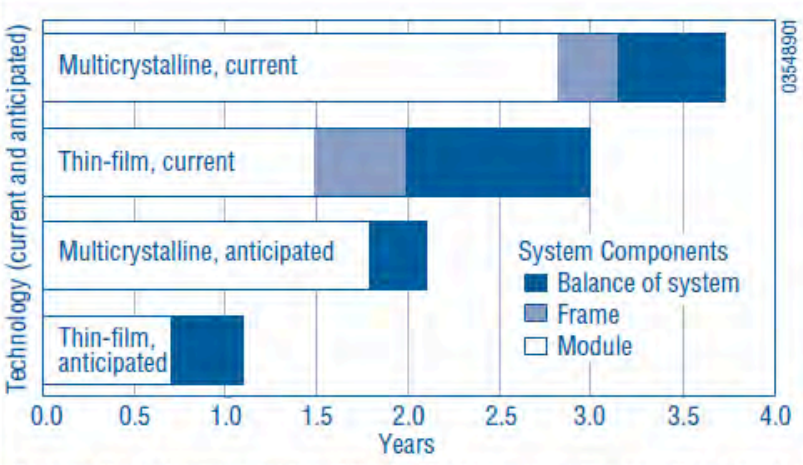

Figure 4.5. Energy payback for rooftop PV system

Source: NREL
Accessed: October 25, 2014. http://www.nrel.gov/docs/fy04osti/35489.pdf

However, information obtained from the article, *UHERO: Tax Credit Incentives for Residential Solar Photovoltaic in Hawai'i*, states that Oahu has the longest payback period (due to the lowest utility rates of all 8 islands) with Kauai having the shortest payback time because it has highest utility rates of all the

[156] James, T., A. Goodrich, M. Woodhouse, R. Margolis,and S. Ong. Building-Integrated Photovoltaics (BIPV) In the Residential Sector: An Analysis Of Installed Rooftop System Prices, November 01, 2011.

islands. From this information and under the tax law it was determined that statewide average payback period is 6.6 – 9.5 year.[157]

Of course this study covers the residential PV trends in Hawaii, and its mass adoption that has been going on for the past 6 years. Additionally, since the retrofit of the Pac Davies Center is a commercial retrofit and not a residential one, a significant price increase and its associated extended payback period are expected due to the total cost of the system and number of arrays. An average variable of 6.6 years, as a benchmark for the duration of the payback, could provide a viable commercial template for adoption of BIPV to the commercial sector.

The payback period is the primary factor which investors, developers and adopters of PV make their decision to implement BIPV. This provides a logical and economic justification of a BIPV system based on a façade retrofit in the dense urban environment of downtown Honolulu. Additionally, with a payback period of 6.6 years, can the system also achieve on-site total electrical energy reductions in the magnitudes of 20 – 40%, this might be possible seeing how Pac Davies is a commercial office whose main operations occur at the daytime hours when the solar production of energy is at its highest point.

Factors to consider in quantifying this on both passive and active success are its Location, Site and Topology. These elements of appropriate façade design addresses environment factors are paramount to the electrical performances and exterior and interior conditions of the PV system, which are complimentary to buildings functions. In shifting towards the systems design, the project will be focused on active capabilities PV energy generation through its on-site power and its relationship with:

- Technology & System.
- Levels PV Façade Integration.
- Energy Harvesting & On-Site Distribution.
- Glare Reduction.
- Provide visual and functional satisfaction.

The terms of quantitative aspects I will not go into details about feed-in tariffs, utility company's role, and factors that do not deal directly with a PV system that values higher integration into the façade of a tropical building

[157] "UHERO: Tax Credit Incentives for Residential Solar Photovoltaic in Hawai'i," UHERO Hawaii, accessed January 22, 2015. http://www.uhero.hawaii.edu/assets/UHERO-PolicyBrief-SolarTax.pdf.

envelope. From all the information above I have quantitatively estimated what is needed to achieved a viable BIPV design and its performance:

Quantitative Energy Targets:

1. Economic payback of total PV system under 6.6 years
2. A total building energy reduction of 20-40%
3. Passive shading that reduces the use of electrical lightings and air conditioning and facilitates interior human comfort.

4.3.2. Qualitative Analysis

The qualitative assessment will be measured on creative displays of beauty, design and cathartic architecture expression. As architects have their own twist on what this means an exercise in subjective design and its justification will be formed throughout the process of the design, as the function this time will dictate the form.

CHAPTER 5:
Conditions and Strategies

5.1. Building Conditions

5.1.1. Location, Site & Typology

A 10-22 story office building in downtown Honolulu would be the ideal site for a BIPV awning system retrofit as factors of geographical isolation, the premium cost of construction and for the extended time it takes for new building projects to develop in Oahu. These goals can assist in updating the city's infrastructure while contributing to Honolulu's architectural and historical preservation needs. The balance between energy performance, economics and aesthetics, requires first determine the site, orientation and needs of the retrofit in question.

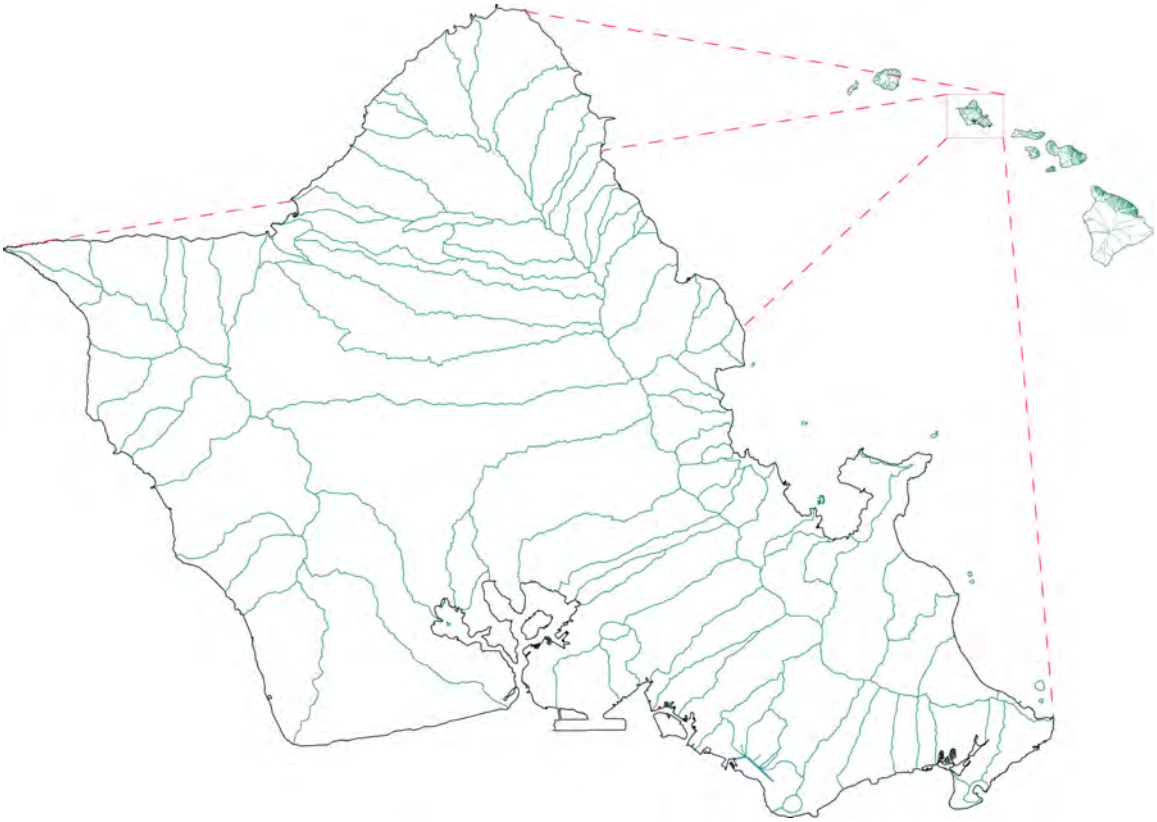

Figure 5.1. Oahu, Hawaiʻi (21.4° N, 157.9° W)

Figure 5.2. Honolulu (21.3° N, 157.8° W)

Classification: Ocean Island Climate[160]
Total land Area (Oahu): 596.7 sq. mi
Population (Oahu): 976,372
Density (Oahu): 632/km^2
Total GDP (HI): $62 Billion
GDP per capita: $48,000 (Honolulu County)
Annual Avg. Temperature: 69.6° – 84.6° F
Annual Avg. Relative Humidity: 68.5%
Annual Avg. Precipitation: 17.1 in
Avg. Solar Irradiance: 5.96 kWh/m^2/day
Optimal Solar Panel Angle: 21.3°

[160] Climate designation established by G.A Atkinson, Former Head of the Tropical Building Section of the UK in the book Tropical Houses by David Oakley. Oakley, David. 1961. Tropical houses; a guide to their design. London: Batsford.

The region of Honolulu was selected because of the climatic viability of PV, due to the amount of electromagnetic radiation the state of Hawai‘i experiences (table 2). Honolulu benefits from having yearly average solar insolation of 5.96 kWh/m^2/day is the highest in the nation. When compared to the national annual average of 4.42 kWh/m^2/day, the solar insolation of Honolulu highly optimal.[161]

Table 2. Percentage of yearly sunshine in Hawai‘i

City	Yearly % of Sun
Hilo, Big Island	41
Honolulu, Oahu	71
Kahului, Maui	67
Lihue, Kauai	59

Source: Current Results Nexus
Accessed January 21, 2015. http://www.currentresults.com/Weather/Hawaii/annual-days-of-sunshine.php.

Geographically, this makes for ideal conditions of PV adoption which accounts for a major boom in the residential and commercial rooftop PV market of Hawai‘i over the past 6 years. Honolulu is not as hot or dry as Kona, Hawai‘i, but is a greater thermal zone of visible light in the electromagnetic spectrum. Additionally, due to the Vog from Mauna Kea’s constant volcanic sulfur gases light radiation is diminished for PV application. This fact does not entirely eliminate the Big Island for PV adoption as it can benefit from more off the grid applications of BIPV due to isolated population locations within the island. Oahu is multi-climatic which benefit the adoption of BIPV within conditions of urban density.

[161] “Solar Insolation,” Solar Insolation.Org, Last modified January 15, 2012, http://solarinsolation.org/.

Figure 5.3. Downtown Honolulu (21°18′12″N 157°51′26″W)

5.1.2. Urban Context

In red rectangle is the Pacific Davies Center and foci of the D.Arch project (fig. 5.4). Located in the center of urban density, the Pacific Davies Center offers an ideal prototype for finding design solutions to the tropical urban issues of:

- Neighboring shading constraints and projected glare.
- Conditions of Urban Density (fig. 5.5).
- Direct lighting entering the interior at certain times of the day.
- Non-optimal setbacks to work with.
- A building of high energy and fiscal consumption.
- A historical building due for a retrofit or renovation.
- Offers high energy potential based the sheer size and area of the façade.
- Has defined the downtown Honolulu skyline for over 45 years.

The above-mentioned issues are unique to a downtown building in Honolulu.

Figure 5.4. Site: Pacific Davies Center

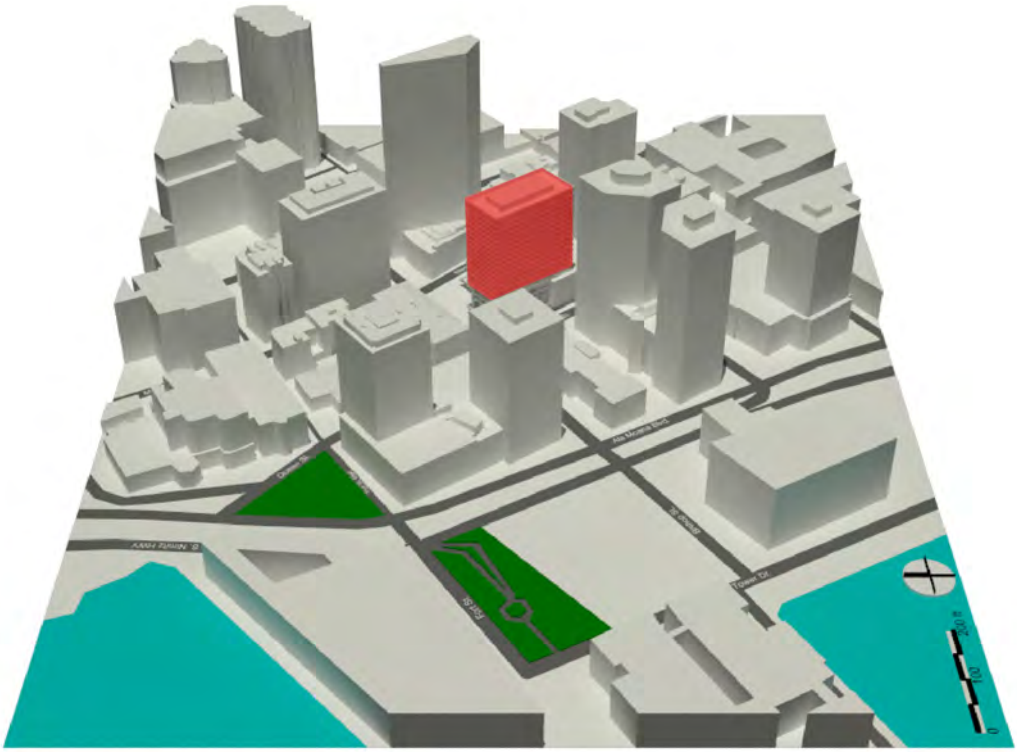

Figure 5.5. Pacific Davies conditions: center of density

5.1.3. Site Analysis

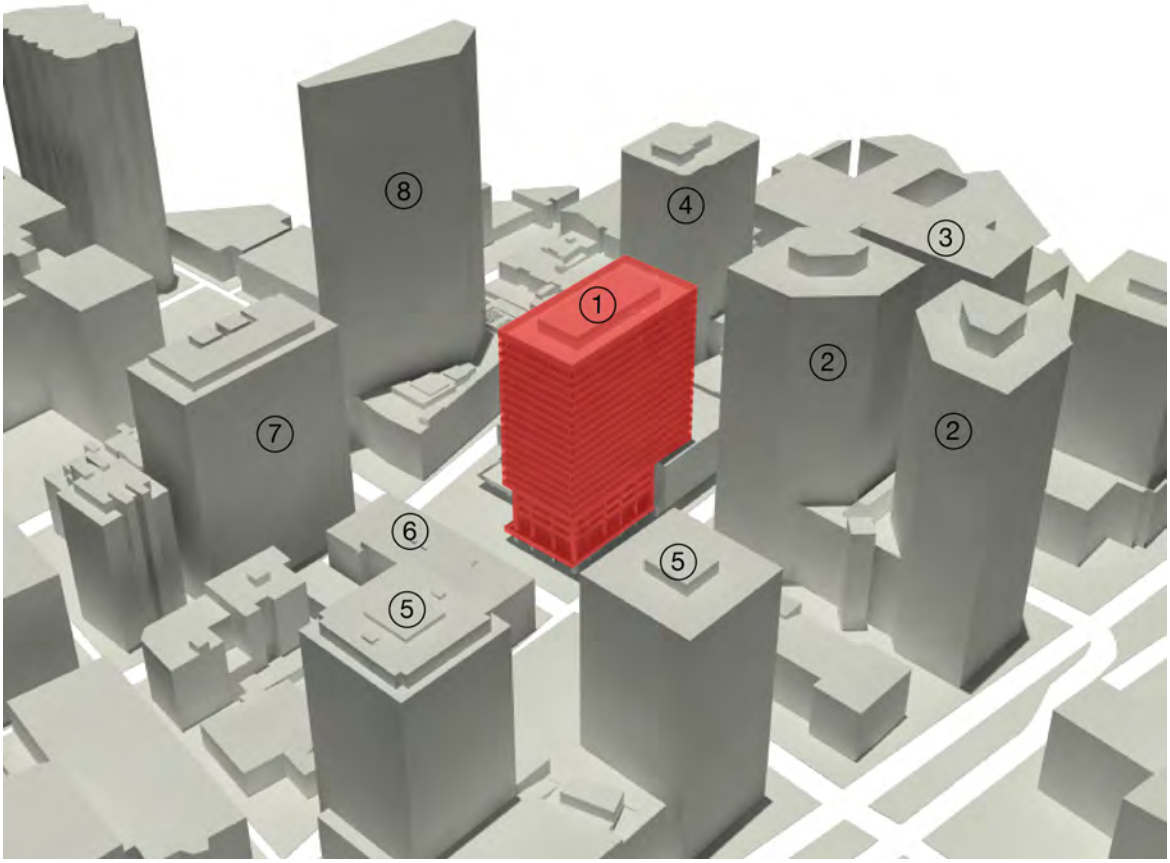

Figure 5.6. Downtown financial district

1. Pacific Davies Center
2. Pacific Guardian Building
3. Harbor Square Apartments
4. City Financial Tower
5. Topa Financial Center
6. Alexander & Baldwin Building
7. Financial Plaza of the Pacific
8. First Hawaiian Bank

Figure 5.7. Neighboring shading constraints

Maximum-to-minimum shading constraints:

1. Pacific Guardian Center
2. City Financial Tower
3. Harbor Square Apartments
4. Topa Financial Center
5. First Hawaiian Bank Building
6. Primary Shading Zone

Conditions of urban density create a shading defense against the unabridged solar radiation coming from the east, south and west line hitting the Pacific Davies Center (fig. 5.7). The building itself is orientated off axis from the cardinal directions of North, East, West and South. However, its corners are pointed in these directions, which creates an interesting interaction with the Hawaiian sun that cause diagonal solar radiation to distribute unevenly on the facades of the building. This causes issues within the PV design but also opportunities in aesthetic and cultural expression.

The neighboring structures specifically that of Pacific Guardian Building, projects a diagonal shadow on the South West façade year round and is the primary shading constraint on the Pac Davies. In the mornings, the City Financial Tower presents shading constraints from around 8-11 AM on the lower portion of the North East façade due to its eastern position from the Pacific Davies Center. The Harbor Square Apartments create a shading line on the lower southern portion of the Pac Davies parking structure but not to the main core as its height is shorter than that of the Pac Guardian Center.

The Topa Financial Building presented shading issues only in the late afternoon till sunset which is not a concern as the late hours of the day only provide minimal solar insolation. However, this is only certain times of the year and as Topa's physical setback is farthest from the Pacific Davies Center and generally allows sun light to hit the upper regions of the façade.

The First Hawaiian Bank building is the tallest building in the state, standing at 430', and only poses minimal shading constraints in the morning due to its easterly position from the Pac Davies Center. Furthermore, because of its polygonal form the building is intelligently designed as its southern façade is diagonally cut to deliver more morning light onto the façade of the Pac Davies center.

The smaller buildings within the primary shading zone do not pose shading constraints on the main core of the Pac Davies Center as their heights only affect the lower part of the building; which is not the main focus of the D.Arch project. Any of the buildings outside of the primary shading zone do not present shading issues, as their setbacks are far enough, they are north of the Pac Davies Center and their heights are short enough as not to reduce the solar radiation from hitting the main core of the Pac Davies Center.

As seen in figure 5.8, the main shading element, the Pacific Guardian Center, is also the main culprit of projecting solar glare onto the Pac Davies Center before noontime. In terms of the glare projecting on the façade, the active side of the BIPV system could benefit through generating more energy than usual as the solar glare focuses the intensity of the light. However, this also creates more heat on the façade, so the passive shading element of the BIPV awning system could combat and benefit from this issue tremendously, as its blocks direct light (glare) from entering the interior of the offices. This reduces air conditioning use, which is the main consumer of energy within the Pac Davies Center.

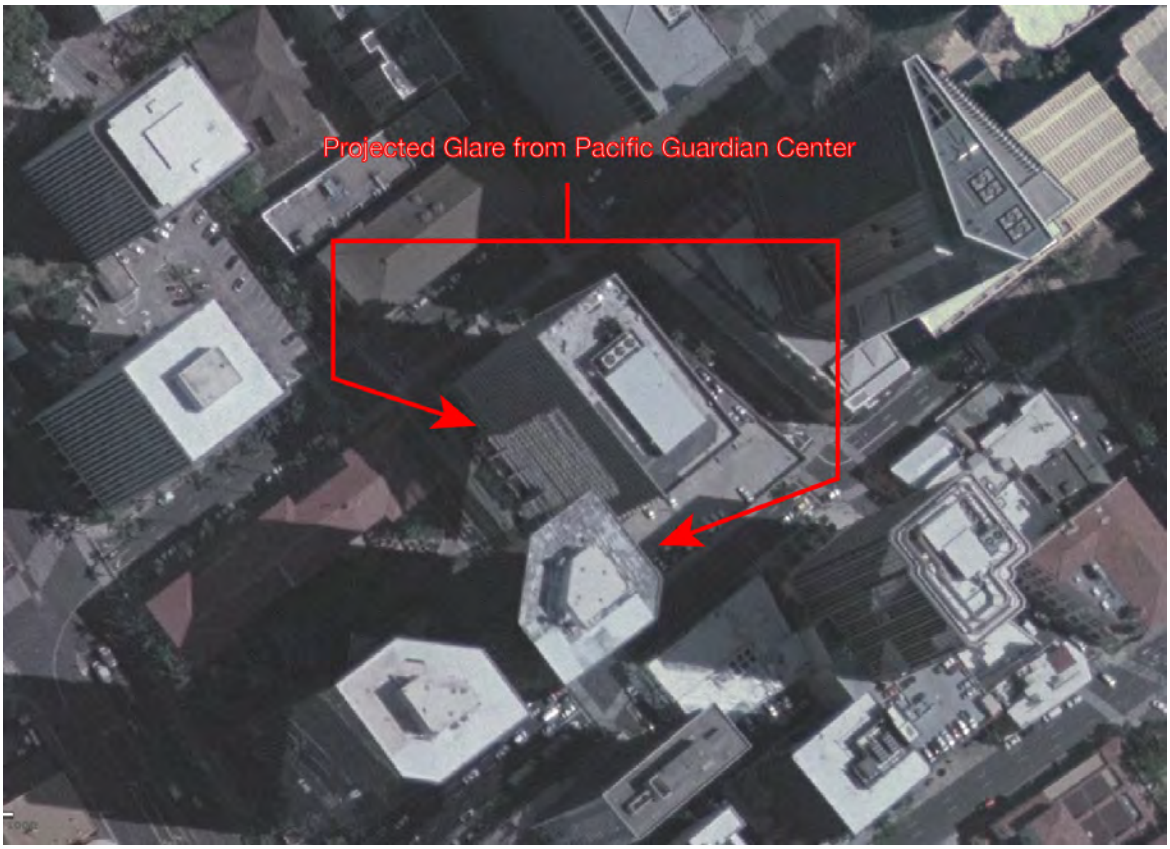

Figure 5.8. Neighboring glare issues

Due to the façade based nature of the BIPV system, the solar harvesting opportunities exist between the gaps and apertures of the surrounding buildings of Pac Davies Center. Utilizing this solar energy hitting the façade and from above, as well as self-shading against it, throughout the entire year to obtain renewable energy as well as conserving the passive site energy of Pac Davies Center, is the main goal of this D.Arch project and could further prove a viable BIPV system for tropical deployment.

Further visual analysis of the Pacific Davies Center dimensions, elevations, sections and floor plans are needed to fully understand the design, construction and form to develop an appropriate façade based tropical BIPV solution.

5.2 Building Analysis

5.2.1. Dimensions

I. Elevations

The elevations of the Pacific Davies Center were modeled on the original construction documents of the Pacific Davies Center from 1970. Presented are the elevations, sections and plans of the Pacific Davies Center. This is done to show existing building conditions and its overall design. Based on the uniformity of the Pacific Davies Center, a design will later emerge modeled upon the shading constraints covered above that can create a new shell or building skin fused to the structure for active and passive energy performances.

The elevations are visually represented to show the 360° off-axis interaction of the sun throughout the whole day: South East, South West, North West and North East. Furthermore, a site key was provided to give cardinal direction guidance and street markers to understand the site position of the elevations. The buildings are not set to any particular scale. This is done to represent the building in its entirety; as larger scale were either too small or large to fit onto one page. This is a recurring image standard that occurs throughout the rest of the D.Arch project.

To date these design documents represent the best and latest visual updates and renders of the Pacific Davies Center based on its original details. Further design analysis will follow in 5.3 Solar Studies and 5.4 Design Considerations to be able to gather what was visually presented to be able to evaluate a BIPV design alternative awning system to he façade of the building.

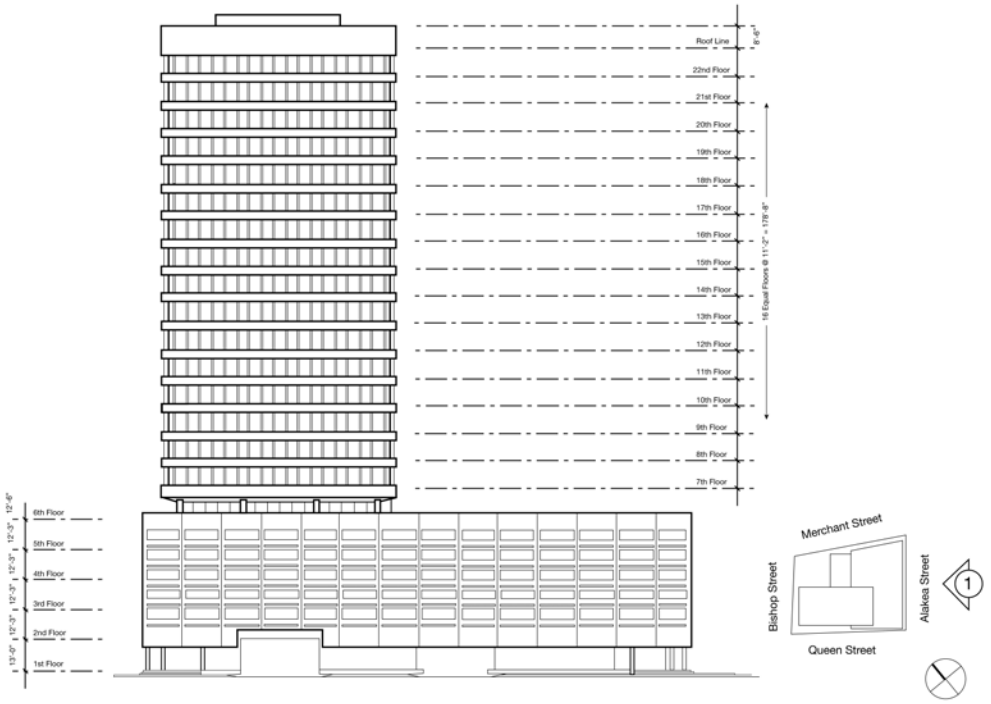

Figure 5.9. South East Elevation

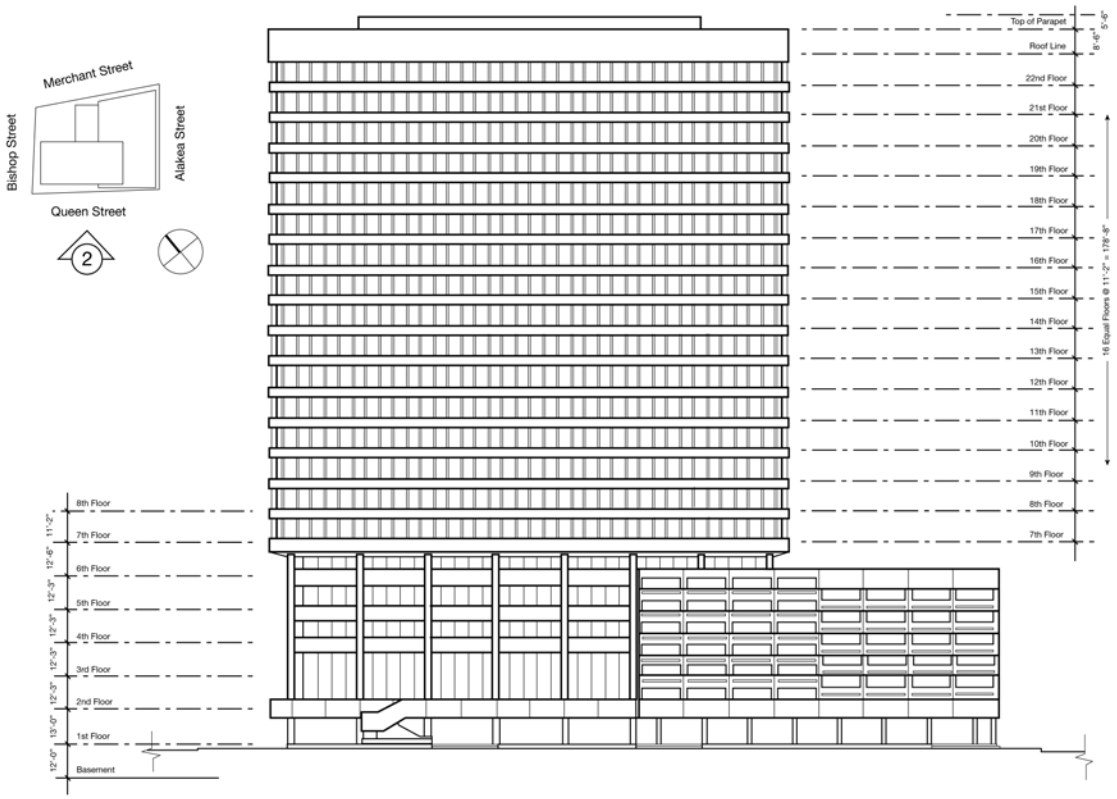

Figure 5.10. South West Elevation

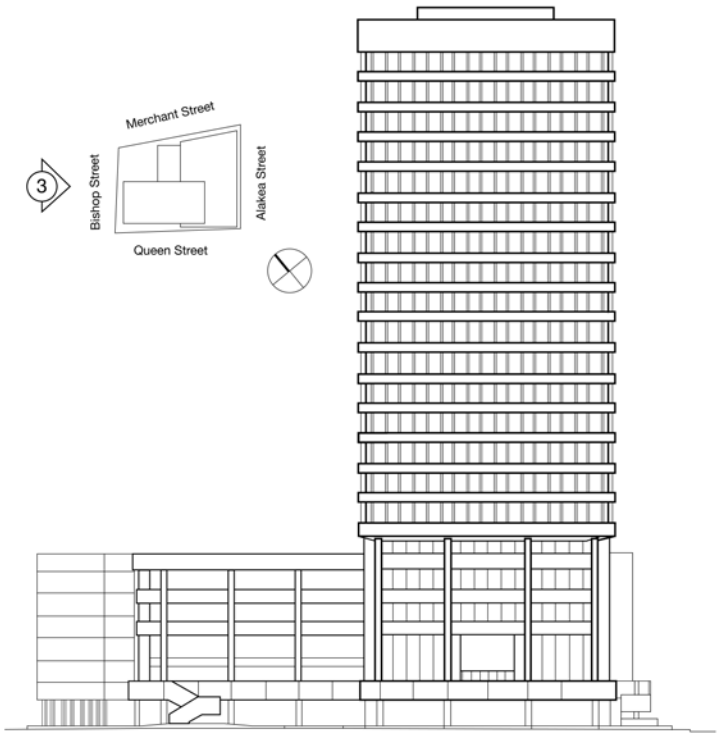

Figure 5.11. South East Elevation

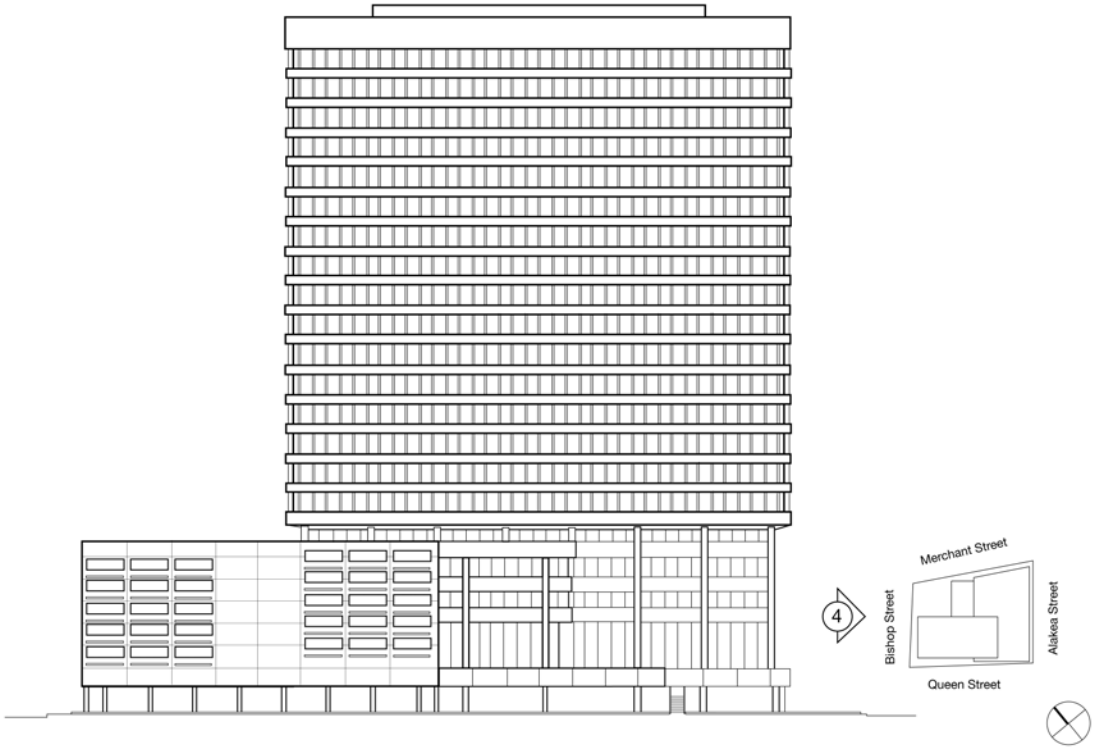

Figure 5.12. South East Elevation

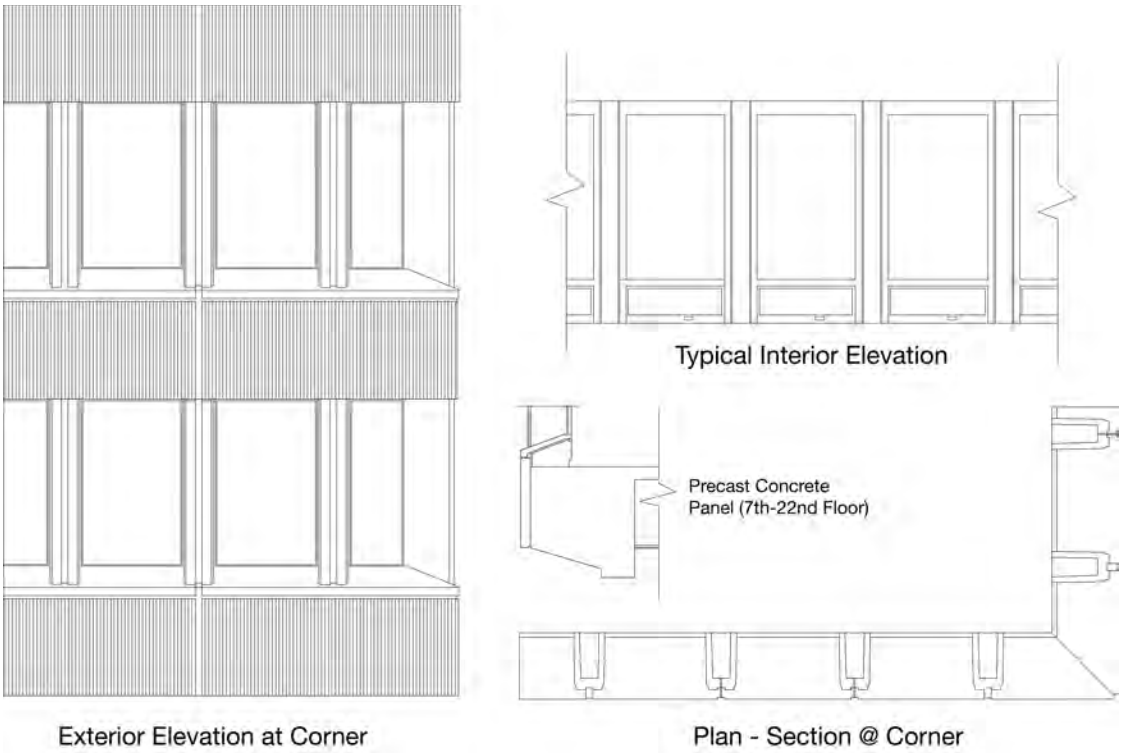

Figure 5.13. Additional PDC elevation, section detail and plan section

II. Sections

As seen in the sections below, the Pacific Davies Center was design intended to act a thermal concrete barrier, weather protector and to insolate against solar heat gain. It works relatively well in this way through its eggcrate construction, which has a depth of 2' 6", and is primarily composed of concrete components: pre-cast concrete panels and spandrels on the exterior and interior concrete planks. It also features 1" rigid insolation at the windowsills, CEM plaster soffits, interior plug load access and fixed glass in PVC liners. Its aesthetic detail on the façade is a sandblasted exterior for its rugged "Brutalist" look.

The floor plan has a total area of 18,050 ft^2. On the typical floor plan, floors 7-22, it features 6 partitions creating 6 offices spaces. However, if renovated you could remove partitions to configure 2 and 4 office with maximize office spaces or even add partitions to get as many as 8 offices; which minimizes spaces but maximizes rental revenue. It also features 4 elevator terminals, male and female bathrooms, janitorial storage, 2 fire escapes and an electrical room.

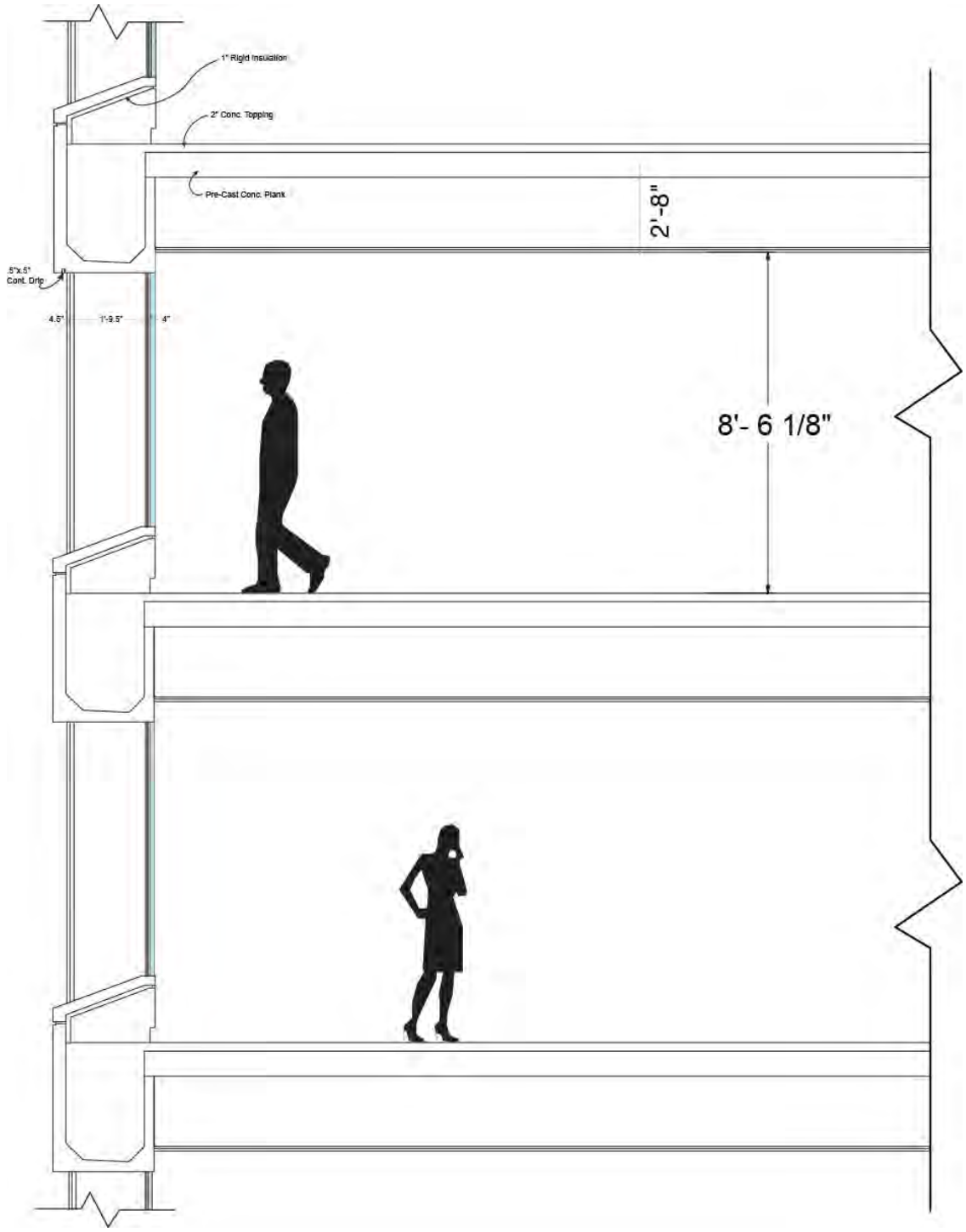

Figure 5.14. Building Envelope & Interior Section: Floors 7th-22nd

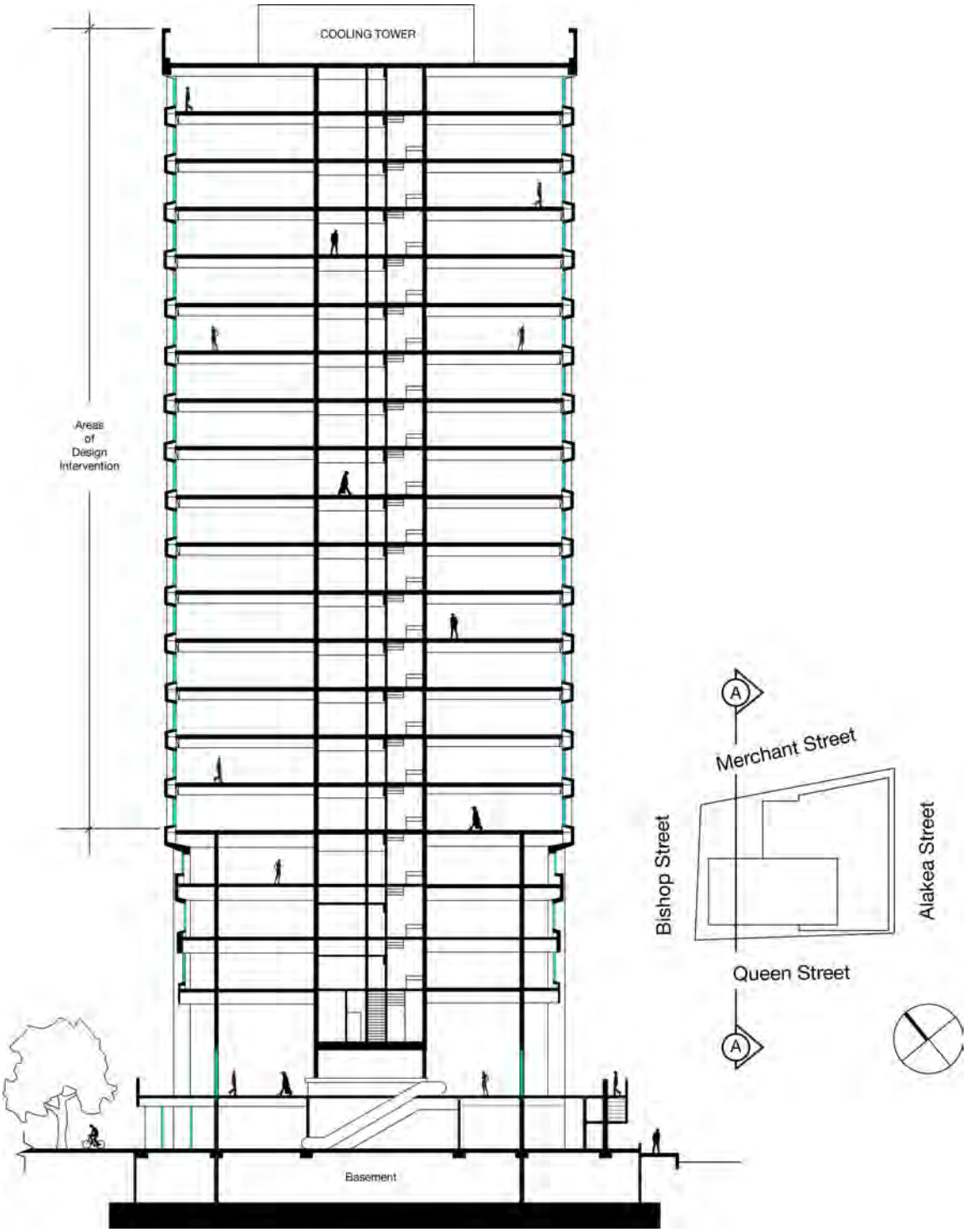

Figure 5.15. Transverse Section

Figure 5.16. Longitudinal Section

III. Plan

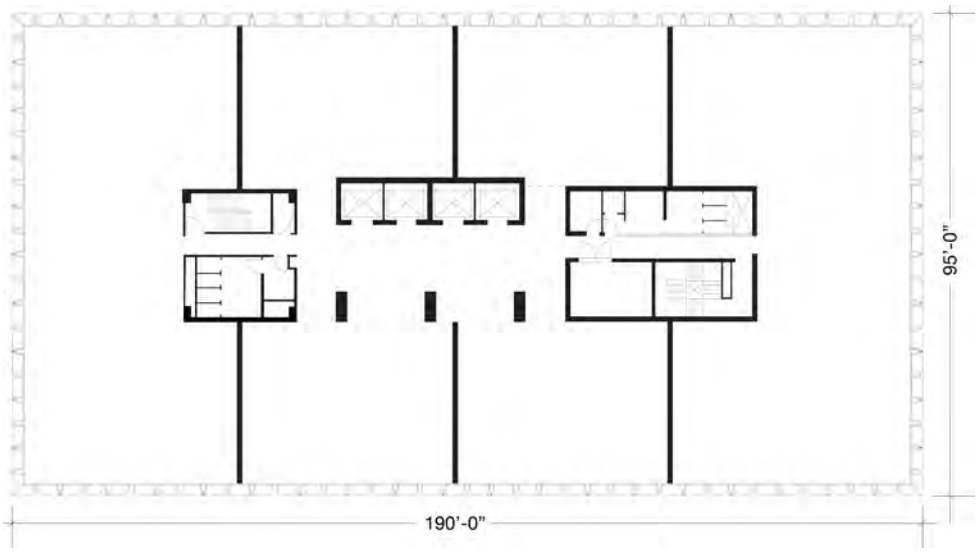

Figure 5.17. Plan: Floors 7th-22nd

5.3. Solar Analysis

5.3.1. Sun Path Diagram

Having analyzed the urban context, location, site, elevations, sections, floor plan and orientation of the building, solar studies were conducted to provide more depth into the buildings solar interactions. Using the Building Information Modeling (BIM) software program Revit, the first solar study was conducted on the Pac Davies Center by looking at its sun path diagram. This was done without the neighboring buildings and their shading constraints.

The reasons for this are to understand the baseline trajectory of the sun, both overhead and laterally, hitting the façade of the Pac Davies Center during different times of the year. Due to our tropical position (21.3° N, 157.8° W), the solstices' and equinox' were analyzed to learn the sun path and its affect on the building. This will come in handy later as these solar studies will facilitate solar and lighting simulations that will guide the design process.

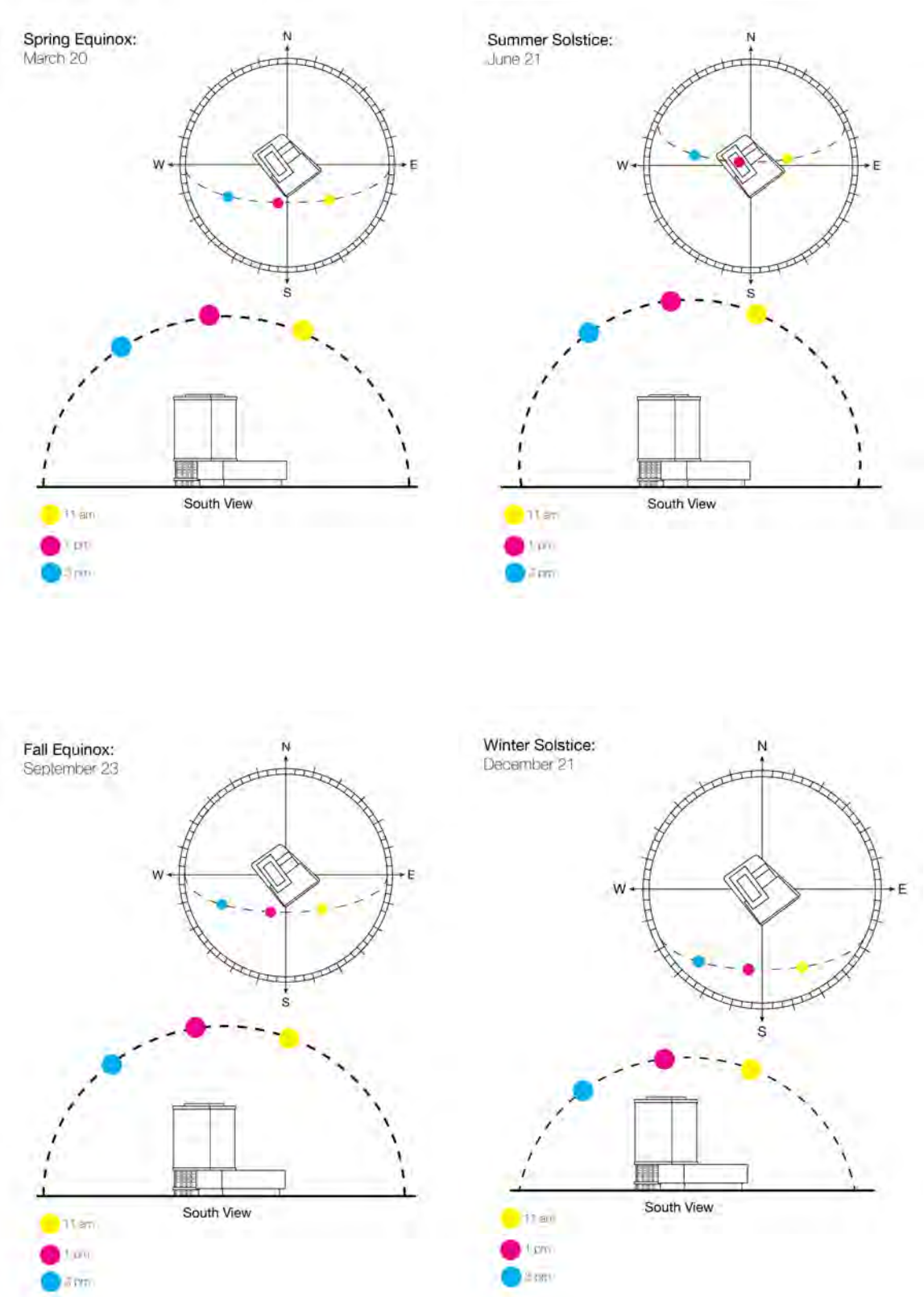

Figure 5.18. Sun Path Diagram: Equinox' and Solstice's

5.3.2 Peripheral Shading Constraints

After running the sunpath diagram, through equinox' and solstice's, further analysis was needed to determine the exact areas of the highest solar potential as well as the shading mask from peripheral shading constraints. Individual renders where developed and superimposed with one another using V-Ray with Rhino 3D, during the times of 11 AM, 1 PM and 3 PM, through North West and South West perspectives. This is done in order to discern the solar potential and shading mask projected on the façade through a visual basis. Having visited the Pacific Davies on the Fall Equinox and Winter Solstice of 2014 and Spring Equinox of 2015, and overlaying the pictures I took of the fenestration, I can say without a doubt that these renders alignment exactly with the existing shading conditions of the Pac Davies.

The neighboring shading constraints from the Pacific Guardian Building present the biggest obstacle of PV placement and renewable energy generation on the South West façade of the Pac Davies Center. Further issues could arise on the passive shading side of the BIPV system, as this shading factor could also over shade the interior, which would trigger increases in the uses of lighting and air conditioning loads. These areas are not to be entirely avoided when designing a BIPV façade, as certain times throughout the day still experience an electrical output due to solar radiation, occurring on the diagonal edge conditions of the shading line during the sun peak hours from 9am-3pm. However, as indicated below by the red outline, these areas to be avoided entirely as they are shaded a majority of the time throughout the year.

The images below represent colors that correlate to the solar radiation hitting the façade during certain times of the day at average, optimal and highest solar insolation times. When you overlay the different times and their solar radiation on the façade, certain combinations of the intensity range, in terms of average, optimal and highest solar insolation, are created. These combinations create points of ideal PV placement. For example, if you were to overlay cyan (3pm) with magenta (1pm) you would get an optimal (orange shade) solar insolation based on the combination of the two colors. The best and highest target solar insolation is a dark color combination of the three: yellow (11am) magenta (1pm) and cyan (3pm). Furthermore, a site legend is provided to orientate the viewer to the perspective referenced.

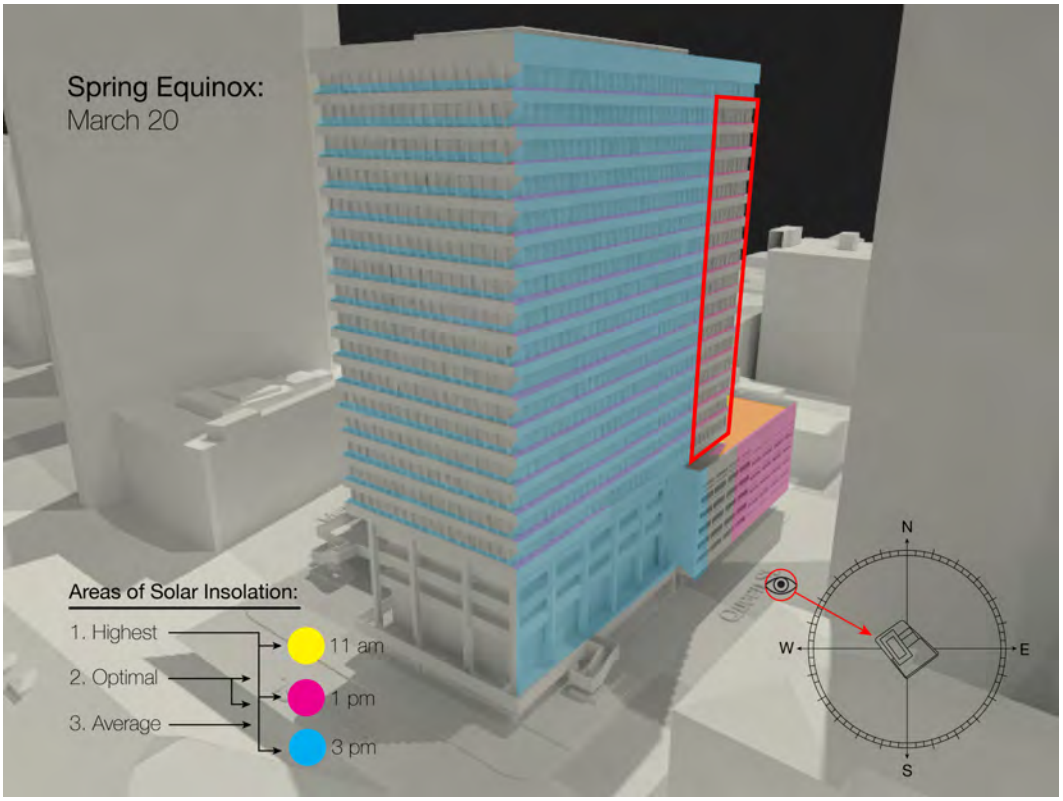

Figure 5.19. Shading Constraints: Spring Equinox, North West Perspective

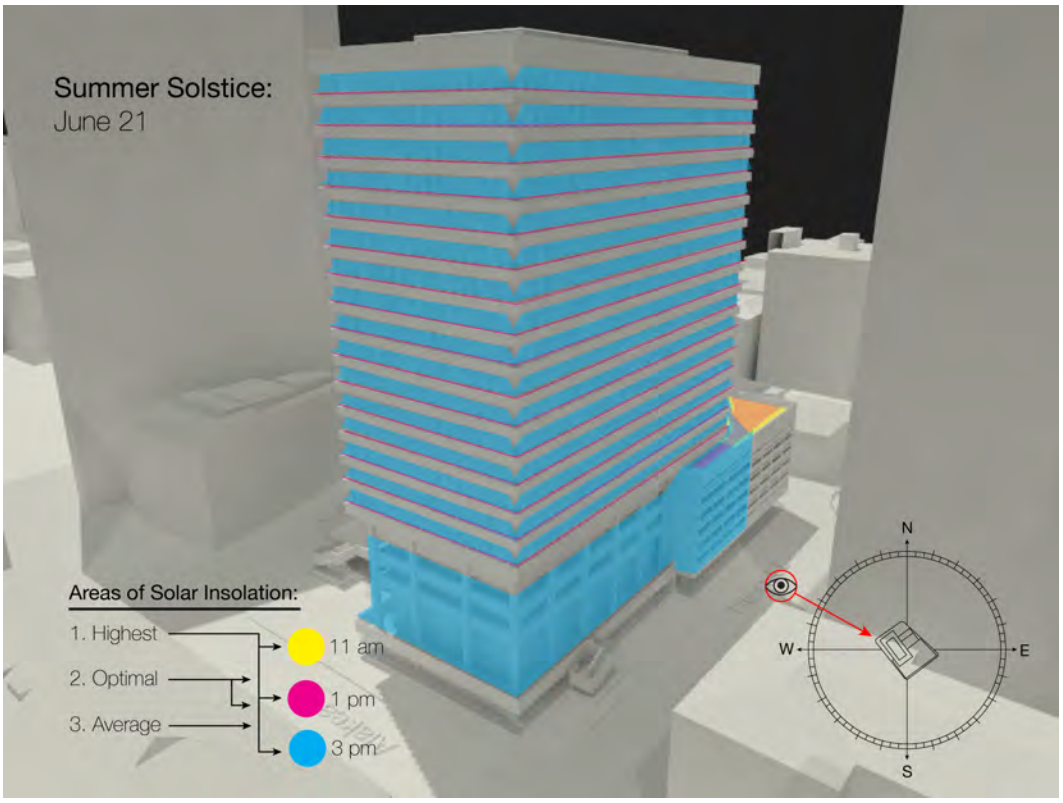

Figure 5.20. Shading Constraints: Summer Solstice, North West Perspective

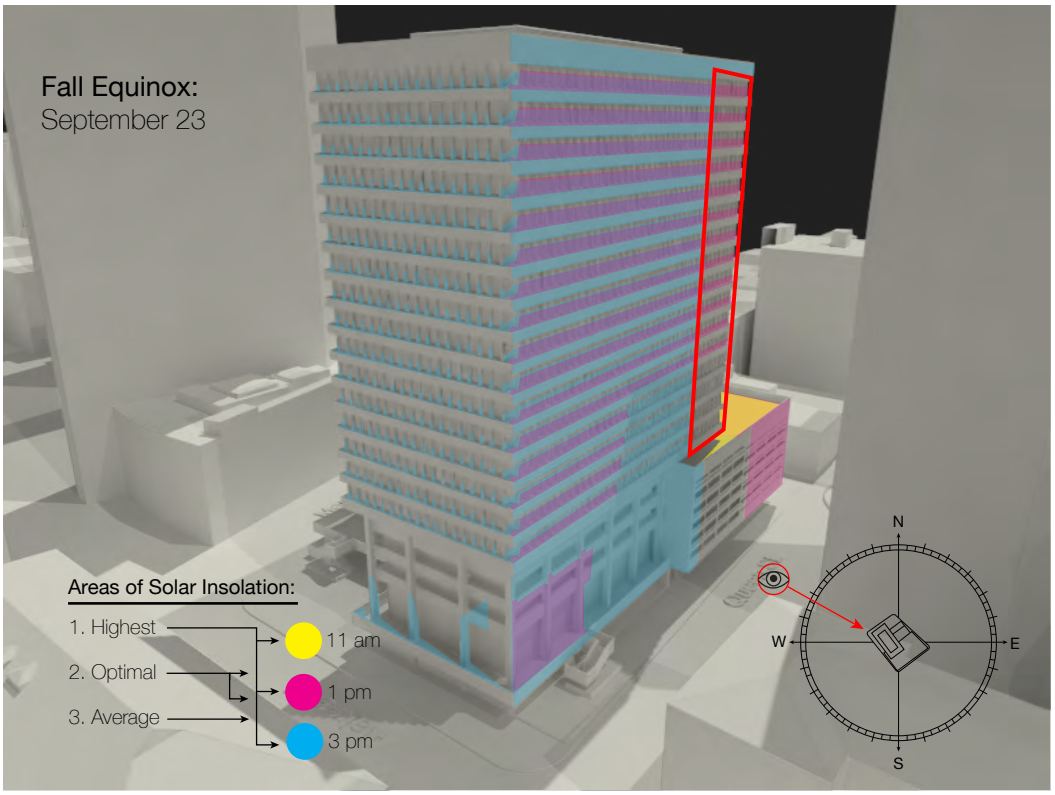

Figure 5.21. Shading Constraints: Fall Equinox, North West Perspective

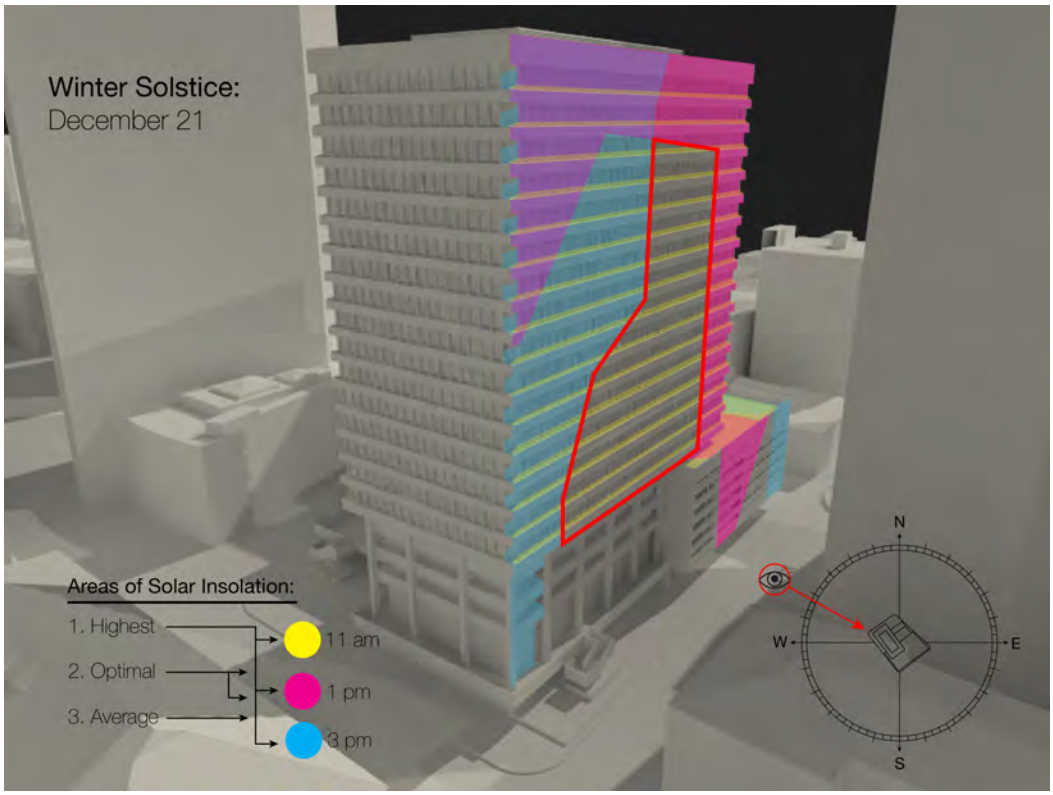

Figure 5.22. Shading Constraints: Winter Solstice, North West Perspective

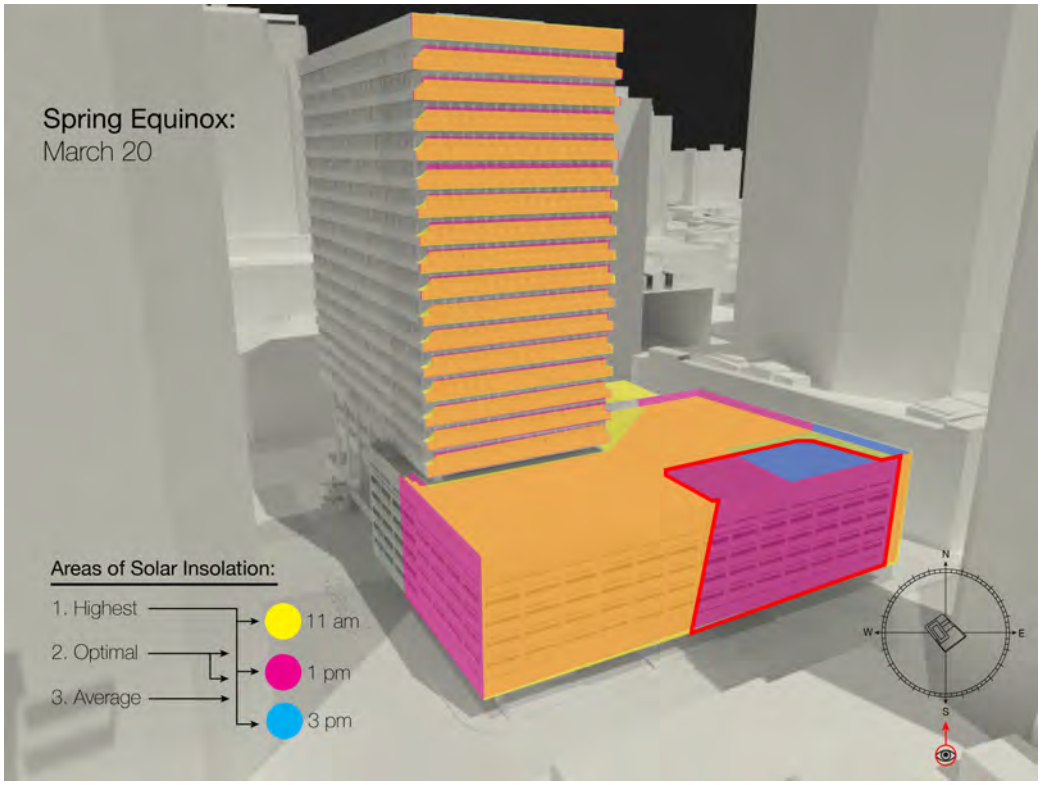

Figure 5.23. Shading Constraints: Spring Equinox, South Perspective

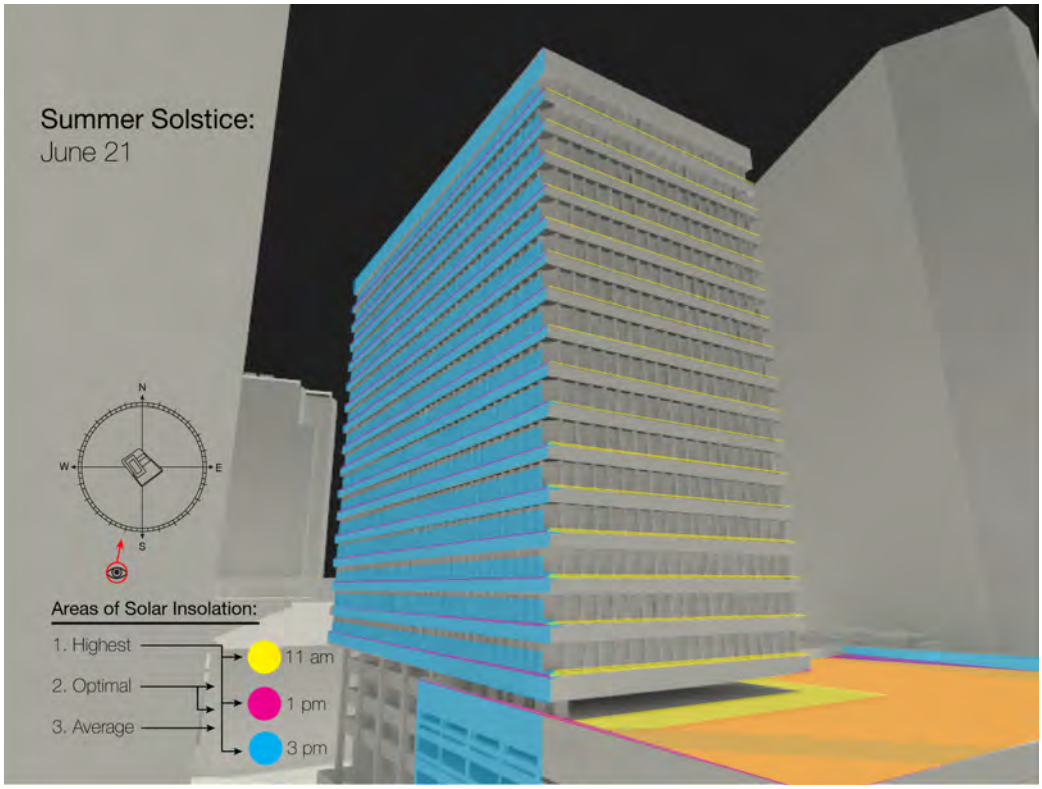

Figure 5.23. Shading Constraints: Summer Solstice, South West Perspective

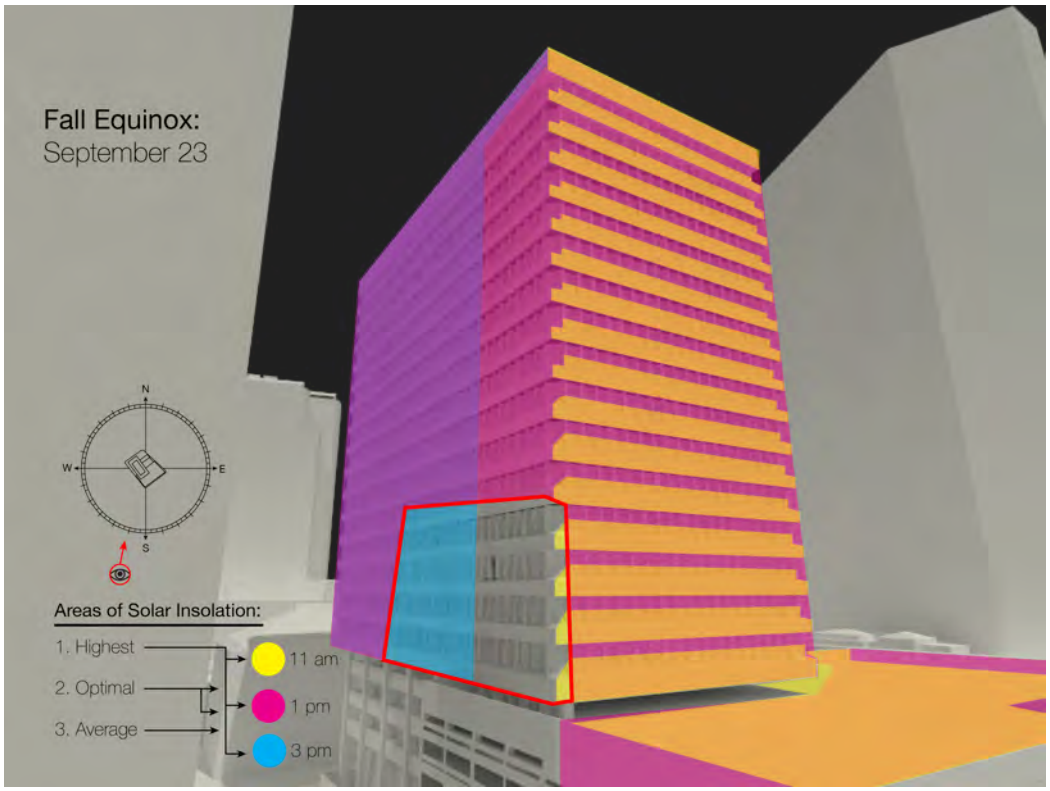

Figure 5.24. Shading Constraints: Fall Equinox, South West Perspective

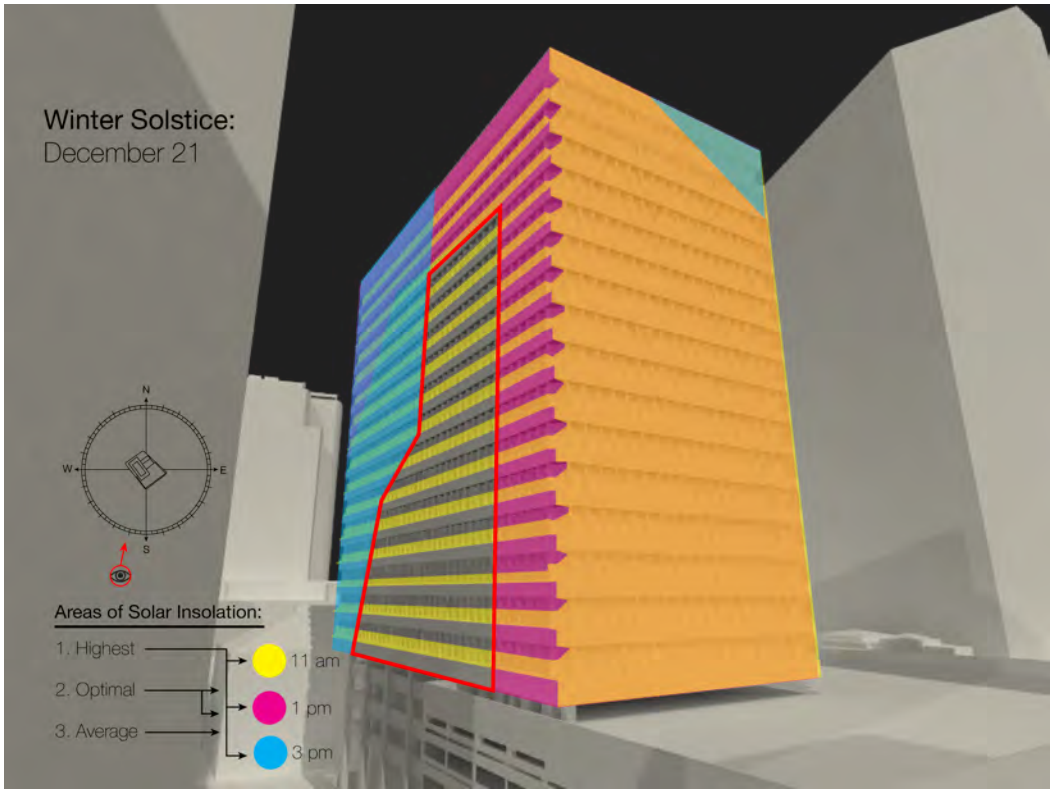

Figure 5.25. Shading Constraints: Winter Solstice, South West Perspective

5.4. Energy Estimations

It is important to estimate the energy consumption(s) that the PDC uses in order to establish a before and after picture of the current baseline vs. the energy saved by the implementation of the BIPV awning system. In doing so we must first evaluate what the energy baselines are in commercial office buildings in Hawai‘i. This establishes what energy conditions of similar commercial office buildings operate under as a basis of comparison in evaluating the baseline energy use of the PDC.

The current energy consumption of a typical Hawaiian office building consumes is from its cooling and lighting loads (fig 5.26). Hawai‘i is a hot and humid tropical climate which increases A/C use, and experiences high moisture content and overcast and rainy days, which increases interior lighting use. In Hawai‘i saves on avoiding national heating cost as experienced in temperate climates. Cooling and lighting costs are the major energy issues in the tropics.

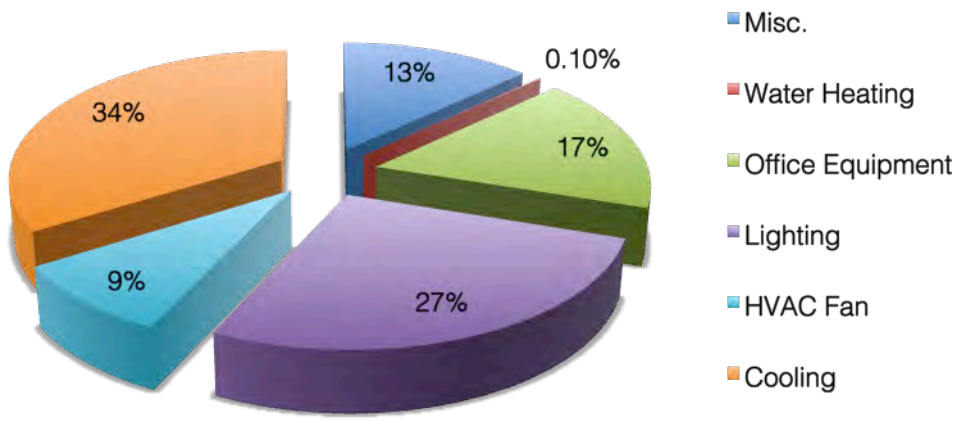

Figure 5.26. Energy consumption for typical Hawai’i office building

Source: *Hawaii Commercial Building Guidelines for Energy Efficiency*, pg. 1-15

It was estimated in *Hawaii Commercial Building Guidelines for Energy Efficiency*, that the "Energy consumption for typical Hawaii office building… [is a]…total 23 kWh/ft^2/Year"[162] Compared against the PDC energy footprint of 25.7 kWh/ft^2/year and you can see that the PDC is consuming above average energy than its commercial office counterparts. This could be due to its size and scale and as being one of the tallest and largest buildings in the state as most commercial offices buildings are not of this magnitude.

Based on the HECO energy bills I complied from the Pacific Davies Center, I was able to calculate its yearly energy consumption (Table 3). These numbers are astronomical in terms of energy and fiscal consumption. Reducing the total power consumption, through the energy conservation measures of the passive shading device with the renewable energy generation through the BIPV system, could save an enormous amount of money, energy and the environment.

Table 3: Pacific Davies Center's annual electricity use

Date	kWh/year	Amount	Days	kWh/Day	$/Day
8/27/13	602,000	$186,780	31	18,812.50	$5,836.86
9/26/13	564,000	$173,235	30	18,800.00	$5,774.50
10/28/13	604,000	$186,036	31	18,875.00	$2,813.64
11/26/13	536,000	$169,777	30	18,482.76	$5,854.38
12/27/13	532,000	$166,869	31	17,161.29	$5,382.89
1/24/14	462,000	$151,951	31	16,500.00	$5,426.84
2/26/14	564,000	$183,693	28	17,090.91	$5,566.41
3/27/14	504,000	$163,452	31	17,379.31	$5,636.27
4/28/14	550,000	$175,429	30	17,187.50	$5,482.15
5/28/14	522,000	$166,128	31	17,400.00	$5,537.61
6/26/14	530,000	$172,873	30	18,275.86	$5,961.14
7/28/14	572,000	$185,226	31	17,875.00	$5,788.32
Total:	6,542,000	$2,081,451	Avg.	17,820.01	$5,421.75

[162] Hawaii Deptartment of Business, Economic Development and Tourism, "Hawaii Commercial Building Guidelines for Energy Efficiency," http://energy.hawaii.gov/wp-content/uploads/2011/10/CommercialBuildingsGuidelinesforEnergyEfficiency2004.pdf.

The entire PDC and its surrounding buildings using the energy simulation program Design Builder (DB) have been modeled. DB is used to simulate the baseline energy estimates needed to create an energy profile of the PDC (fig 5.27).

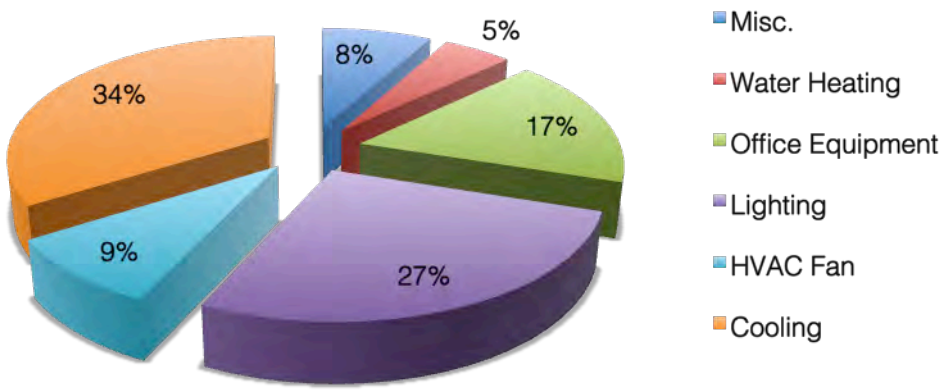

Figure 5.27. Baseline energy consumption of Pacific Davies Center

The baseline energy consumption of the PDC, even though it was 2.7 kWh/ft^2/year higher than the average commercial office building in Hawai'i, aligned relatively similar to the energy profile of its average counterpart (except in the areas of water heating and miscellaneous energy uses). Being able to establish these energy estimates allows the D.Arch project to move forward with the baseline needed for the energy, before-and-after, comparisons of the PDC and application of the BIPV system. This allows for both quantitatively and qualitatively evaluation of the BIPV system effectiveness and methodology.

5.5. Design Strategies

The appropriate design strategy is done by addressing the energy, physical technicalities and aesthetic issues inherent in the PDC. By defining the existing architectural conditions to which the PDC adheres to, the next move is in complementing its features and adding updated value to it through the addition of the BIPV awning system. The environmental conditions at seasonal times of the year could hinder the BIPV system due to surrounded shading constraints caused by neighboring buildings.

However, as shown, Honolulu is ripe with resources in harvesting solar energy, as it has the highest kWh/m^2/day, with the highest energy prices in the nation. These two factors are at odds with one another and are the conflicting drivers behind the renewable energy adoption within Hawai‘i.

PDC is contributing to mass energy consumption. On a design basis the greatest shading constraint is that of the Pacific Guardian Building, affecting the South West façade in both glare and shade. From the shading mask cast upon the PDC, this line will determine the BIPV awning system design. The eggcrate window design of the PDC, and its density as a thermal barrier, it would be excessive to over clad the entire building with BIPV shading devices in order to increase its passive shading potential.

Utilizing BIPV through specific points on the façade can provide for solar insolation and passive shading optimization. By reducing the amount of PV, as opposed to uniform cladding, you are saving on the total installed cost, through reduced labor and module(s) cost, and creating a faster return on investment while at the same time maximizing both use of light and shade.

In the next chapter, energy and environmental simulation programs will be used to test this every hypothesis and navigate the goals of achieving aesthetic architectural harmony through retrofitting the existing conditions of the PDC while also endeavoring for a higher and more efficient energy potential inherent within the practices of BIPV.

CHAPTER 6:
Environmental Simulations

6.1. Energy Estimations

Two environmental simulation programs were used to quantify the power potentials of 10 BIPV design iterations in order to establish a final BIPV design iteration. The first program was used to measuring the active energy potential testing 10 different BIPV design iterations and its energy thresholds. This was done in two parts: #1 run energy simulations on the façade to establish the energy thresholds and its shading profiles; and #2 to test #1's energy patterns at the appropriate Hawaiian latitude of 21.3° with mock up PV arrays.

The second energy program used the final BIPV iteration, as determined by the later, for calculating the baseline energy of the PDC and the resulting passive energy savings as implemented by the final BIPV iteration. Both environmental simulations are a valuation in determining the balance between aesthetics and energy performances that will produce and validate the final BIPV iteration.

6.2. Solar Insolation Studies

In order to determine the exact solar insolation of the PDC façade for purposes of electrical energy harvesting, radiation mapping and energy simulations are used to quantify the exact kWh/m^2/year baselines. This provides a method to determine surface areas of highest energy potentials. These baselines aid in the efficient placement of BIPV awnings through the examination of thermal heat signatures created by the simulations. A separate review of 10 iterations will be simulated to determine which single or combination of balances provides the greatest active and passive energy. These solar insolation studies provide both qualitative and aesthetic elements necessary in applying an efficient BIPV architectural design.

6.2.1. DIVA Analysis

For radiation mapping the plug-in program DIVA was used in conjunction with Rhino 3D, a Non-Uniform Rational B-Splines (NURBS) based program. It was developed by the Harvard Graduate School of Design and stands for "Design, Iterate, Verify and Adapt". It is described, by its now parent company, Solemma as a "…highly optimized daylighting and energy modeling plug-in…[that]…allows users to carry out a series of environmental performance evaluations of individual buildings and urban landscapes..."[163]

DIVA is very helpful in determining BIPV performance as it provides a visual tool in representing specific climate interactions that occur on a building's surface against environmental and weather data scenarios at any given point in time. The accuracy of DIVA has found acceptance in the architectural industry. From the Sun path diagrams and peripheral shading constraints conducted in chapter 5, the solar envelope and its thermal and shading thresholds start to emerge (fig 6.1). To fully quantify the energy factor (kWh/m^2/year) of the PDC façade and evaluate the solar radiation mapping, DIVA provides an excellent tool to determine energy output and placement of BIPV technology.

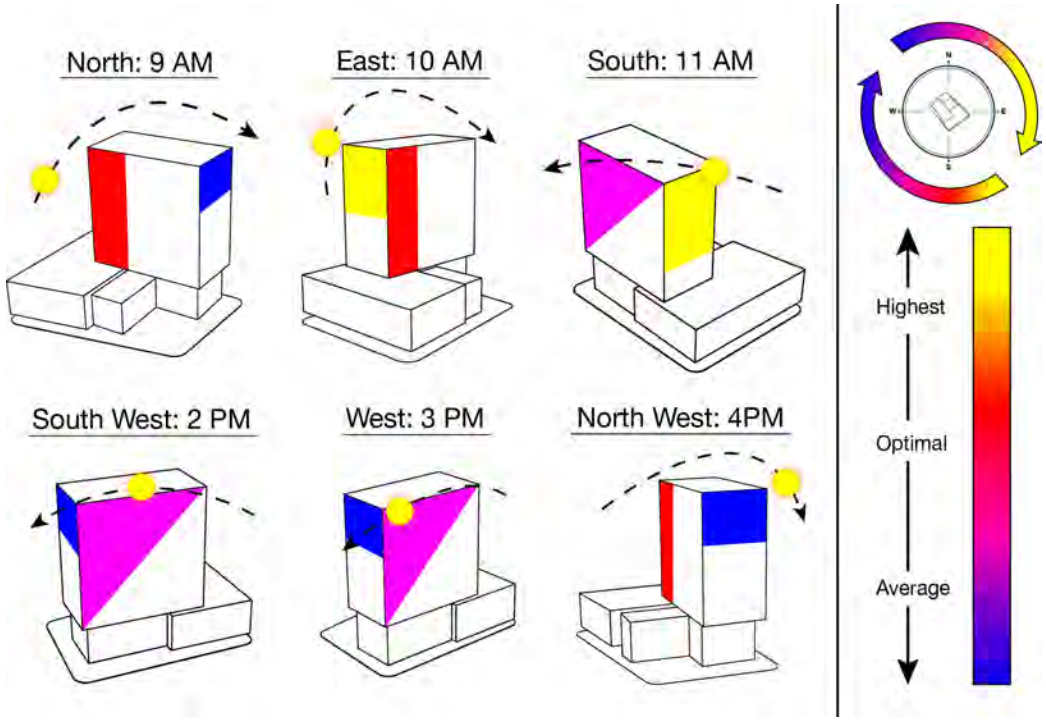

Figure 6.1. Solar threshold diagram

[163] http://www.solemma.net/DIVA-for-Rhino/DIVA-for-Rhino.html

I. Radiation Mapping: Active Energy

Parametric Modeling with Grasshopper (another software compatible DIVA with Rhino 3D plug-in) was excluded and not used due to the complexity and algorithmic learning curve necessary for execution and because of the time limit needed for this D.Arch project. Instead, DIVA's default simulation program was utilized through using the "Daylight Grid-Based" options "Radiation Map" tab function. The default metric chosen was the "Cumulative Sky Method" on a yearly 24-hour basis and the advanced parameters geometric density of 100.

Applying individual nodes were based on a one-foot (1') offset from the surface and 3.25' spaced from one another on 4 planes of the entire façade, together were used to simulate the data and radiation mapping (fig 6.2).

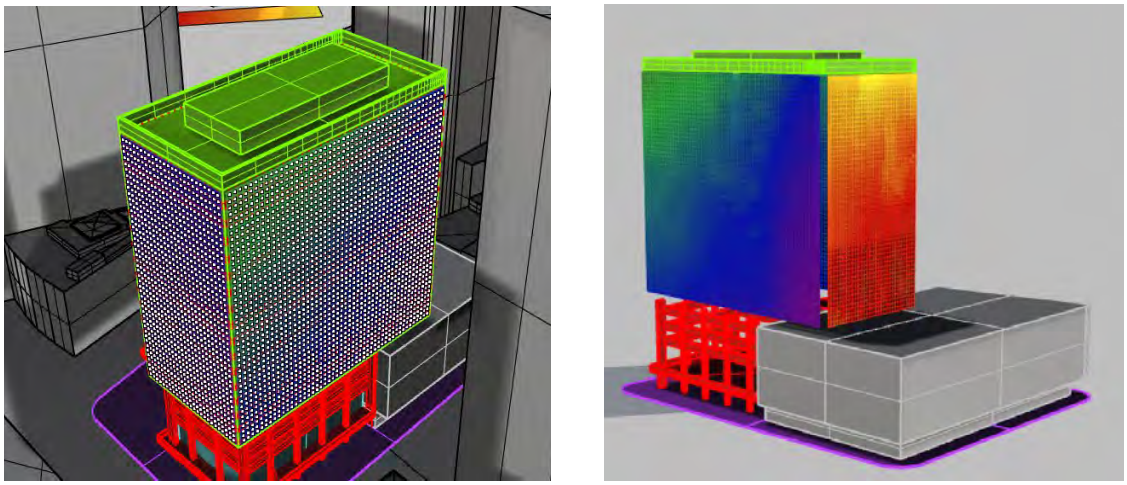

Figure 6.2. DIVA Simulation: Nodes-to-Radiation Map

The surrounding building's light and shading effects was a factor to consider while developing the simulated radiation map. From these simulations the areas of solar insolation are now visible, representing the highest-to-lowest kWh/m^2/year areas occurring on the PDC façade (figs. 6.3 – 6.7).

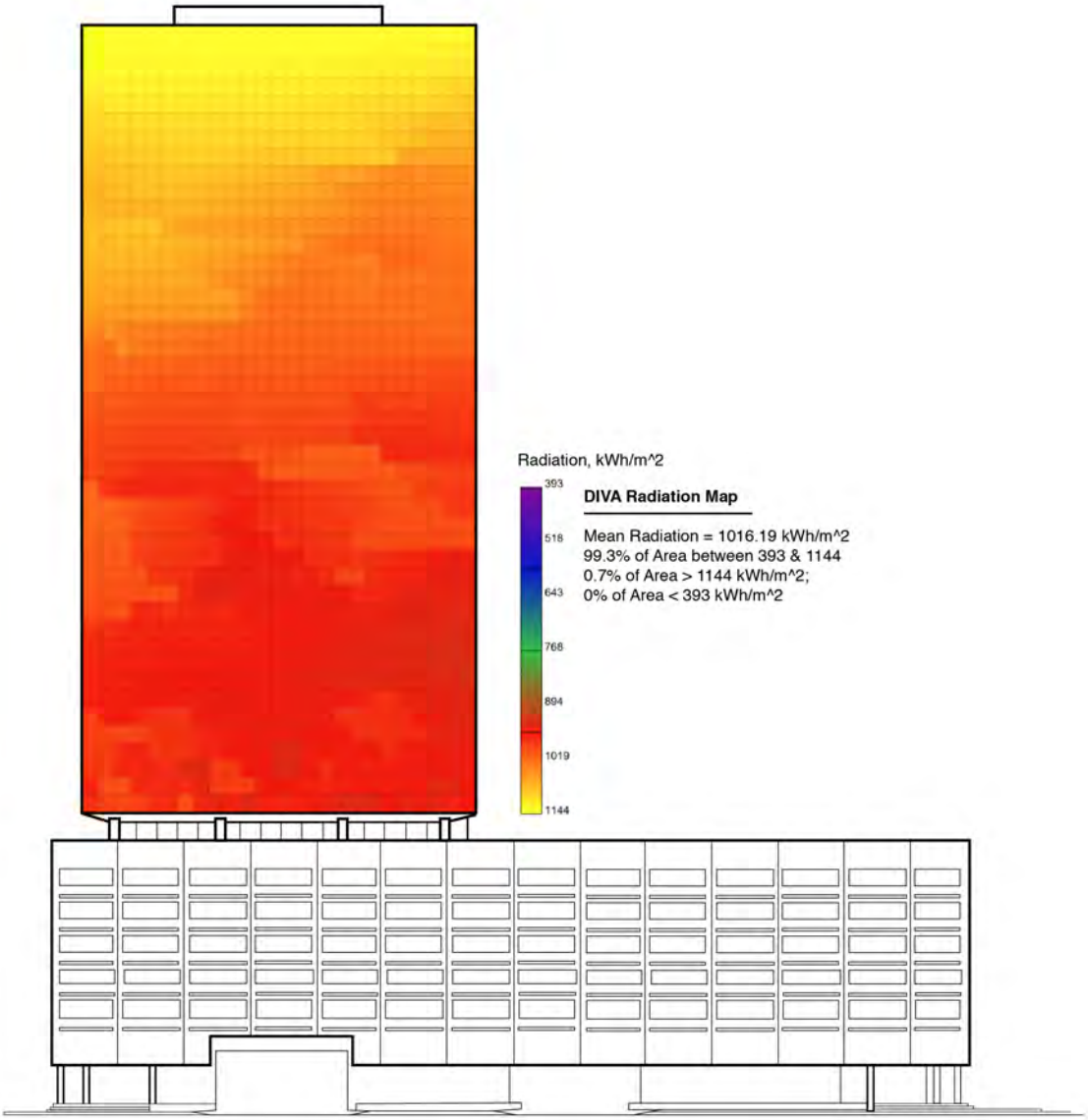

Figure 6.3. Radiation Map: South East Façade

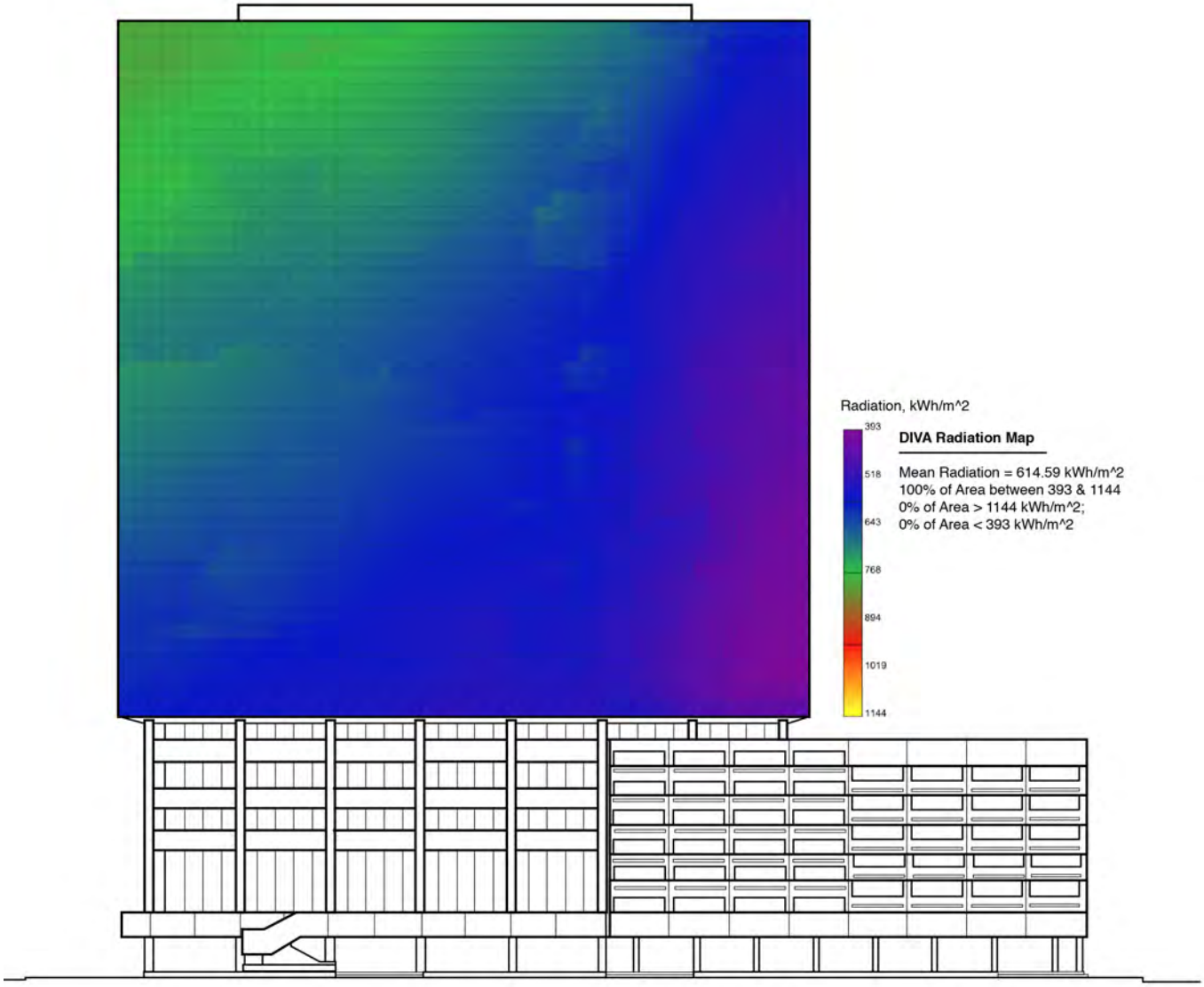

Figure 6.4. Radiation Map: South West Façade

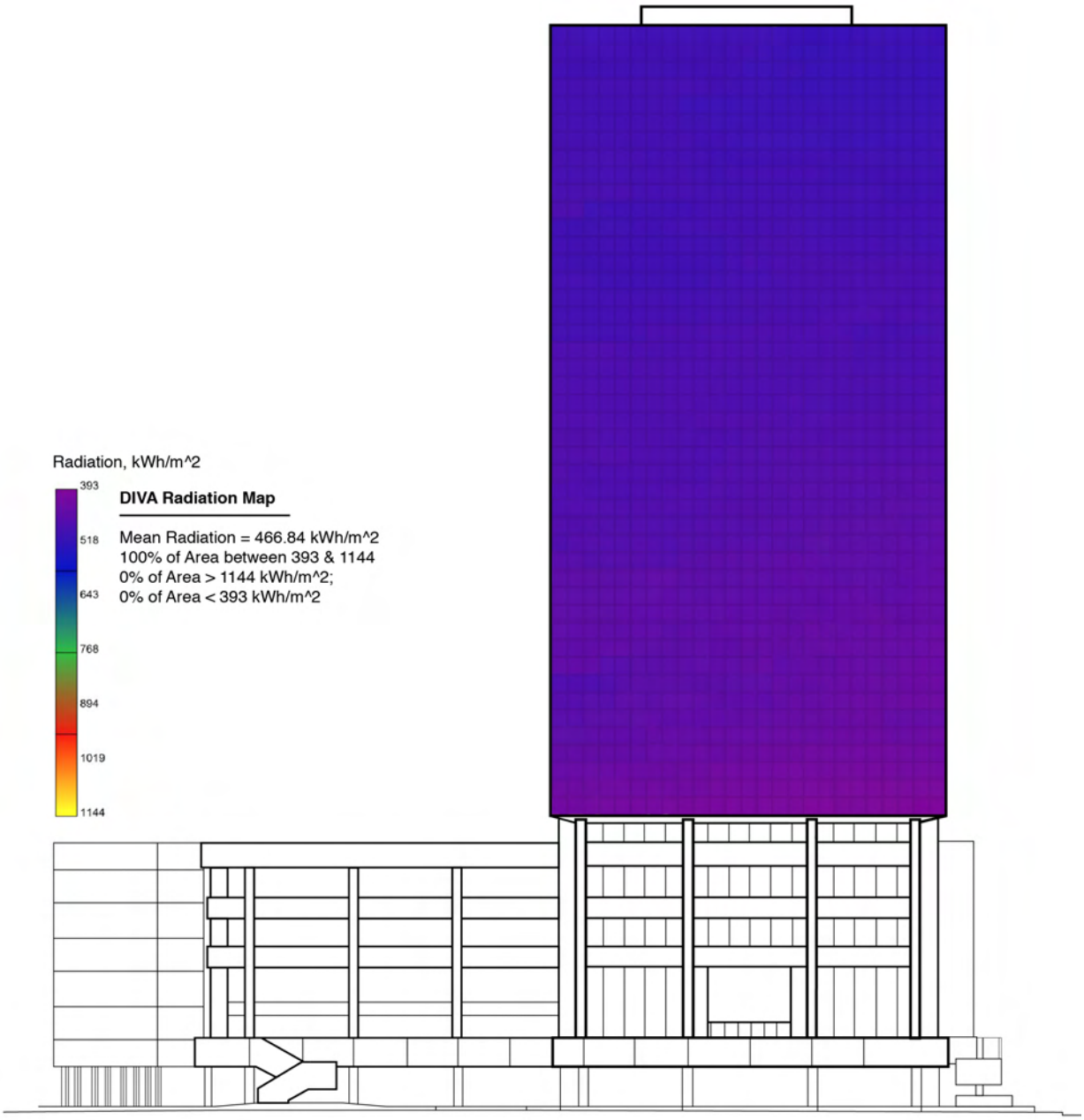

Figure 6.5. Radiation Map: North West Façade

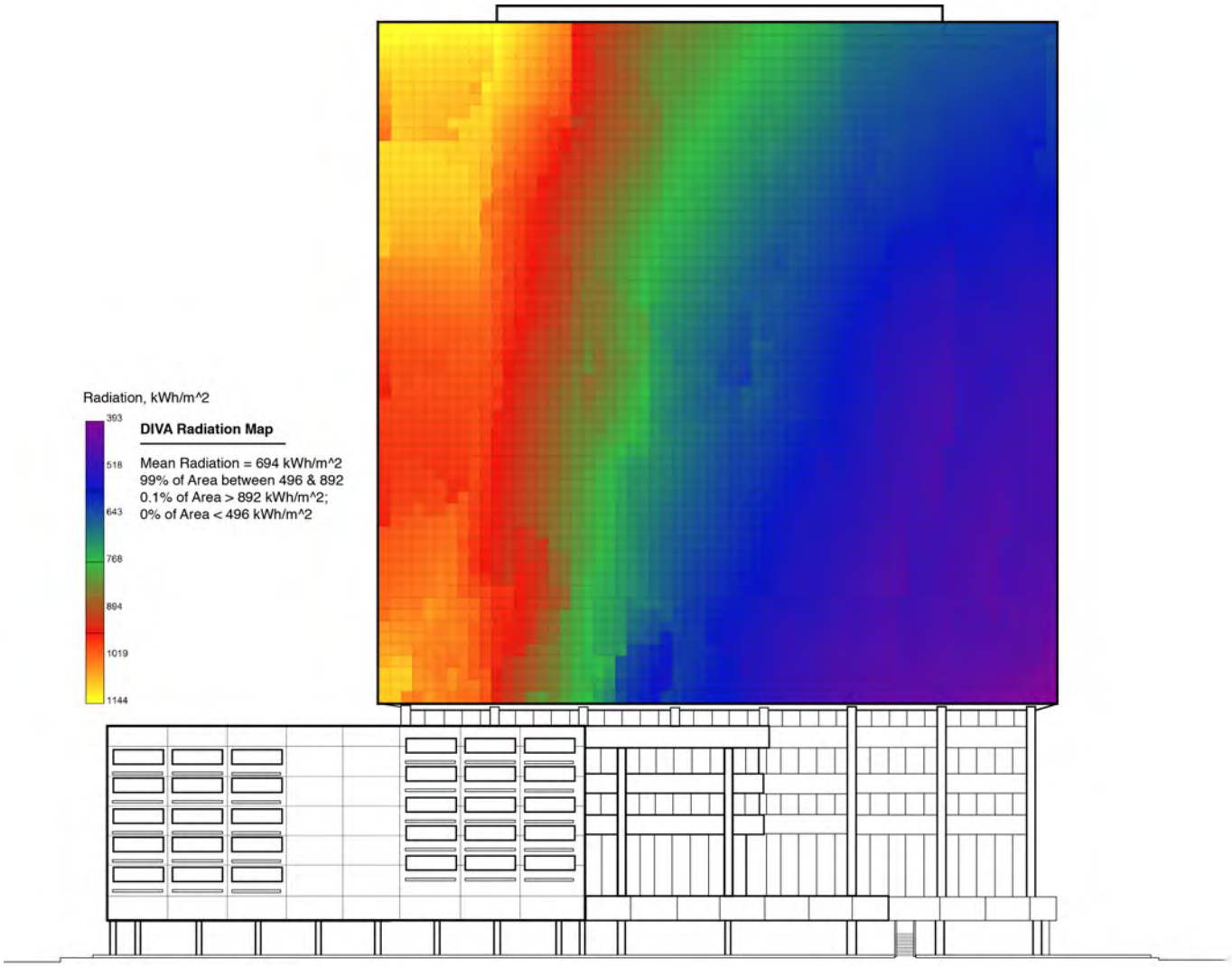

Figure 6.6. Radiation Map: North East Façade

The radiation map legends reveal that the solar insolation range was 393 – 1144 kWh/m^2/year with a mean average of 768.5 kWh/m^2/year. With 1144 kWh/m^2/year being the maximum energy potential factor, this is well below Hawai‘i’s solar insolation, which average factor (5.96 kWh/m^2/day) equaling only 3.13 kWh/m^2/day. Note that this factor exceeds the current world BIPV leader as Germany’s factor is only 3.01 kWh/m^2/day.

Keep in mind that this is only the vertical surface area of the façade and not its horizontal plane, which the solar insolation metric adheres to, that is being represented. The more horizontal we get to the latitudinal angle of 21.3°, the higher the energy potential will be. Rooftop analysis with BIPV applications are not part of this review. Hawai’i has the potential to greatly benefit from BIPV because of its high solar insolation.

The total factor of the kWh/m^2/year read out is important as it establishes the energy baselines illuminating the PDC façade against factors which affect total BIPV performance-the surrounding buildings and environmental data. This factor informs us where the highest and lowest energy potentials are located: the uppermost area of the South East façade and Eastern corner of the façade and the lowest energy potential located in the North West façade. This comes as an asset to dictate the form of the 10 iterations and the most efficient and final form of the chosen BIPV awning scheme.

An analysis of the solar interactions on the PDC façade are essential to determine the exact threshold areas and additional simulations are needed to find the exact shading line and its energy potentials. Using the above radiation map legend, the energy range of 390 – 1100 kWh/m^2/year was divided into 10 sections, and simulated to determine the energy threshold lines (fig. 6.7).

The energy profile of 1144 kWh/m^2/year was left out, as anything above the 1100 kWh/m^2/year proved optimal for energy utilization, due to ideal location at the top of the building, and was therefore superfluous to the energy profile analysis. The simulations below encompass the entire façade at 10 energy thresholds. The blue area is anything under the above threshold; i.e. 390-391. The area was calculated then multiplied by the energy profile to get the total kWh/m^2/year power potential.

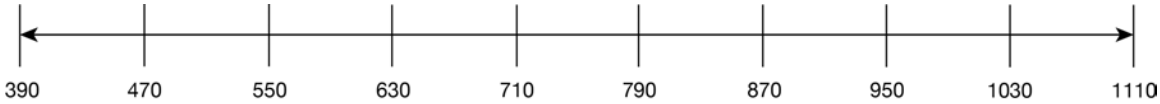

Figure 6.7. Minimum – Mean – Maximum Metric

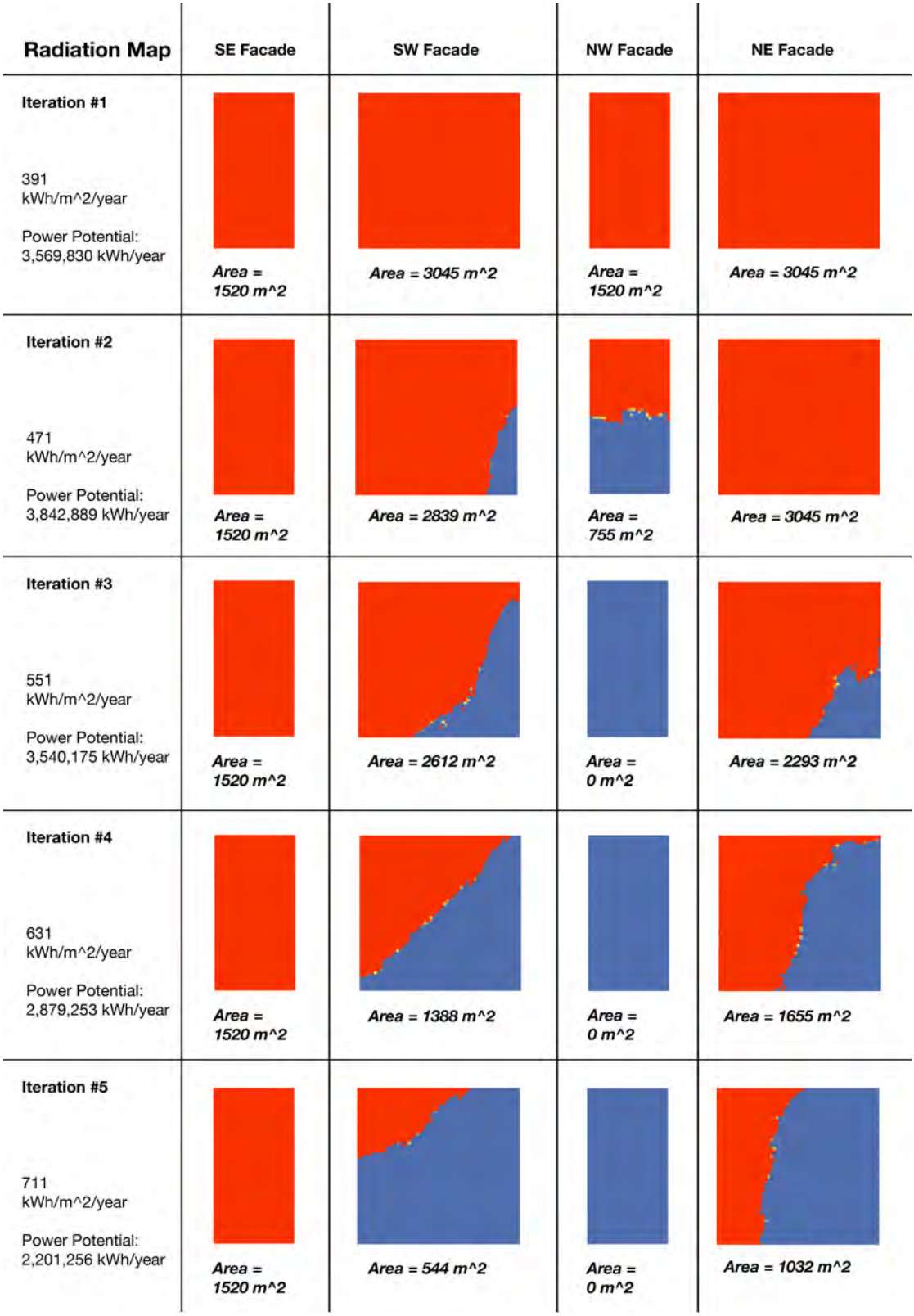

Figure 6.8. Radiation Map thresholds: Iterations 1-5

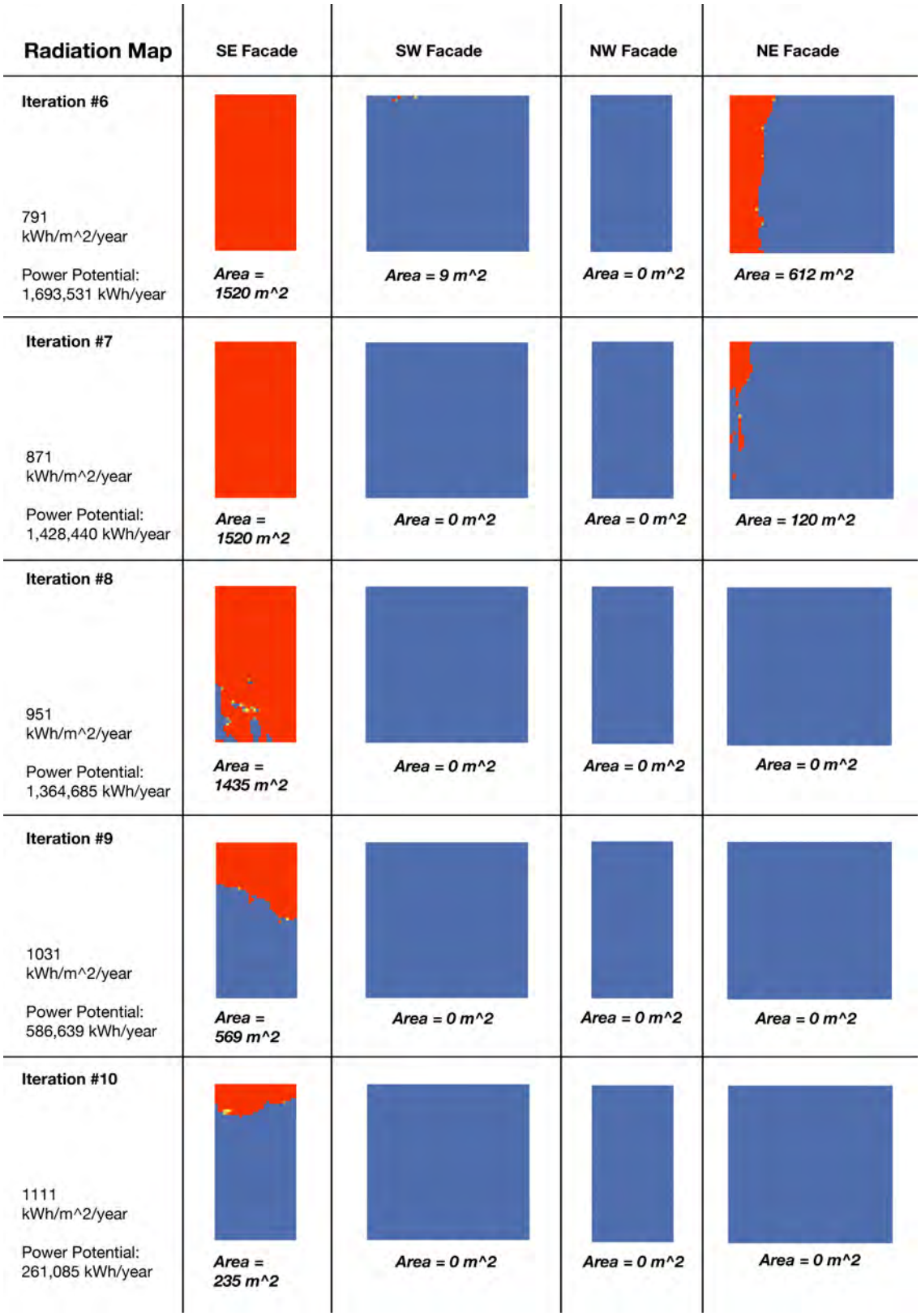

Figure 6.9. Radiation Map thresholds: Iterations 6-10

The energy factors and thresholds are now in place to facilitate a point of departure into the second design phase of radiation mapping. This now establishes the 10 iterations and provides a basis of energy comparison to find an ideal combination that will later merge into an efficient and aesthetically harmonized combination of design.

The simulations above were the first step in a two-step process. The first step is to run radiation mapping based on the vertical façade format of 90°. This allows the energy thresholds and shading lines to be established to determine the line at which to model mock up PV arrays to run in step two. Taking these energy profiles and modeling planes on the spandrels, as a mock up in place of PV arrays, at 21.3°, we can now simulate the environmental conditions and energy potentials of what the BIPV system could experience based on surrounding urban density and direct solar radiation. As compared to step #1, step #2 will experience and even higher kWh/m^2/year as the appropriate tilt has now been modeled for testing.

Keep in mind that this angle of 21.3°, is fixed and based on a yearly average suggested for the Hawaiian latitude. There could be more ideal angles at which to set the PV modules that could be designed with the parametric modeling to increase energy efficiency and reduce the overall payback of the BIPV system. However, this would increase customization and installations/labor costs and add complexity to the overall process as well.

As noted below the minimum-to-maximum kWh/m2/year legend varies as removal of some artificial planes affected the output and overall minimum-to-maximum power range. As the lower planes are removed the overall kWh/m2/year mean goes up as it approaches the upper roof conditions which offer the highest energy output due to unabridged shading conditions. In determining the total power potential, the total area of the PV planes were multiplied by the mean kWh/m2/year. The dark purple rectangles represent the removal of the planes entirely correlating to the energy thresholds established in the first radiation mapping simulation.

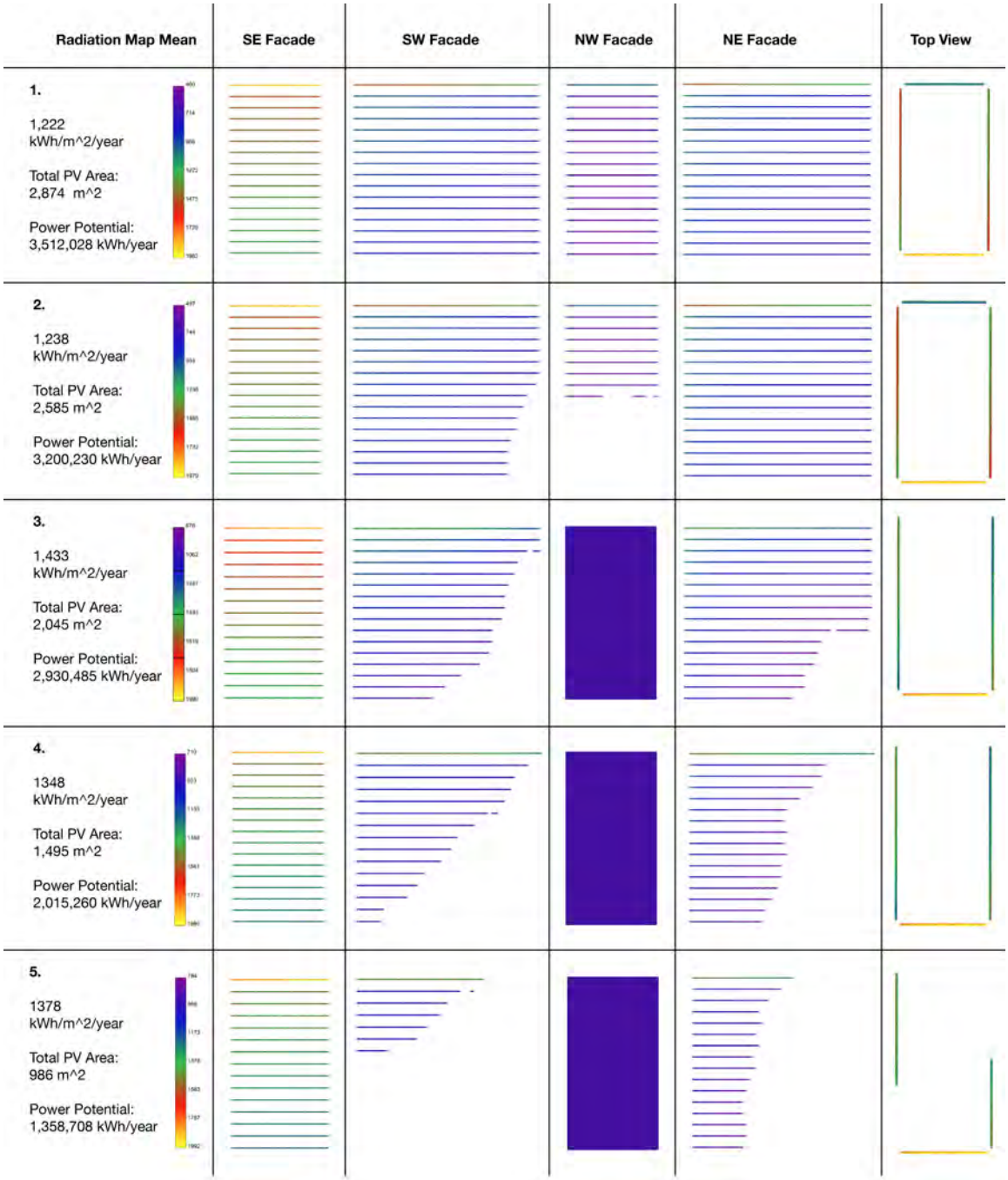

Figure 6.10. Radiation Map on PV arrays: Iterations 1-5

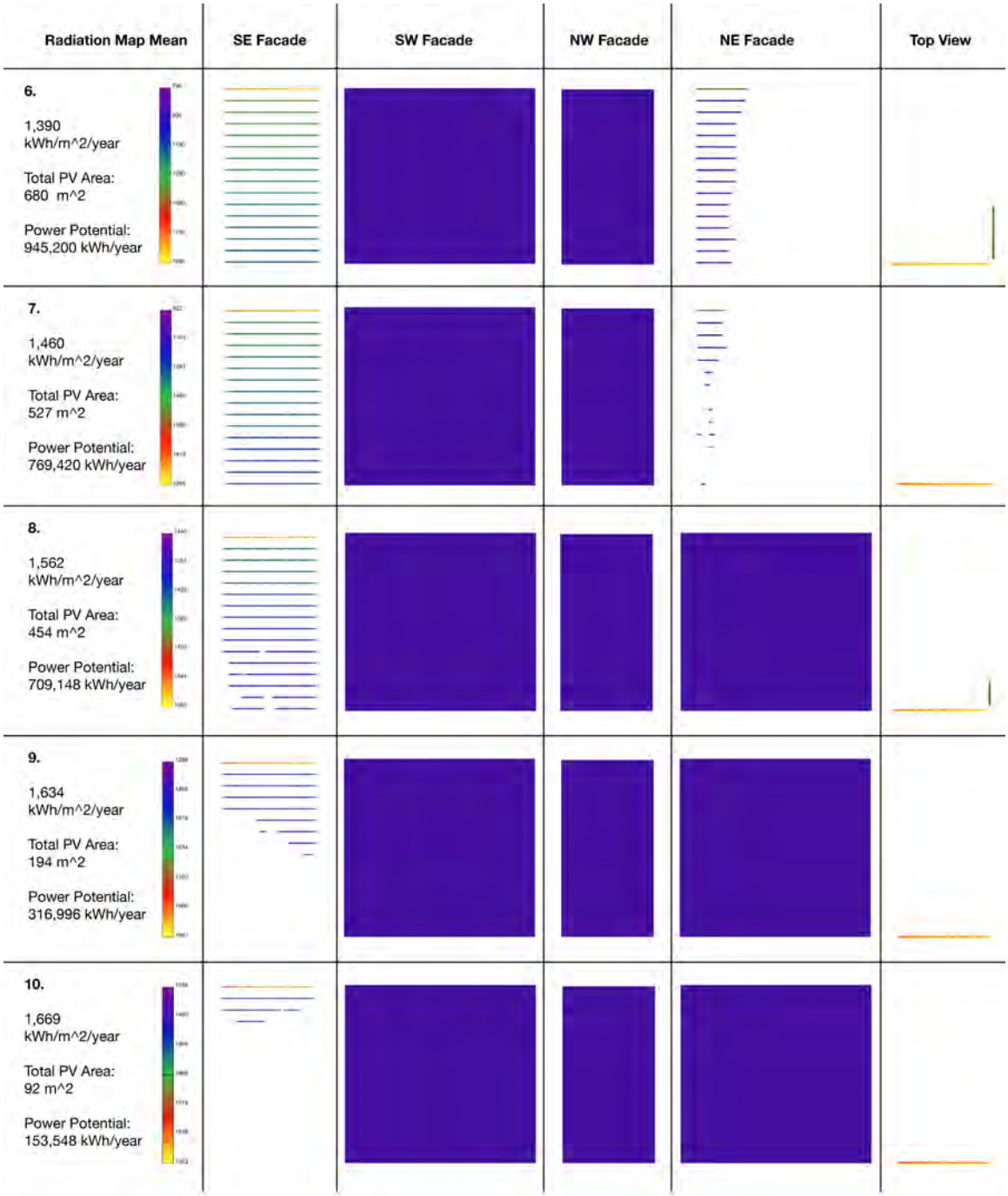

Figure 6.11. Radiation Map on PV arrays: Iterations 6-10

This represents the power potential hitting the surface of the planes set at the 21.3° in the urban area of downtown Honolulu. Iteration #1 has the most power potential based on its uniform nature of PV arrays spanning the entirety of the PDC and iteration #10 has the lowest power potential based on its scant use

of PV arrays. However, this is misleading because the less PV modules that are used on the entire building, but strategically placed at the top of PDC, can obtain more energy per ft^2 but its gross power potential decreases due to a lack of overall PV modules. Translating to the fact that the higher the PV arrays are located nearest the roof the higher its kWh/m^2/year and its average mean goes up in power potential.

A balance needs to be struck in order to utilize both gross energy output and net energy efficiency. This can be accomplished by proper modeling of BIPV. These simulations exclude the conversion efficiency of the modules and power losses due to neighboring shading constraints. Some iterations could be over shading areas of the façade that are already shaded by the neighboring building. This affects the power generated as the PV modules are themselves shaded which stops energy output and the modules could be shading areas that don't need to be shaded. This would increase lighting use in the PDC to make up the reduced lux factor on the interior and increases costs and energy consumption.

Designing to maximize energy potentials are offset by shading performance as both elements are necessary to determine total BIPV efficiency. Yazdani Studio best highlights this quandary with their responsive building skin design proposal for the new the U.S. Courthouse in Los Angeles:

> "The optimization strategy…where daylighting can be of greatest benefit while avoiding zones with high amounts of solar radiation…[opens up the issue that]…The more the shade is opened to increase natural light or improve views, the more the building is exposed to the sun's heat. To comprehensibly quantify energy benefits, daylighting analysis must be used in tandem with the solar radiation analysis performed…"[164]

In using this methodology to achieve total energy optimization, both passively and actively, the BIPV design in question is using the strategies above and measuring the energy savings by simulating the passive energy potential of shading devices themselves to determine total efficiency.

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[164] Yan Krymsky, "A New Way of Visualizing Solar Radiation," *Responsive Skins An exploration of Paratonic Surfaces in Architecture* (blog), January 13, 2013, https://yazdanistudioresearch.wordpress.com/2013/01/13/a-new-way-of-visualizing-solar-radiation/#more-1021.

6.3. Energy Conservation Simulations

6.3.1. Design Builder

I. Establishing Shading Baselines: Passive Energy

In order to determine the power potentials from the BIPV shading device on an energy conservation level, the project must first establish the elements of the existing baseline energy loads of the PDC. After this is achieved the project can then have the existing baseline energy consumption a basis of comparison vs. energy savings created by the final BIPV iteration. Based on the HECO energy bills I was able to secure from the PDC, I was able to calculate its yearly energy consumption (table 4).

Table 4: PDC's Utility Bill

Date	kWh/year	Amount	Days	kWh/Day	$/Day
8/27/13	602,000	$186,780	31	18,812.50	$5,836.86
9/26/13	564,000	$173,235	30	18,800.00	$5,774.50
10/28/13	604,000	$186,036	31	18,875.00	$2,813.64
11/26/13	536,000	$169,777	30	18,482.76	$5,854.38
12/27/13	532,000	$166,869	31	17,161.29	$5,382.89
1/24/14	462,000	$151,951	31	16,500.00	$5,426.84
2/26/14	564,000	$183,693	28	17,090.91	$5,566.41
3/27/14	504,000	$163,452	31	17,379.31	$5,636.27
4/28/14	550,000	$175,429	30	17,187.50	$5,482.15
5/28/14	522,000	$166,128	31	17,400.00	$5,537.61
6/26/14	530,000	$172,873	30	18,275.86	$5,961.14
7/28/14	572,000	$185,226	31	17,875.00	$5,788.32
Total:	6,542,000	$2,081,451	Avg.	17,820.01	$5,421.75

The energy and fiscal consumption for the PDC is astronomical for one of the 10 largest buildings in the state. Reducing the total power consumption through the use of passive shading devices could save enormous amounts of money, energy and regional GHG emissions.

From there I modeled the entire PDC and its surrounding buildings using the energy simulation program Design Builder (DB) (which is popular amongst Engineers and Architects as it is BIM and CAD compatible) (fig. 6.12). Replicating these utility bills and kWh/year estimates provide a basis to run multiple energy simulations representative of the PDC. The factors of the total energy use from the PDC utility bills provided the necessary energy conditions of the PDC in the digital simulation process of using DB.

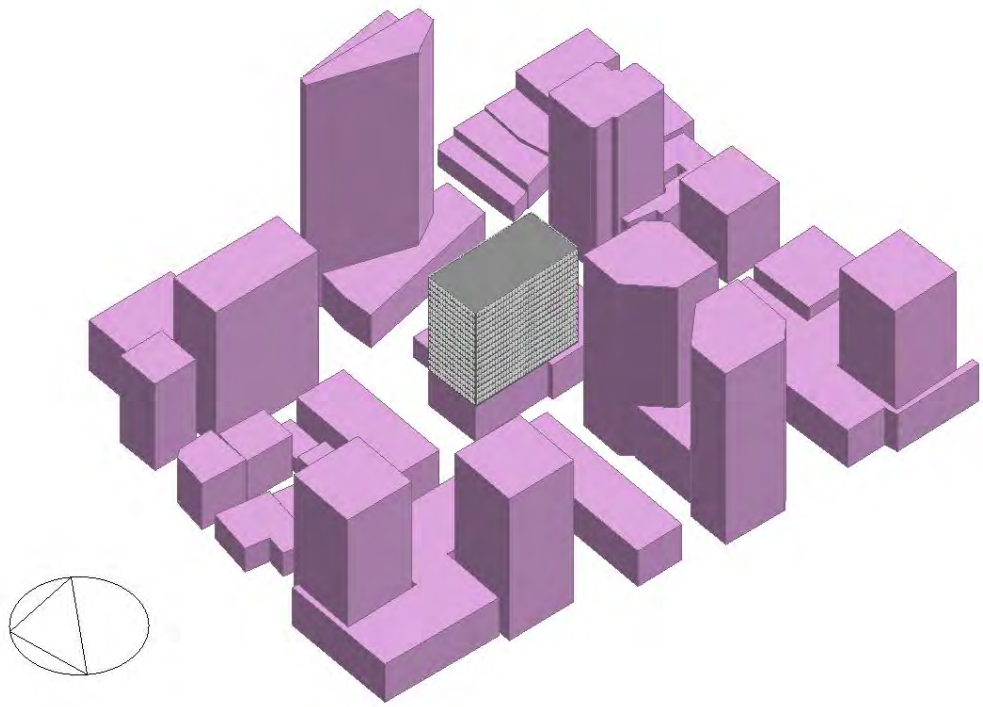

Figure 6.12. Perspective View in DB

Once the variables were filled in and calibrated for the energy targets, I simulated the DB baseline energy estimates, put them in excel and created an energy profile of the PDC (fig 6.13). Surprisingly, the PDC simulation aligned almost exactly to energy profile of the "Energy consumption for typical Hawai'i office building" (Fig. 5.21); except say in the areas of water heating and miscellaneous energy uses. This is a good barometer to go off of as the energy estimations were simulated as best as possible to replicate the real conditions of the PDC.

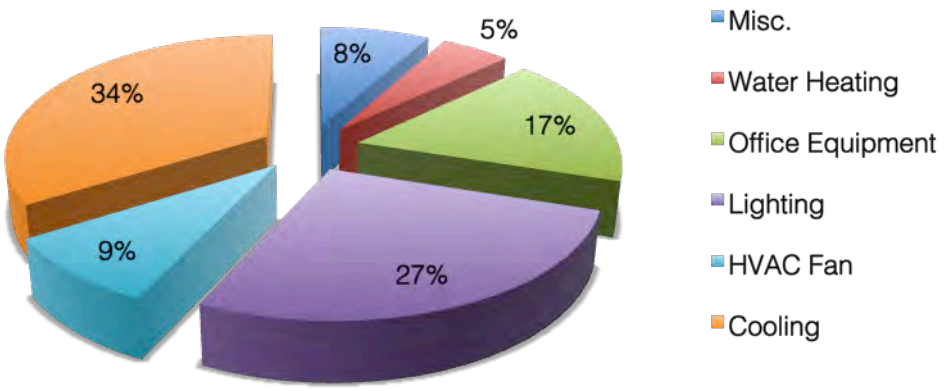

Figure 6.13. Baseline energy consumption of PDC without PV

These energy estimates are invaluable to the design process, as it allows the D.Arch project to move forward with the baselines needed for the energy comparisons of the PDC with and without the BIPV system. This is done to measure quantitatively and qualitatively the energy estimates and values in the visual effectiveness of the BIPV system.

II. Simulating BIPV Shading Devices

In modeling the shading devices, there was a previous attempt at designing the shading devices to function as PV arrays in order to measure potential kWh/year output. This was done to determine if energy data from DIVA and DB differed or shared similar results in order to reach comparable averages between the two. Even though DB had PV design and testing capabilities, when creating the PV modules both were only able to calculate a PV array of 30. My design scheme of 52 PV arrays is limited by the DB and PV simulation limitation of 30 arrays, thereby requiring a theory extrapolation of the BIPV system.

The strategy of getting the active PV data from using DB proved faulty. The program itself has an antiquated interface and design capabilities and proves that digital simulation restrictions of BIPV has not yet reached a software modeling zenith acceptable to the building industry. No software today can fully integrate BIPV and determine accurately its kWh/m^2/year output. Because of this defect the pursuit using DB to obtain active PV generation plus passive energy

simulations together were eliminated. The focus now turned to a strategy of using DB primarily to determine the passive side of the BIPV energy equation.

Arrays were created using a single plane or “block instance” and tilt at 21.3° to try and represent as real as possible the PDC and its surrounding conditions. From the 10 iterations of the DIVA Radiation Mapping, 6.10 - 6.11, the final iteration, which will be discussed in detail in Chapter 8 as to its qualitative and quantitative justifications, incorporates the final iteration below:

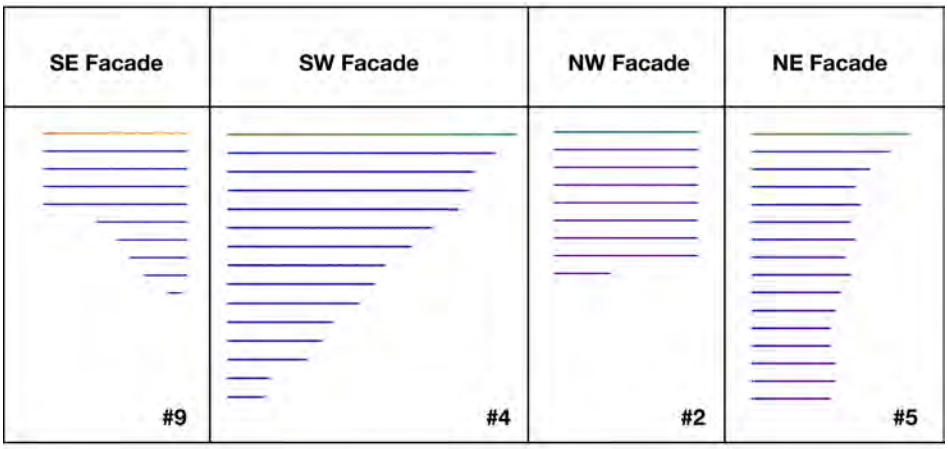

Figure 6.14. Final BIPV Design Iteration based on DIVA Radiation Mapping

Figure 6.15. SW View of final BIPV Design Iteration in DB

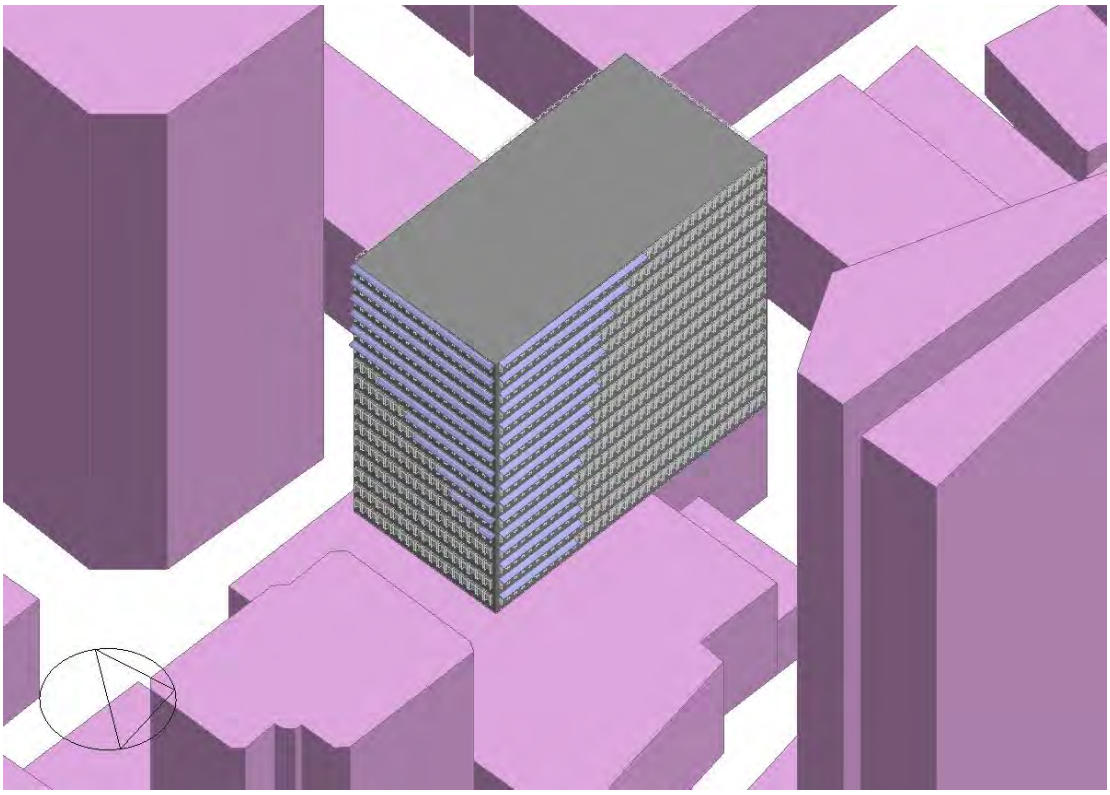

Figure 6.16. NE View of final BIPV Design Iteration in DB

The PV shading devices created a total building energy reduction of 3% due to a 5% electricity reduction in cooling loads in the PDC. Therefore the cooling loads went from 34% to 29%. The shading devices reduced the direct light experienced on the North East, East, South East, West and South West areas of the façade. Because of the passive shading devices alone it can be estimated that over $74,670/year, 88,470 kWh/year and .31 kWh/ft^2/year was saved.

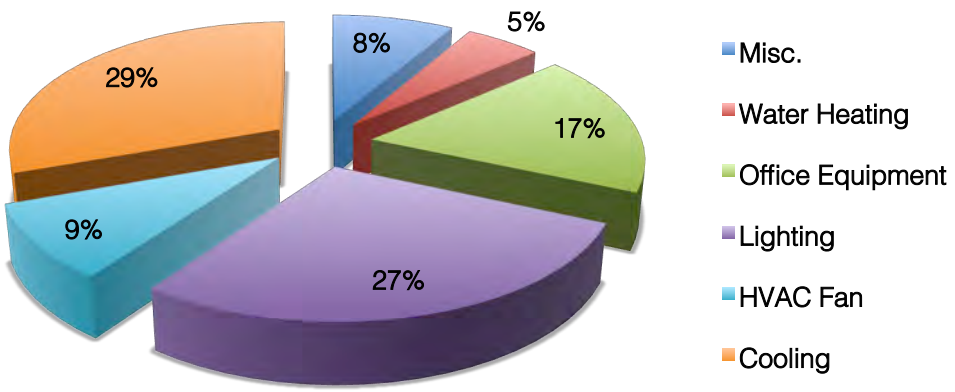

Figure 6.17. Passive energy reductions with BIPV awning system

An interesting phenomenon happened wherein the electrical loads associated with the lighting of the Pacific Davies did not increase, even though a reduced lux factor occurred due to over shading at certain times of the year. This occurred possibly because of the final iteration choice, in which the BIPV awning system was situated in the right places to block the direct solar gain to keep the electrical lighting consumption levels relatively stable throughout the year; or more importantly Monday-Friday from 8AM – 5 pm during the office hours of the PDC.

From the passive implementation from the BIPV awning system, we now know a majority of the PDC's electrical consumption factors stayed the same accept in the cooling loads. This is important, as the energy from cooling loads is typically the most expense and energy intensive when it comes to a building's electricity consumption.

Conclusion:

These simulations programs are architectural tools to merge the digital and theoretical with the physical variables of PV in order to validate a tangible architectural design. The results reached can provide BIPV design justification. The reason I choose to use these simulation programs, both DIVA and DB, was because I wanted to be able to push myself in a field that provided quantifiable data with energy differences and qualitative visuals for aesthetic possibilities.

As a visual learner, I also wanted to observe with my own eyes the interactions of the thermal heat signatures and solar insolation created on the threshold(s) of the façade. This is the strength of these programs. Whether it may be simulations in computational fluid dynamic (CFD), radiation maps or daylight factors (which we will see in Chapter 7), these programs help people understand the physical science and electric magnetic spectrum interacting with the surface of the building. In essence, architecture is a field based on visual communication and hard science. These programs help bring those factors to life through simulating understandable and universal imagery.

Caveat emptor: The current simulation programs are extremely time consuming, limited in what they can do, use up way too much computer RAM and requires a knowledge of physical and building science. The majority of the dissertation was spent modeling and running simulations. However, there was not enough time to run all iteration to find out the energy profiles on the passive side of DB for all 10. The final iteration was chosen based on a balance of BIPV energy creation, shading and aesthetics.

There are practical reasons as to why simulations of this nature are outsourced from architectural firms and into engineering or specialists firms. Simulations are too time consuming to do on a daily basis in a professional environment, as the responsibilities fall outside what an architect is suppose to do and requires additional labor expenses. Hopefully, better computers, software and technology could change these negative aspects.

Major gains are needed if the basic architectural designer and laymen are able to maneuver through daylighting and energy simulation programs to test and verify their designs. Building Information Management (BIM), Sketch-Up and NURBS programs like Rhino-3D are closing this gap. Technology, interface and the architectural field itself has changed dramatically over the past

15 years and it will only be a matter of time before energy simulation programs are commonplace.

A BIPV software program that specifically integrated BIM, Sketch-UP, NURBS, Rhino-3d, and which also had new BIPV elements, could greatly speed up the process and acceptance to BIPV implementation. Currently, crude software exists that address only an elementary plane atop rooftops and fail to address building material design testing. Most of these are software plug-in's and require converting files, say from CAD or BIM, and importing into said programs which cause issues with the completeness of the model and excess data being imported or data not converting smoothly. The hardware and software of architectural computing are seriously lacking and needs great improvement before industry acceptance of BIPV can be expected.

Simulations in the schematic design (SD) and design development (DD) phases of architecture are primarily done when utilizing these energy simulation programs. This is the very reason I chose it was to run through SD and DD for the purpose of understanding the PDC's energy behaviors and in achieving an target energy payback and energy generation to prove power savings through shaving off energy consumption through active and passive techniques ingrained within BIPV.

What follows next in chapter 7 is one more daylight simulation and finally finding out what the active energy generation is of this BIPV system using preferred design methods and calculations.

What was established from using DIVA:

1. Energy thresholds and its baselines on the vertical façade.
2. Energy potential of 21.3° angled PV plane/scheme based on #1.
3. The Final BIPV design iteration based on a combination of simulation choices of #2.

What was established from using DB:

1. Energy baseline of the PDC.
2. Reduction of PDC's energy baseline on the above #3 BIPV iteration.

CHAPTER 7:
BIPV System

7.1. BIPV Design Development: Final Iteration

In developing the appropriate BIPV awning system, an analysis into the final design iteration (as decided upon in Chapter 6) must be examined in light of a combined use of façade iterations SE 9, SW 4, NW 2 and NE 5. The focus is to determine the most efficient shading thresholds and solar energy profiles, balanced against the purpose of aesthetic function.

Iterations #1 - 5 (figs. 6.10), provide massive power potentials that could be utilized simply based of the area and solar availability that encapsulates the PV area and its tilt. Three (3) of the #1-5 iterations provided the best utility. These three façade iterations, SW 4, NW 2 and NE 5, were able to harvest productive energy at the most optimal parts of the building, its upper and diagonal regions, and shaded against direct light and glare entering the buildings interior.

Iterations in a more fully draped and uniform manner, like iterations in columns 1 and 2, produced the most energy in aggregate but at an increased cost, as this model requires more PV modules, longer installation times and added labor. The highest energy per capita or ft^2 was the iteration columns #5 – 10; specifically section SE 9 façade. Even though its total output was lower than iterations columns #1 – 5, it still functioned at a higher more energy efficient rate, as this area produces the most focused solar insolation on the façade.

Power performance gains led to the final iteration. For aesthetic reasons, the final scheme was chosen based on its diagonal profile, which followed the energy thresholds of the surrounding shading constraints and formed a dynamic appeal. The PDC's identity and alignment with the sustainability goals of the 21st century were kept as a forward thinking proposal in choosing the final iteration.

By simply draping the façade entirely with PV, like in iteration column #1, it did not provide efficiency for the PDC. Efficiency is obtained both aesthetically and electrically by exploiting the rhythmic forms of its diagonal profile. Below are rendered images and a floor plan displaying the final BIPV awning iteration set in its urban dense environment.

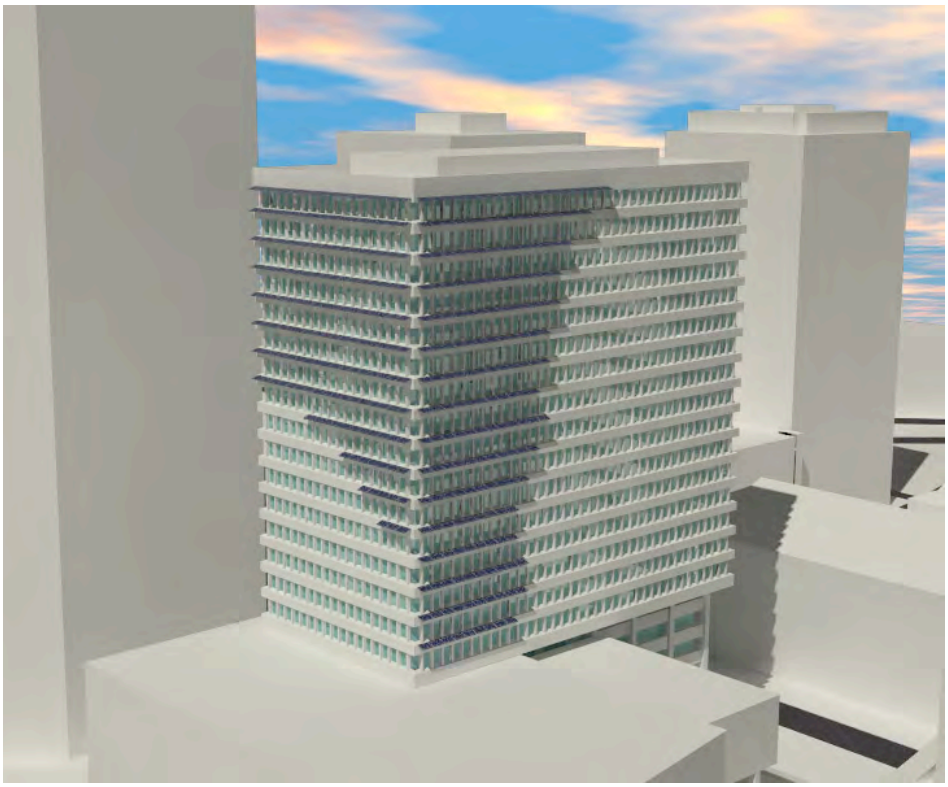

Figure 7.1. Eastern Perspective of PDC from City Financial Tower

Figure 7.2. East Perspective of PDC

Figure 7.3. West Perspective from the Topa Financial Center Building

Figure 7.4. West Perspective

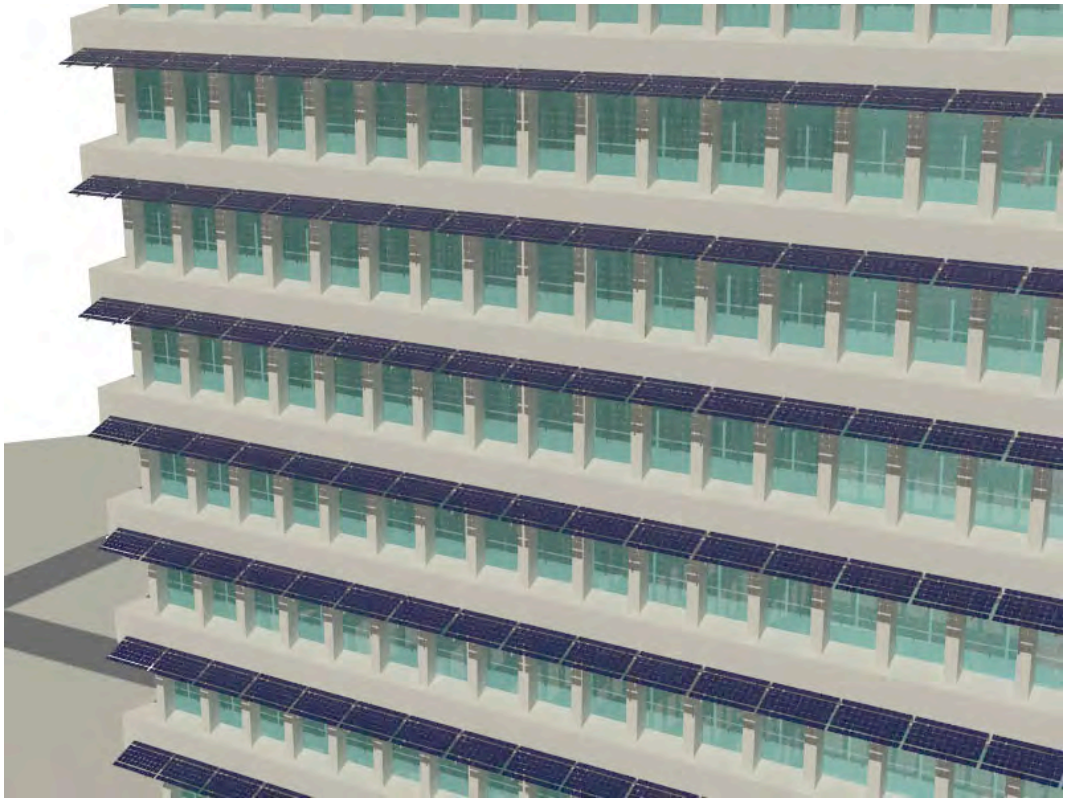

Figure 7.5. BIPV Awning System married to the PDF façade

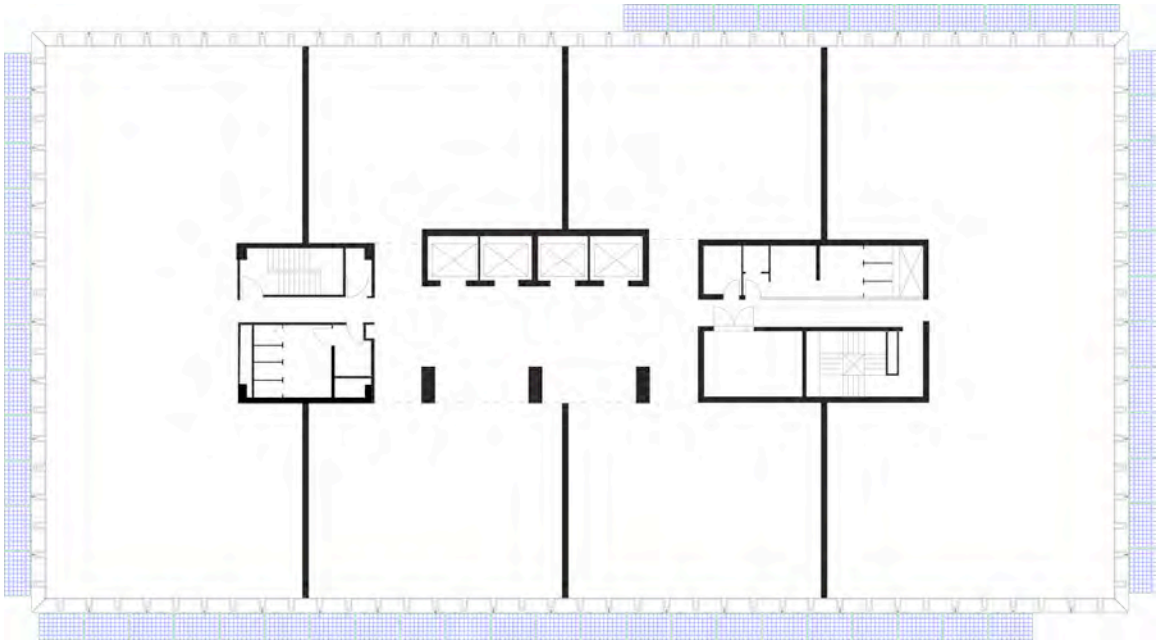

Figure 7.6. 22nd Floor Plan with BIPV Awning System

7.1.1. Daylight Factor

In developing a metric for determining the passive lighting conditions of the BIPV awning, a Daylight Factor (DF) was used in calculating the affects of the baseline interior lighting vs. the final BIPV iteration and its light reduction affects on the interior. Using DIVA these simulations relates to what DB was analyzing, but on an illuminance level not an energy conservation level. Both are passive simulations but this technique is a ratio of internal to external daylight light levels.

It is mentioned in the book *Mechanical and Electrical Equipment in Buildings*, that the "Daylight Factor as a means of expressing interior daylight illuminance is both absolute and relative."[1] Meaning that the DF is applicable to any building façade, and its apertures, regardless of shape as its ratio corresponds to relative changes in both interior and exterior illuminance.[2]

DF is typically used in initial schematic design phases of architecture, which is why I choose to adopt this method of analysis: an attempt to produce a quick estimate for judging the daylighting performances of the final BIPV iteration. Typically this ratio can be determined by how high and large windows are in a building envelope contrasted with the floor area of each daylight space.[3] To calculate the DF manually you use this formula:

DF = (Indoor Illuminance from daylight ÷ Outdoor Illuminance) x 100%[4]

Daylight Factor, within the schematic phase, provides useful data, visual simulations and information as to the direct, ambient and diffuse lighting entering the interior as affected by the form of the façade and BIPV awning system.

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[1] Walter T. Grondzik, *Mechanical and Electrical Equipment For Buildings* (Hoboken, N.J.: Wiley, 2010), 598.
[2] Ibid.
[3] Ibid., 219.
[4] Ibid.

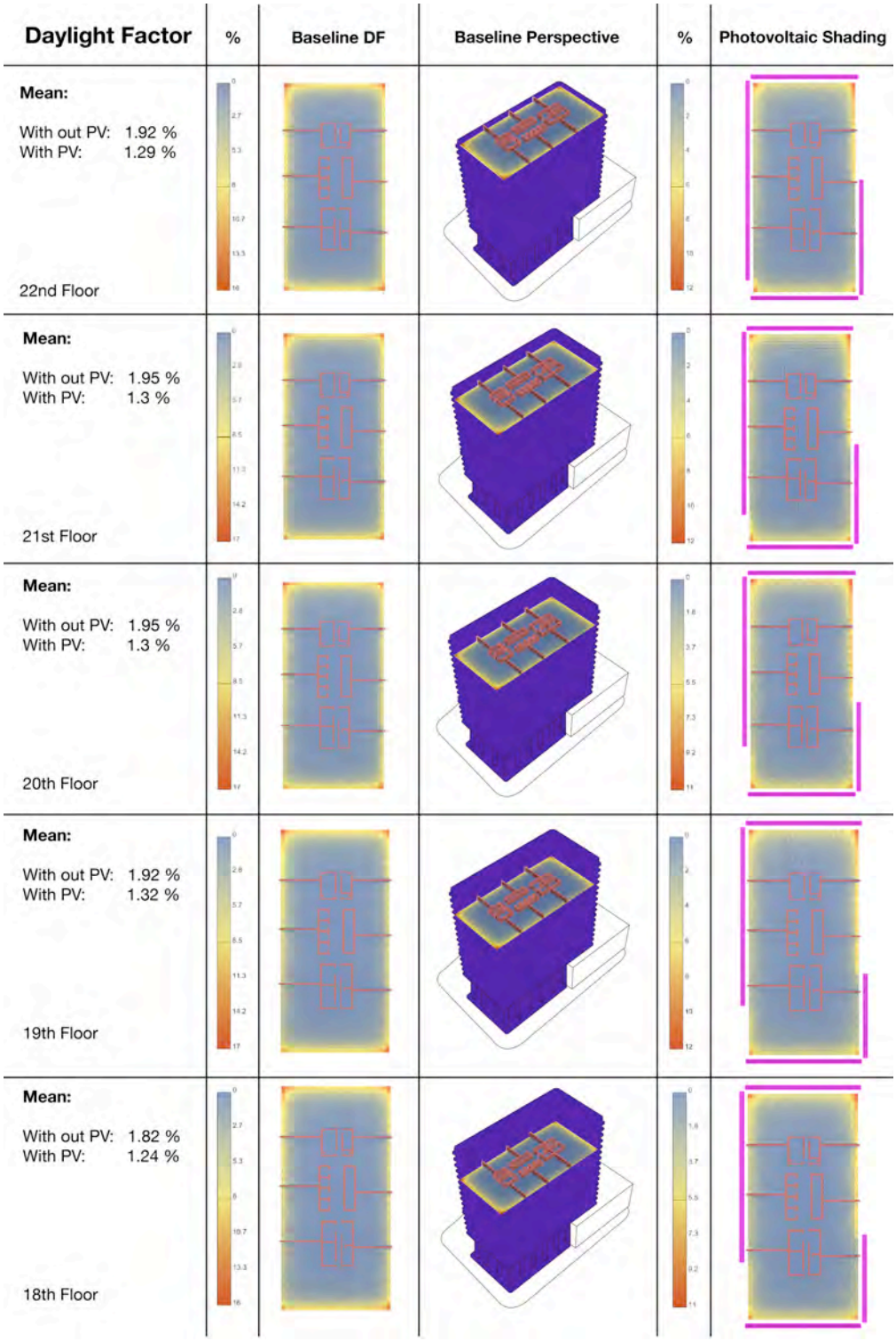

Figure 7.7. Daylight Factor 22nd-18th Floors

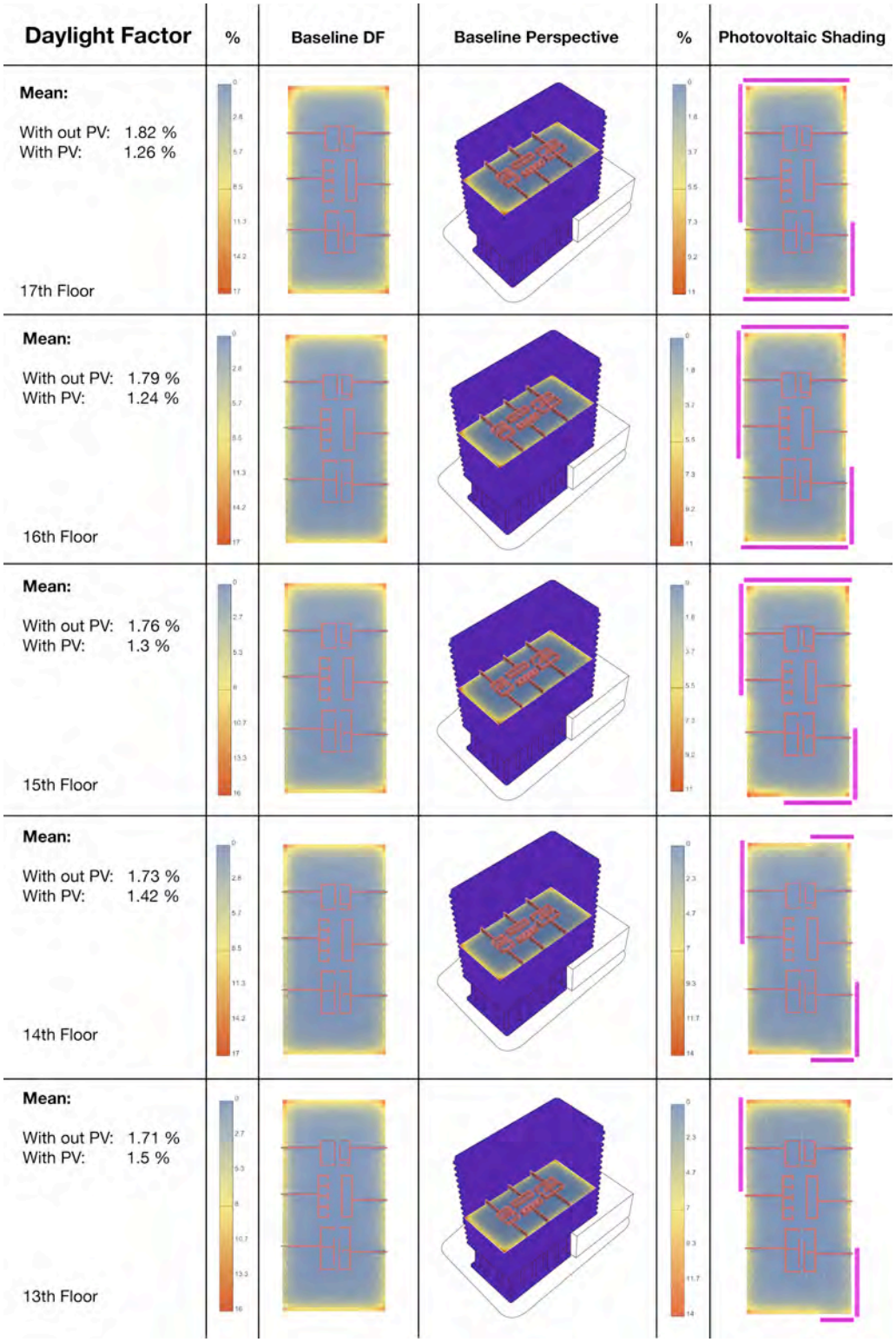

Figure 7.8. Daylight Factor 17th-13th Floors

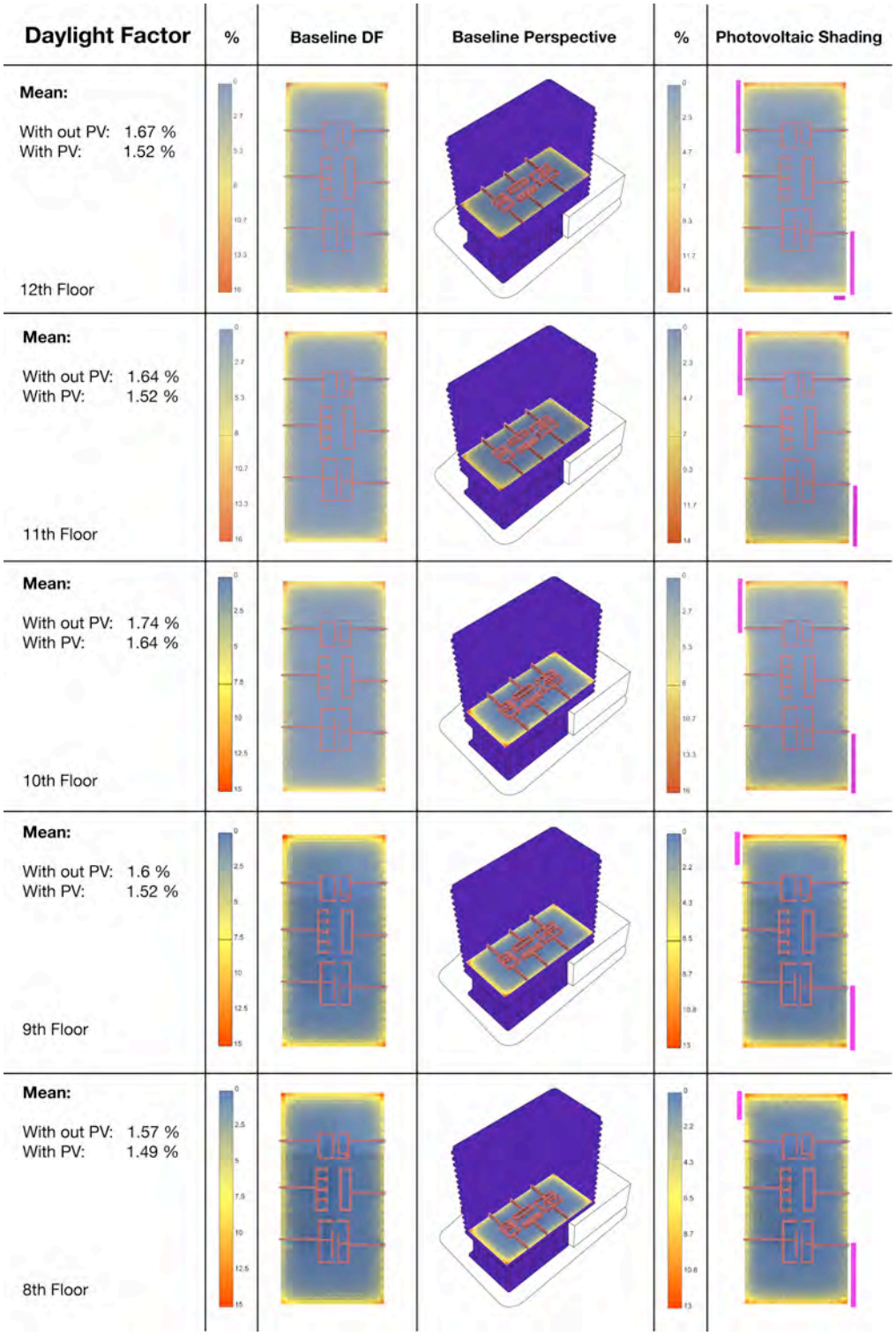

Figure 7.9. Daylight Factor 12th-8th Floors

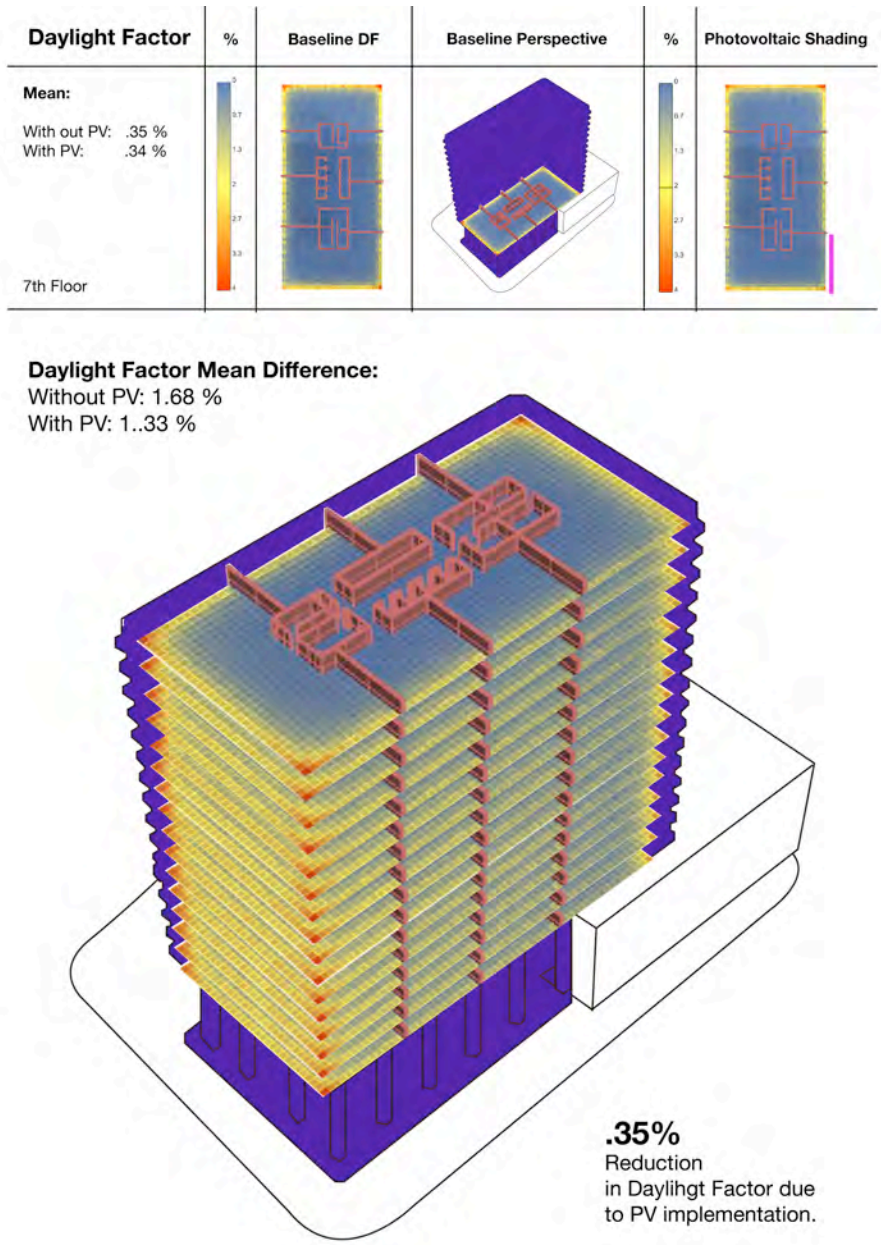

Figure 7.10. Daylight Factor 7th Floor and DF Reduction %

Figure 7.11. Interior render without BIPV Awning System

Figure 7.12. Interior render with BIPV Awning System

As you can see the addition of the BIPV shading devices reduced the interior lighting effectively but with leaving enough ambient lighting to carry out daily operations. In using the final BIPV iteration, it reduced the total overall DF by .35%. Not to dramatic of a drop, but since it is a ratio this could be seen as a subtle yet effective tool for measuring shading devices on the exterior of the building envelope.

7.1.2. PV Module Selection

In order to design a well rounded BIPV apparatus as a system, the component parts must incorporate effectively into BIPV awning system. Starting with the PV modules and exploring three (3) PV choices, the proper selection will yield the most efficient, both aesthetically and performance wise, BIPV apparatus (table 5).

By the process of elimination of the three PV modules, certain factors play into determining the best one for the job (figure 7.13). First, the PV module that best promotes the concept of building skin replacement and interoperability must be considered. Second, the kW power potential and its cost; Third, is its tangible applicability.

Aesthetically, the Sunfilm 490 was the most appealing as it had the highest wattage, thin-film material, frameless features and high tech appearance, which holds the best possibilities for building skin replacement. However, performance and cost data needed to compare the information for design implementation was unavailable in the marketplace. After a diligent search I could not find a broker that sold the module, even through its Sunfilm AG LinkedIn Company Profile. Other deficiencies was that it its conversion efficiency was only 8.6%, it weighted 238 lbs., its dimensions were too large for façade implementation and it was made in Germany equating to high shipping costs.

With the Stion STL-150, its material was based on CIGS technology (an industry leader of generation #2 PV eclipsing generation #1 c-Si PV), made in the U.S., was the least expensive module with the lowest weight factor among the three modules and was frameless. However, it also had the lowest wattage output and seemed visually to be more like a TV screen than a glass type thin-

film PV module, which is not the aesthetic appeal a BIPV shading device should project in regards to this project.

Table 5. PV Module Choices

Specifications	LSX 260[5]	Stion STL-150[6]	Sunfilm F490[7]
Type	c-Si (Mono)	CIGS (Thin-Film)	Amorphous Thin-Film (μc-Si/a-Si)
Structural	Frameless	Frameless	Frameless
Solar Cells	60 (Wafers)	134	Unknown
Efficiency	15.0%	14.0%	8.6%
STC Power/Area	260 W	150 W	490 W
Length	65.5"	65.2"	102.4"
Width	41.0"	25.8"	86.6"
Depth	1.4"	1.06"	Unknown
Module Depth	.3"	.24"	.3"
Module Area	18.65 ft^2	11.68 ft^2	61.2 ft^2
Weight	64 lbs.	33 lbs.	238 lbs.
Price[8]	$1.39/Watt or $361.40/Module	$0.84-$100/watt or $180/module	Unknown
Country	US	US	Germany

The Lumos LSX 260 represents the best adapted technology for interoperable use, both in hardware (shading device) and in software (electrical transfer). It had simple MC-4 DC power connectors that allowed the ease of, USB like, clip in power, with the option of mounting a micro-invertor on the back of the panel. Since there were gaps in between the wafers, a light phenomenon is created which provides a light transmittance factor of 10%. This resulted in semi-transparent pathways for the light to dance within the interior throughout

[5] Images and data: https://www.lumossolar.com/content/pdf/LSX-201502.pdf
[6] Image: http://www.civicsolar.com/product/stion-stl145-145w-cigs-thin-film-framelessblk-us-solar-panel, Data: http://www.stion.com/wp-content/uploads/2013/03/Stion-Product-Data-Sheet-STN-Module-135-150.pdf
[7] Model F490 Solar Panel from Sunfilm AG, Images: http://en.votum.cz/pdf/datasheet_model_f_engl.pdf, Data: http://www.posharp.com/photovoltaic/solarpanel.aspx?pid=1b23267f-2302-48ab-9a3a-dbcb76efd80d
[8] Prices based on after federal and state tax credits and estimates given found at freecleansolar.com

the day and did not completely block out the upper view of the sky when looking out from the interior.

Lumos LSX 260 **Stion STL-150** **Sunfilm 490**

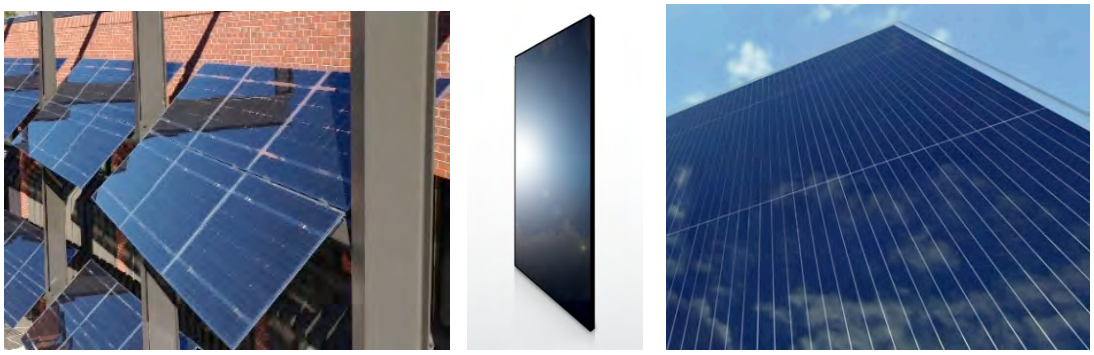

Figure 7.13. Visual appearance of Three PV modules

It was decided that the Lumos LSX 260 was the most optimal choice for the BIPV apparatus as it was the module that delivered the most information on its specifications, was highly recommended and made in the U.S.A. In addition, it had a track record as a proven BIPV shading device, was frameless and its aesthetic glass appearance was a contributing factor as the prime choice which echoed the dissertation goals of building material replacement through PV material integration (fig. 7.14).

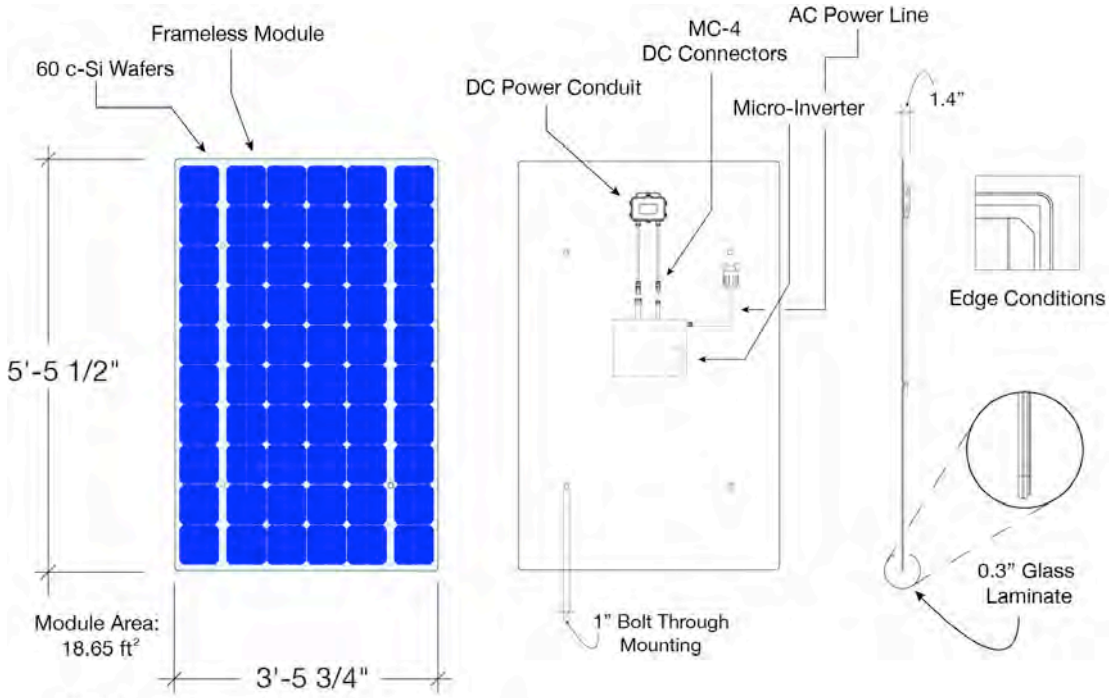

Figure 7.14. Lumos PV Details: Software & Hardware

7.1.3. BIPV System: Unit to Whole Assembly

The components that will be used to facilitate the main technological element, the PV module, will comprise the entire apparatus of the BIPV system. In trying to reduce the number of components involved in the apparatus, exactly six (6) components were decided upon (fig. 7.15). This was done for ease and efficiency of installation, reduced labor and cost of parts. Together all these components are used per whole unit of assembly to complete one BIPV awning system, of which there are 770 BIPV awnings totaling to 53 BIPV arrays. Below are the entire hardware parts of the BIPV apparatus system:

1. Aluminum Piping (1,526)
2. Nuts (3,052)
3. Bolts (3,052)
4. Washers (3,052)
5. Neoprene Washer (3,052)
6. Expansion Anchors (4,578)

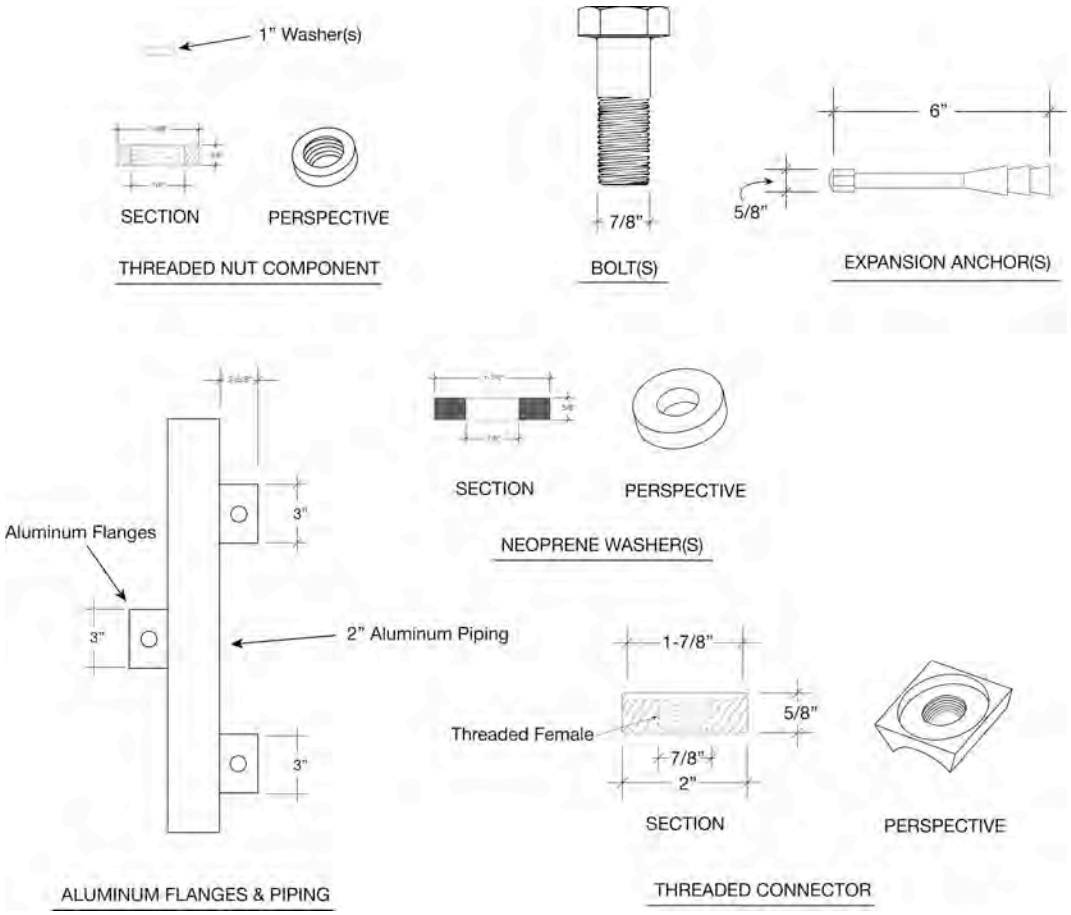

Figure 7.15. BIPV Component Details (Hardware)

The flanges and threaded connectors are both aluminum and part of the aluminum piping, counting as one whole unit, which supports the PV module and are to be welded together in a fabrication shop previous to installation. The numbers in the parentheses above, represent the number of units to be used for installation of the entire system.

The hardware components of the BIPV awning system are meant to be installed in three sections:

1. Unit-to-whole assmebly of all the components (fig. 7.15).
2. Take whole assembly, #1-5 consolidated, then fastened to the wall with #6 and ready electical connections from interior to the exterior of the building envelope.
3. Install PV module(s) to aluminim bracket hardware, (fig. 7.16), then connect eletrical AC power line from exterior to the interior eletrical point of contact; either directly to the plug loads or central eletrical loads of the PDC.

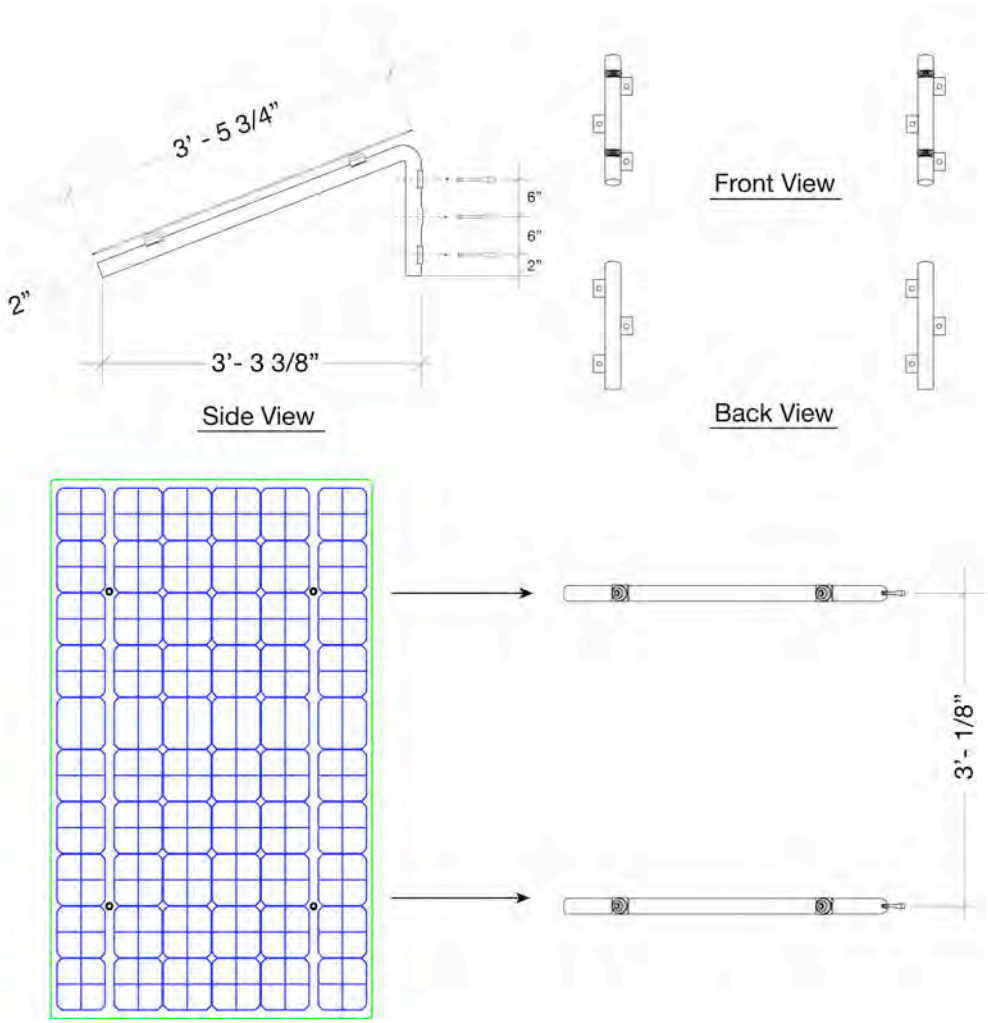

Figure 7.16. BIPV System Assmebly

As you can see in figure 7.17, an exploded view of the BIPV apparatus sheds lights on its total construction. The parts are assembled and applied to the building envelope, which facilitates an interoperable process as the hardware (apparatus) integrates with the software (electrical) connections in the architectural threshold thereby creating the “BIPV system”.

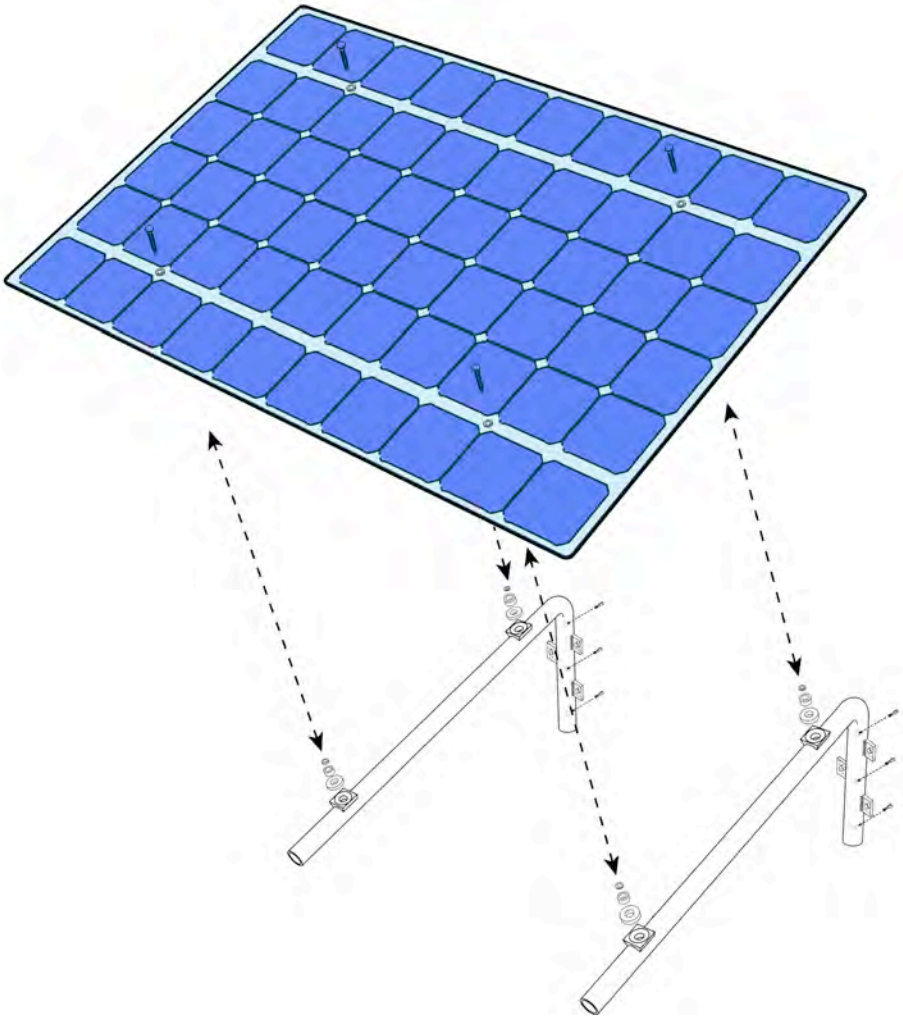

Figure 7.17. Exploded view of BIPV apparatus

Having established design development of the BIPV awning system, the next step is in looking at how the harvested solar energy works with on-site power to supply the building with energy. Below are power supply diagrams showing how the BIPV system transfers its renewable energy throughout the PDC.

7.2. BIPV Power Supply Method

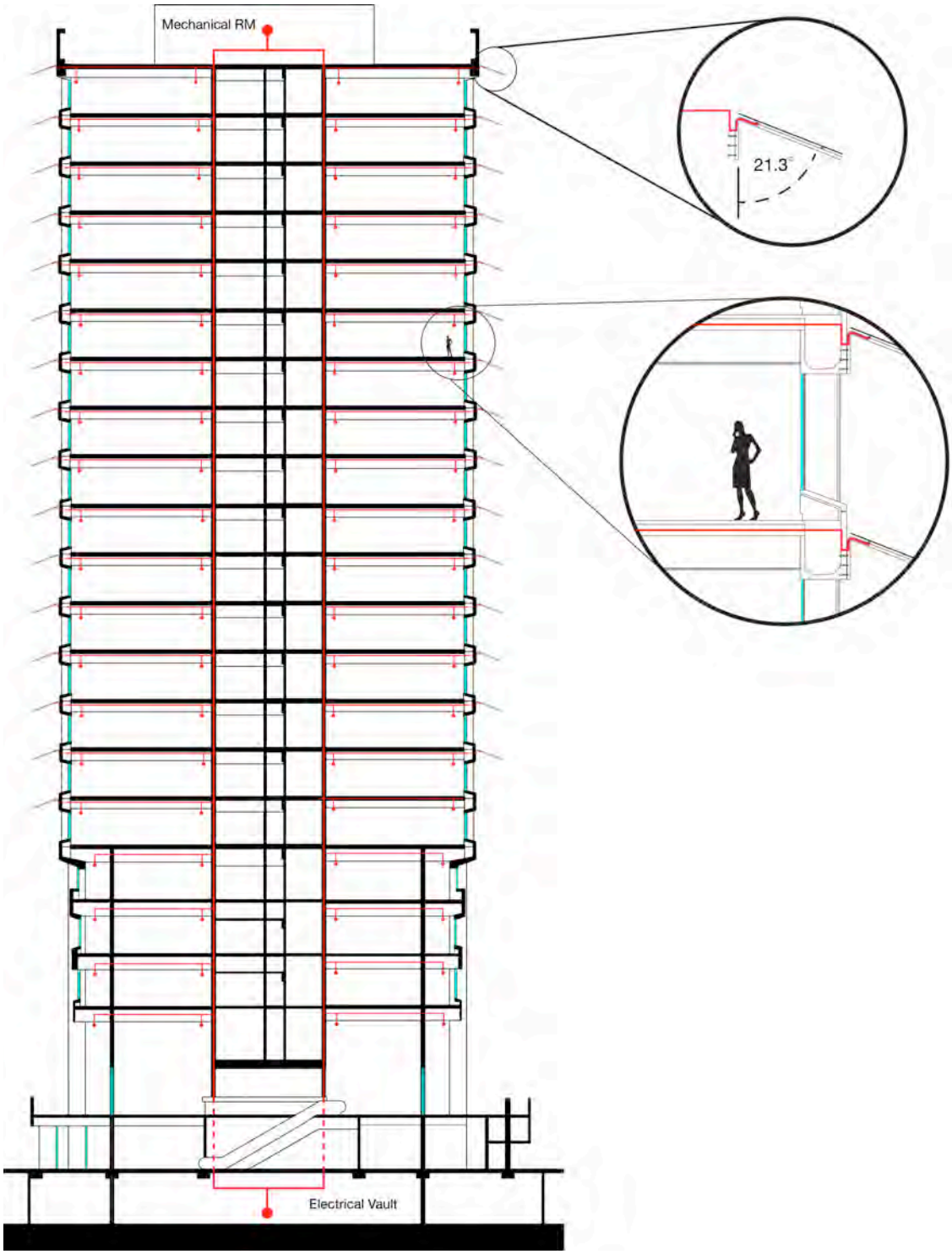

Figure 7.18. Transverse section with BIPV power supply

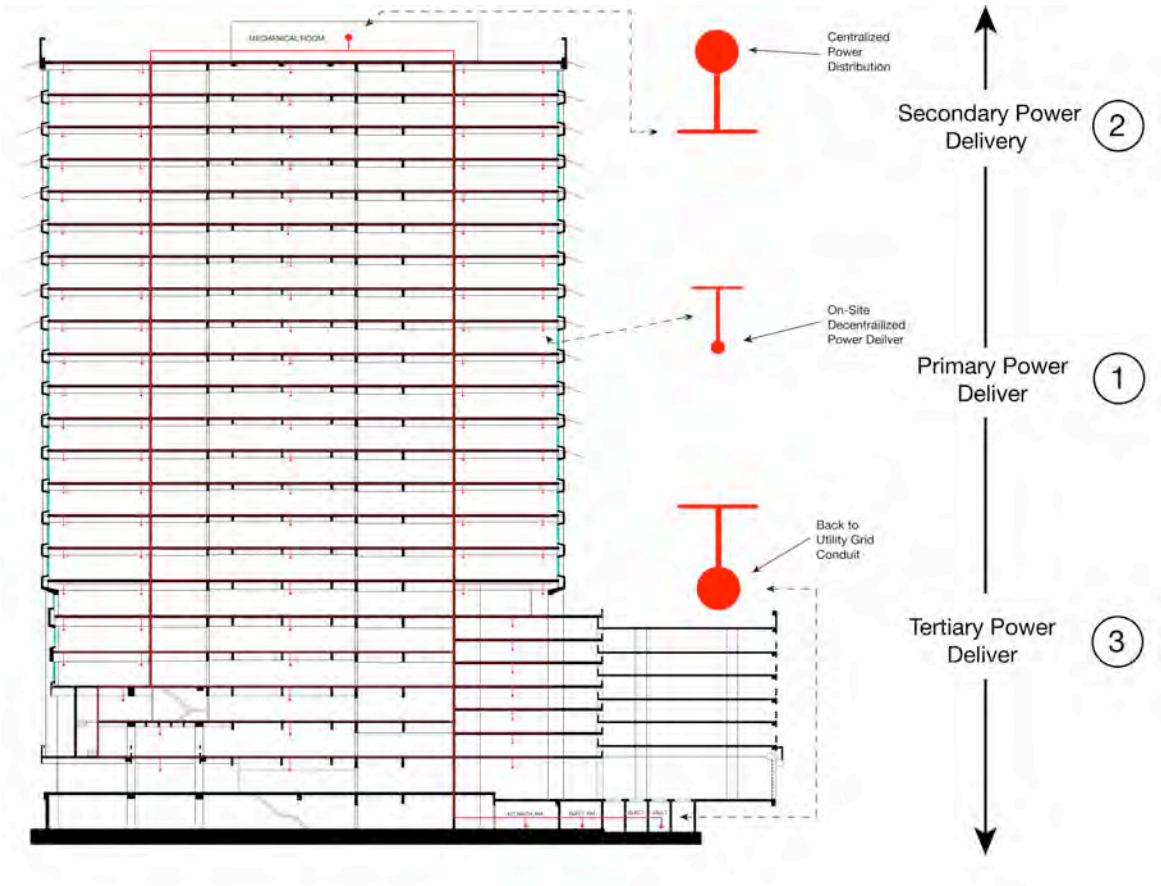

Figure 7.19. Longitudinal section with BIPV power supply

The sections diagram the energy goals in utilizing the on site power capabilities of the BIPV system (fig. 7.18 – 7.19). Power feeds into the building as Section #1 acts as the primary power delivery. The initial renewable energy generated feeds into the building as AC current, and not only separates itself from the source power feeding into the PDC, but further decentralization occurs on a micro scale from the on-site central power conduits that flow into the mechanical and electrical rooms.

In delivering the solar energy to the plug loads of the offices (the most used points of energy consumption in the building), it reduces the initial energy consumption of the office equipment, which stands at a baseline consumption of 17%, and the miscellaneous electrical loads, a baseline consumption of 5%. Furthermore, if the solar power was directed into the interior lighting system, then further energy savings could occur in reducing the 27% of total energy consumption attributed by the lighting system of the PDC.

If any energy is left over from the Section #1 energy transfer, then the secondary power deliver points of renewable energy are redirected towards the mechanical rooms, for either possible storage or for reducing the total PDC electrical loads across all energy sectors. Application could include the possible reduction of the total cooling loads; which now stands at 29%, after the DB simulations demonstrated the passive reductions of the BIPV system.

If there is any surplus energy, i.e., in the summertime or very sunny days, from Section #2, it can be sent to the basement electrical rooms and redirected onto the utility gird to be bought back by HECO (the utility company). This energy transfer can provide revenue or energy credits, which could further reduce overall expenditures, both electrically and fiscally, within the PDC. However, the rate of consumption is so great that this tertiary energy strategy might never be achieved unless on the weekends when energy consumption drops dramatically when most office employees are at home.

The energy of the BIPV system applied directly to office energy consumption will increase energy efficiency and act to redistribute energy autonomy from the utility grid.

7.3. BIPV Power Potential

It is very hard to determine the architectural accuracy of a structure until it is built. Energy systems are equally incalculable. Environmental and human error factors exist in reality and are not reflected in simulations. The architect has to rely on his skill, knowledge and expertise as well as equal talents of all involved in the project to determine the accuracy of the initial endeavor.

In reaching the final BIPV iteration an examination of the total power potentials of the 10 iterations was required. Estimates of the total or baseline power potential of all the iteration was difficult without computer modeling. Below is the initial formula in determining the iteration's power capacity that was used on the simulations in figures 7.20 – 7.21.

[# of Modules x 260 Watts]/1000 = #kW

#kW x 5.8 (DT Honolulu peak sun hours/day) x 365 days/yr = #kWh/year

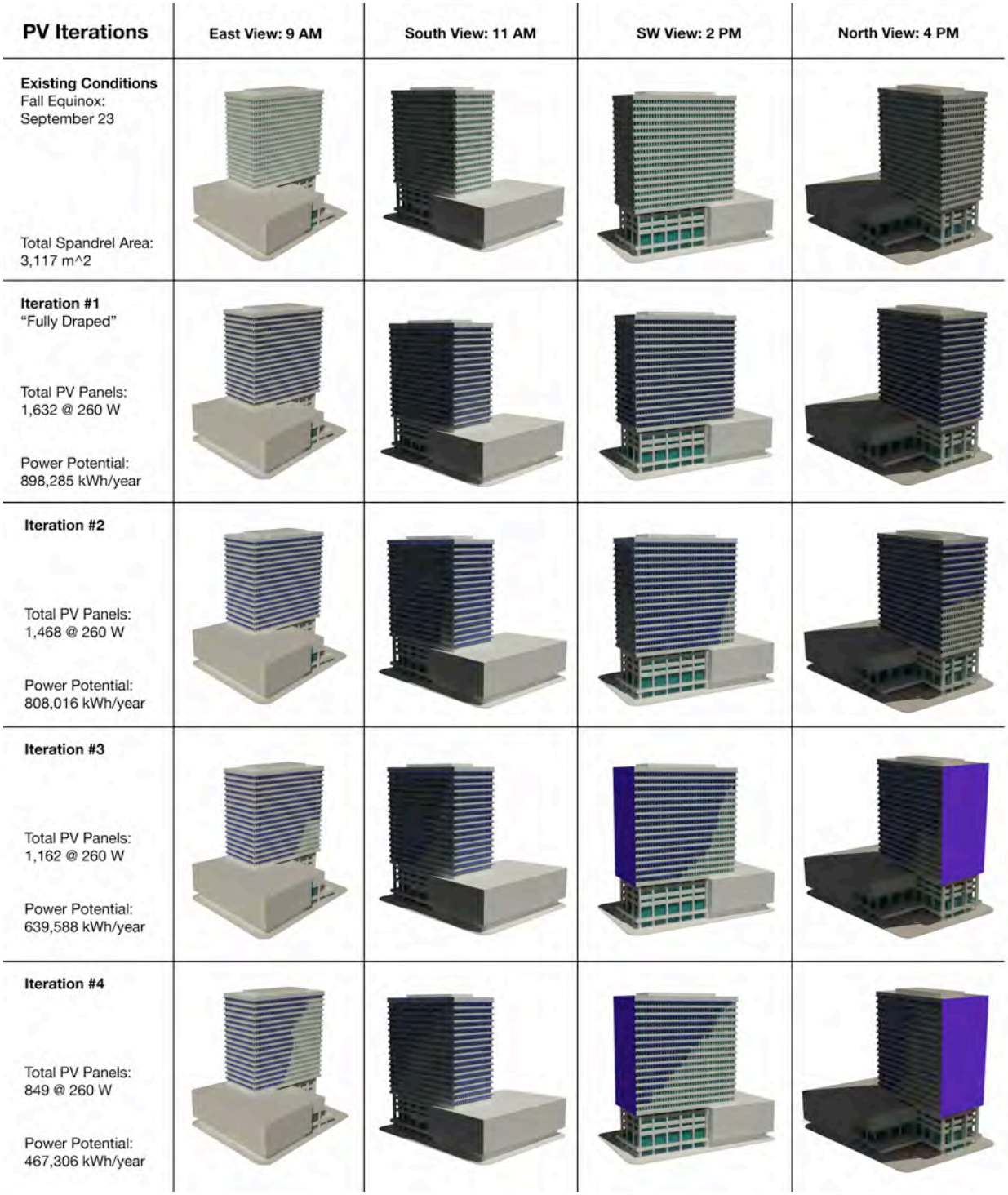

Figure 7.20. BIPV Iteration 1-4 Redux

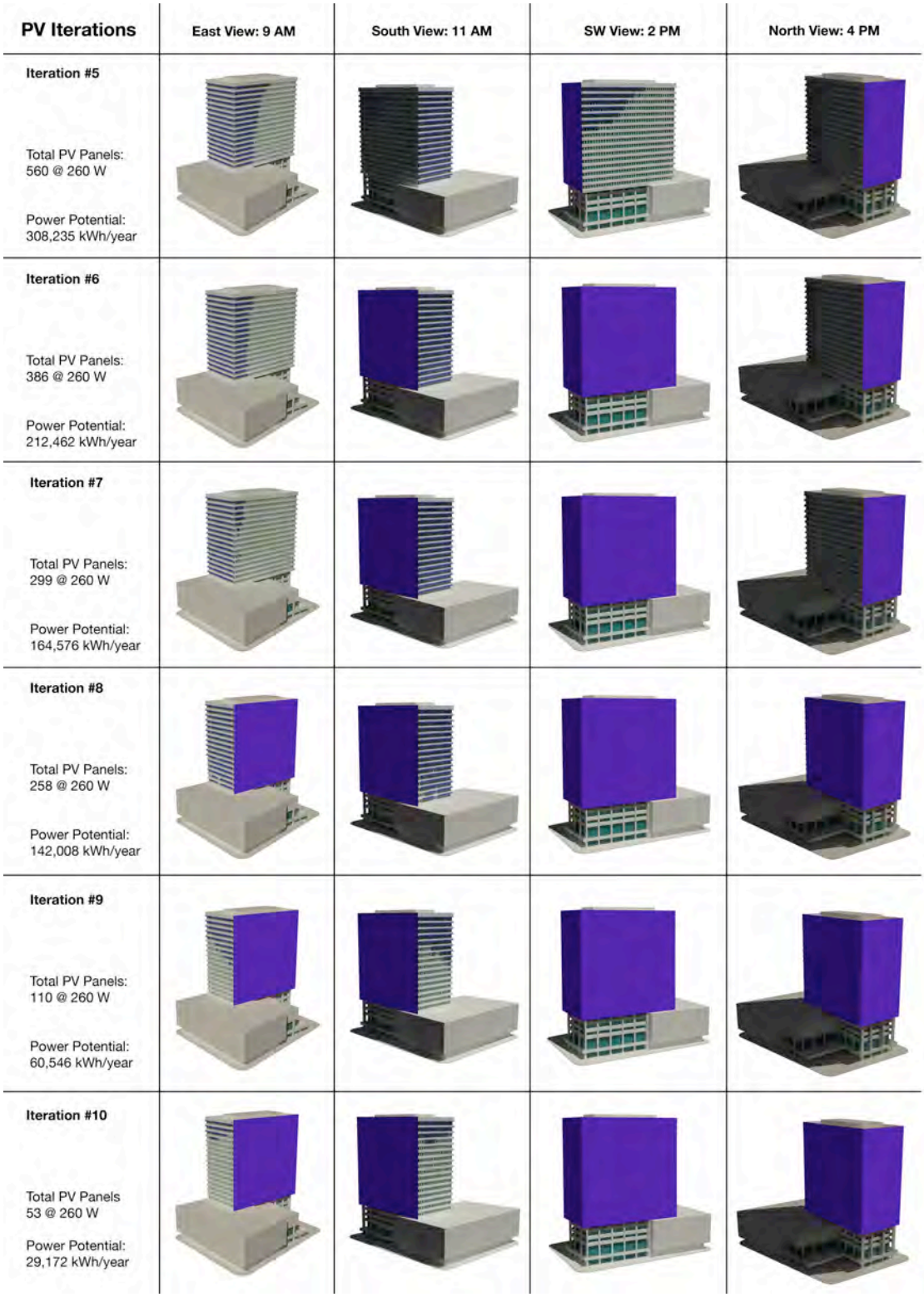

Figure 7.21. BIPV Iteration 5-10 Redux

The interations above are simulated from figures 6.10 - 6.11 and calculate the PV modules maximum electrical energy output over the entire BIPV system. If you compare this to figures 6.10 - 6.11 you can see a major reduction in the kWh/year factor. This is because the area of the simulated PV in 6.10 – 6.11 assume a standard of PV area x yearly mean solar insolation. Other variables exist when trying to determine the exact energy output of each system and its iteration.

Figures 7.20 – 7.21 falls into a similar quandary. The power potentials above do not consider the tilt angle, azimuth or the conversion efficiency of the modules. Additionally the above calculations are just the Standard Testing Conditions (STC) wattage of the modules, i.e., PV cells under laboratory conditions that are measured under a solar irradiance of 1,000 W/m2, cell temperature of 77°F, and air mass of 1.5.

This is the nameplate electrical output and its maximum power potential of the modules and not its nominal or more tangible electrical performance. More quantifiable formulas are needed to determine the accurate power potential of all the BIPV iterations.

7.4. Orientation for Energy Estimations

Using the online PVWatts calculator, I was able to use the kWh/year and total kW potential variables needed for all the iterations. Other key variables are worthy of consideration before calculation of BIPV iterations kWh/year, $/year generated, and payback accounting formulas to reach an ROI. The topic of building orientation is plays significantly into the energy performance of the PV modules and its system.

The PDC orientation is off center from the cardinal directions of true North, East, South and West. This affects its ability to gain maximum solar insolation as opposed to other more optimally oriented buildings (fig. 7.22). For instance if a module was pointed directly 180° due South, you could expect an average solar insolation factor of 5.72 kWh/day with an energy potential of 1533 kWh/year (table ?).

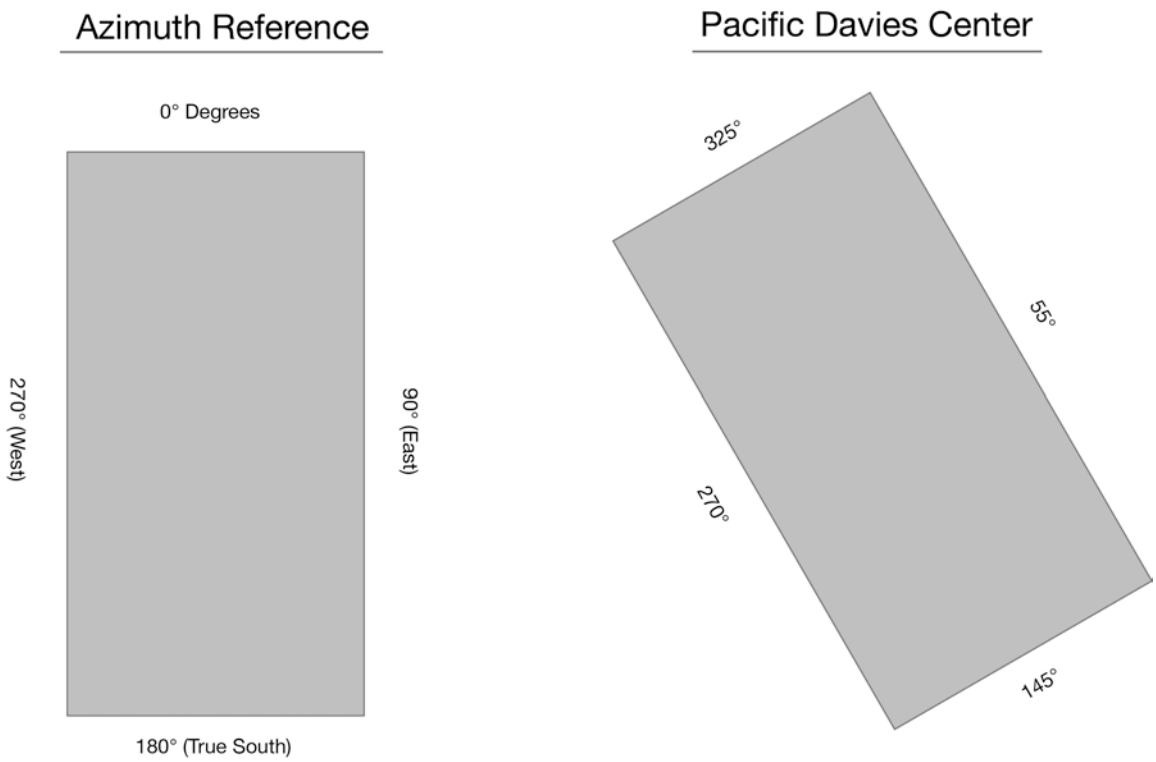

Figure 7.22. Azimuth Reference vs. PDC Orientation

Having a South-facing array is the most optimal for Hawai‘i, due to our tropical latitude in the Northern hemisphere. This affects energy production. Since the south facing façade is off axis, at 145°, it creates a percentage drop off from that of the optimal orientation (180°); meaning that it loses about .06 kWh/day and 13 kWh/year. This is not a tremendous loss of energy but small things add up over the life of the PV system which affect its payback period and power potential.

This is difference, and its percentages, are magnified when you solar insolation hits the other sides of the façade (table 6). PV specialist Jordan Little, of Spider9 Energy Storage Solutions, suggests that, “The orientation to South is more important than the tilt angle of the panels production-wise”, as being an optimal building placement. Once the southern degree was established I was able to enter in all the missing variables needed to find out the kWh/year and $/year the BIPV iterations generated.

Table 6. Orientation Estimations[9]

Orientation	kWh/day	kWh/year	% Diff
(Optimal) 180	5.72	1533	
55	4.95	1334	14%
145	5.66	1520	1%
235	5.52	1490	4%
325	4.76	1278	18%

7.5. BIPV Energy Production

Using the PVWatts calculator on the NREL website I enter the variables of:

- DC System Size: Varies on the 10 BIPV Iterations and Final Design
- Module Type: c-Si (15% Efficiency)
- Array Type: Fixed
- System Losses: 14% (PVWatts default)
- Azimuth: 145°
- System Type: Commercial
- Fed. & State Subsidies: 65%
- $/kWh: $0.24 (NEM Price)
- Installed Cost ($/Watt): $4.85[10]

After entering in all those factors I submitted the data and was given the kWh/year and amount of money generated per year (table ??). With the payback calculations it is assumed that the kWh was priced at a reduced cost through the Net Energy Metering (NEM) scheme of $0.24 with HECO and not your average $0.36/kWh residential or commercial $0.29/kWh pricing.[11] NEM is an arrangement with the utility company wherein the ratepayer gets energy or financial credit when excess renewable energy is generated on-site, usually from solar power, and fed back into the utility grid. The relationship supports the "tertiary power delivery" method outlined in figure 7.19.

[9] Table estimates provided by Jordan Little, Director of Energy Storage Development at Spider9, LLC.
[10] $/kWh and installed $/watt quoted by Jordan Little, Director of Energy Storage Development at Spider9, LLC.
[11] Estimates based on current residential rates and 2013 "P" type commercial rate: http://www.heco.com/heco/Residential/Electric-Rates/Average-Electricity-Prices-for-Hawaiian-Electric,-Maui-Electric,-and-Hawaii-Electric-Light-Company

Table 7. BIPV Iterations[12]

BIPV Iterations		kW	kWh/year	$/year generation	Load % of PDC
	1	424.32	668,564	$240,683	10.2%
	2	381.68	601,379	$216,497	9.2%
	3	302.12	476,024	$171,368	7.3%
	4	220.74	346,855	$124,869	5.3%
	5	145.6	229,409	$82,587	3.5%
	6	100.36	158,128	$56,925	2.4%
	7	77.74	112,488	$44,095	1.7%
	8	67.08	105,692	$38,050	1.6%
	9	28.6	45,062	$15,224	0.7%
	10	13.78	21,712	$7,815	0.3%
Average		176.20	276,531	$99,811	4.2%
Final Iteration		200.2	315,692	$113,557	4.8%

Based on all 10 BIPV designs the highest power potential was from iteration 1-10, as expected, with total energy coverage of the PDC averaging 4.2%. However, in running the calculations for the final BIPV iteration it was revealed that the final scheme beat the average with total energy load coverage of the PDC equaling 4.8%. This was a major accomplishment in the D.Arch project as it balanced not only aesthetics, in earlier discourse, of the final BIPV scheme (fig. 7.23) but in power potential of beating out the average of the 1-10 BIPV iterations. What remains after this is in determining of the payback period (ROI) and total cost of the final BIPV awning system (table 7).

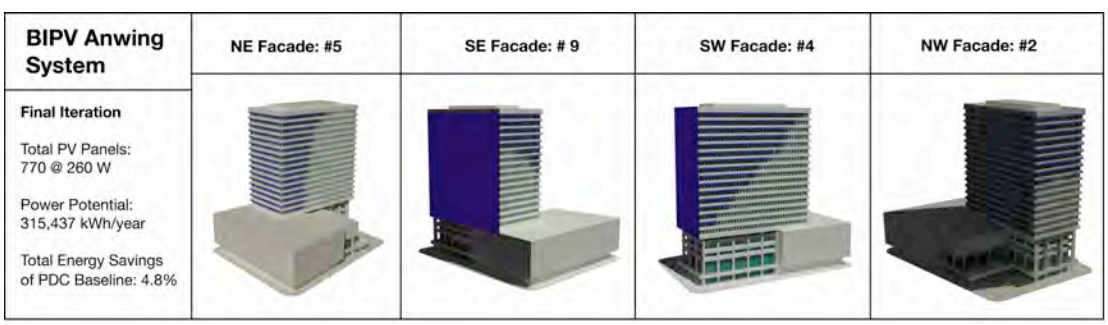

Figure 7.23. Final BIPV Scheme

[12] BIPV iterations energy estimates generated from PVWatts calculator: http://pvwatts.nrel.gov/index.php

7.6. Final Payback & Total Systems Cost

Below is the final payback of the final BIPV awning system (SE9 + SW4 +NW2 + NE5). From the results it was determined that the pack back period of the BIPV system was 4 years. This calculation proves the economic viability of the system as it beats out the average pack back period of a PV system, which takes in Hawaii, 6.6 – 9.5 years.

Table 8. Final BIPV iteration calculations[13]

	Projected Annual kWh Production	Projected Utility Rate (kWh)	Avoided Utility Cost	Net Savings
Year 1	315,692	$0.24	$75,008.42	$(264,831.08)
Year 2	313,482	$0.24	$76,717.86	$(188,113.22)
Year 3	311,288	$0.25	$78,466.26	$(109,646.96)
Year 4	309,109	$0.26	$80,254.51	$(29,392.45)
Year 5	306,945	$0.27	$82,083.51	$52,691.06
Year 6	304,796	$0.28	$83,954.19	$136,645.25
Year 7	302,663	$0.28	$85,867.51	$222,512.75
Year 8	300,544	$0.29	$87,824.43	$310,337.18
Year 9	298,440	$0.30	$89,825.95	$400,163.13
Year 10	296,351	$0.31	$91,873.08	$492,036.21
Year 11	294,277	$0.32	$93,966.87	$586,003.07
Year 12	292,217	$0.33	$96,108.37	$682,111.44
Year 13	290,171	$0.34	$98,298.68	$780,410.12
Year 14	288,140	$0.35	$100,538.91	$880,949.03
Year 15	286,123	$0.36	$102,830.19	$983,779.22
Year 16	284,120	$0.37	$105,173.69	$1,088,952.91
Year 17	282,131	$0.38	$107,570.60	$1,196,523.51
Year 18	280,157	$0.39	$110,022.13	$1,306,545.64
Year 19	278,195	$0.40	$112,529.54	$1,419,075.18
Year 20	276,248	$0.42	$115,094.08	$1,534,169.26

In table 8 is the total systems cost of the BIPV awning system. After a combined savings of 65%, due to current federal and state subsidizes, the

[13] Excel formula provided by Jordan Little, Director of Energy Storage Development at Spider9, LLC.

system only costs $340K. This is a major price deal as without the subsidizes the total cost would be $971K.

Table 9. Total systems cost of the final BIPV Iteration

System Cost	$970,970.00
Federal Tax Credit (30%)	$291,291.00
State Tax Credit (35%)	$339,839.50
Total Cost	**$339,839.50**

Conclusion

Calculating the energy harvesting capabilities of the BIPV iterations and final design determined the optimal performance levels and narrowed the field for the most efficient model. The BIPV designs provided kWh/year averages to calibrate against one another in order to discover the clandestine form to energy function. Additionally, averages with daylight factors were explored to determining a reliable metric on which to judge the final BIPV awnings system and its affects on interior illuminance. These averages supported the designs' feasibility as a renewable energy retro-application of architectural techniques and building technology designs that provide active power harvesting and passive energy conservation.

The results of the final BIPV design proved itself both qualitatively and quantitatively efficient in applications of economics and aesthetic performance. The active capabilities of the BIPV system(s) provided small energy yields in comparison to the overall total energy consumption of the PDC. However, this energy evaluation and BIPV designs showed that fractional improvements have large impacts over the life of a system and that immediate or smaller energy targets are feasible in the efficient use of renewable energy redistribution through on site power.

CHAPTER 8:
Conclusion

8.1 Findings & Observations

In assessing the BIPV retrofit applications for urban power utilization and energy savings, a great deal of design themes were proven through simulations, formulas and data calculation. Averages of energy estimations provide a guideline in measuring a balance between aesthetic value and power efficiency. Simulations were done in order to determine the certainty of the BIPV system and its iterations. The final BIPV awning scheme (iteration SE 9, SW 4, NW 2 and NE 5) accomplished a total combined energy savings of 7.8% measured against the total PDC energy loads and produced a payback period of just over 4 years; which exceeds the average Hawai'i residential payback period of 2.6 – 5.5 years. This energy savings equates to a power factor of over 511,697 kWh/year, reduced the building energy footprint by 1.77 kWh/ft2/year and generated over $176K in its first year of implementation.

This energy savings was accomplished by the dual nature of the BIPV shading device, which produced passive energy savings of 3%, based on a 5% total reduction in PDC cooling loads, and an active renewable energy generation of 4.8%. I was not able to achieve the 20-40% total energy reductions I outlined in chapter 4. However, I was able to beat the average payback in Hawai'i, which establishes that this model proves itself as a viable model for 21st century architecture where future building typologies will incorporate energy efficiency, electrical performance and progressive aesthetic expression.

The current and future problem of the triple convergence (climate change, urban density and the utility grid) requires a building methodology that can be adopted in pan-tropical regions where high economic growth and environmental susceptibility are ever expanding.

Currently, with the PDC, as with most large scale dense and urban buildings, the energy savings quandary lies in mitigating energy consumption as its power comes from an inefficient means of energy acquisition, i.e. source

power, as it uses massive amounts of electricity on office equipment, space cooling and balancing human comfort. One of the dissertation goals was in reducing the energy bills of the PDC, which exceeds $2 million dollars annually with an energy expenditure that was 6,542 MWh/year, on some factor to make a noticeable percentage difference in its total consumption.

The issue of specifically designing to conserve energy is widely acknowledged in the building industry. Research from the City Energy Project (CEP), which was established by the Natural Resources Defense Council, found that the biggest buildings in the cities only represent 3 – 4% of the total building stock, yet they represent over 40 – 50% of the total square footage and energy consumption in the entire city and from this the most inefficient large buildings consume about 4 – 8% as much energy as contemporary energy efficient buildings of the same scale.[165]

This PDC case study falls in this category as it can be applied to similar urban conditions whose massive energy consumption plagues the world's environment and strips all its natural resources. However, an examination in the systemic issues of urban density and its energy management consumption dilemma is beyond the scope of this dissertation.

The primary observation carried forth from research and design of the all the BIPV iterations and its final awning scheme, is that BIPV's role as a building adoption method proves optimally beneficial and can become the most effective tool for merging energy autonomy (renewable electricity) with architectural (visual and functional harmony) concepts.

8.2 Future Considerations & Predictions

In considering the future gains in energy façade retrofits, the interoperability of the PDC system could benefit highly from PV modules being able to use a clip system, similar to the cassette system of the CIS buildings in 3.1.1., at attachment points of the bracket system that allows the module to clip "in" and "out" of a frame housing the BIPV apparatus system. This allows for faster and less expensive labor, installation and repair. Operational costs to access the panel and its BOS are equally reduced and allow for faster maintenance and operation.

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[165] Peter Fairley, "10 U.S. Cities Tackle Efficiency", Architectural Record, March 2014, pg. 30.

The clip in/out panel system is interoperable, in its mimicry to a USB port, going from hardware to a software component, thereby creating a functional unit (figure 8.1). This clip system was influenced by the foresight of future markets being created to recycle and or repurpose solar panels for a continued lifecycle elsewhere in the world.

These recycled PV parts could be used in third world countries where the need for renewable energy, off the grid applications and energy black outs are commonly experienced. Having a clip "in and out" system will allow them to swap out old PV modules for new ones at a reduced price and increased efficiency gains.

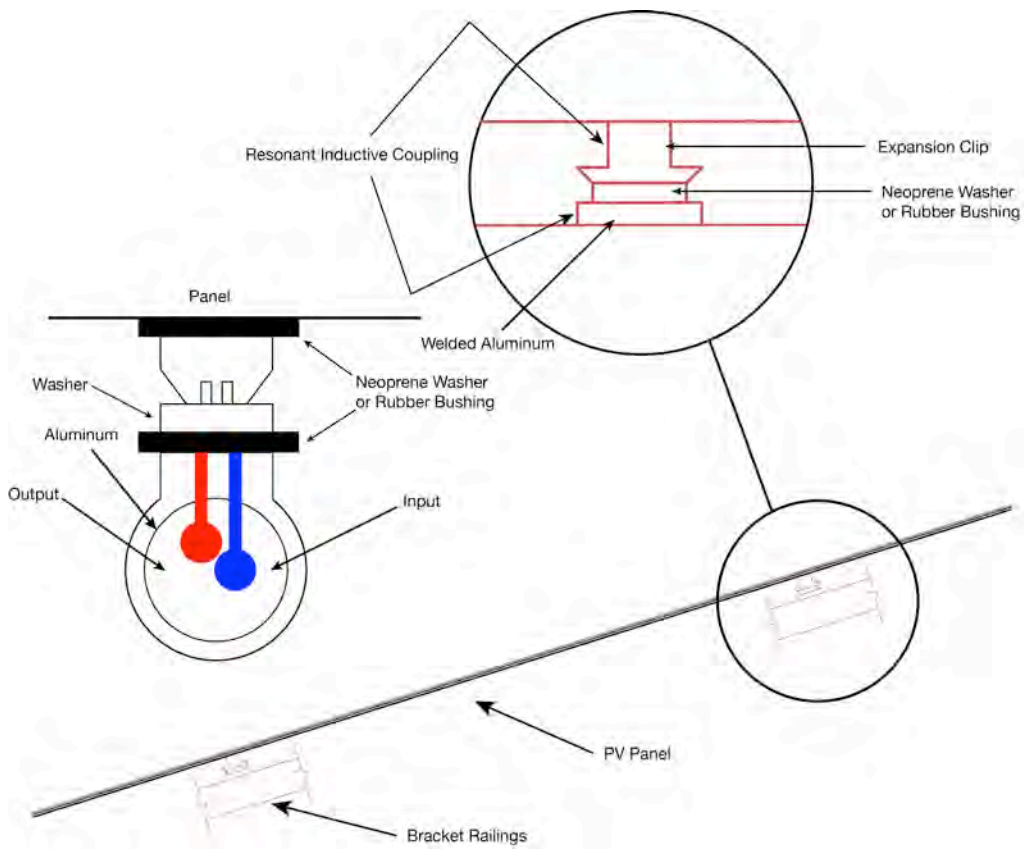

Figure 8.1. Schematic of PV "Clip" system with Wireless Power Transfer

Simplification of the BIPV system's clip can be achieved through what is known as near field wireless power transfer or "Resonant Inductive Coupling." This could eliminate the wiring and some parts of the BOS entirely as the functionality of renewable power generation and transfer flows and is

unhindered by physical wiring. This feature could reduce the total installation costs ($/Watt) as less overall installation time, parts and labor would be needed.

A wireless energy transfer removes the factor of cable deterioration, mechanical failure due to human intervention, power losses due to the "bottlenecking" of wiring and the risks of electrocution. As lately as 2011 a 220-Watt wireless energy transfer was achieved over an 11.8" gap at 95% efficiency.[166] The wireless energy transfer would greatly complement the mechanism of the PV clip system as it could be used and installed by anyone and anywhere, as an electrical background is not needed.

Based on the concepts above and upon review of the Triple Convergence in Chapter 1, BIPV's Interoperability in Chapter 2 and the Case Studies in Chapter 3, I predict future replication of the photosynthetic processes being achieved within PV, and applied into architecture through the technologies of either DSC or OPV (generation #3 PV). DSC or OPV technology will prevail because, as referenced in Chapter 3, a process similar of photosynthesis is already part of these energy transfer methods.

These technologies also merge the benefits of generation #1 (efficiency & durability) and #2 (low production costs, low mass & flexibility) and are created out of more sustainable and cost effective materials. DSC and OPV are transparent and semi-transparent, flexible and can easily integrate into glass.

Glass integration and flexibility are possible within Thin-Film (generation #2 PV). As such I predict that thin-film PV will establish the first framework and template for cross application into the architectural built environment or even consumer products. Because of its shear surface area, available solar energy insolation and applicability, thin-film PV could be the fastest method to be accepted as a building industry standard. Greater industry-wide use of this product provides for lower unit pricing, spurs further investment, research and design.

BIPV's will reach a point of technological transition when increased technology efficiency, lower costs and broader consumer and commercial applications become economically and socially accepted as an industry standard. This gradual transition starts with BIPV design interventions, such as the BIPV awning system of the PDC, and acceptance of energy conservation methods on the part of the user.

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[166] Seung-Hwan Lee and Robert Lorenz, "Development and valiadaiton of Model for 95%-Efficiency 220-W Wireless Power Transfer Over a 30-cm Air Gap", November/December 2011.

8.3 Conclusion

Accomplishments of BIPV, as part of an architectural scheme, were made in the area of aesthetics, energy performance and efficiency. The final design was highly influenced by the case studies in chapter 3. Combinations of awning, shading devices and canopy – elements of PV technology, guided the process of recognizing valid form and optimal angles that shaded but also created a perpendicular light harvesting for optimal energy acquisition. It is said, "Energy was, is and will remain the basic foundation which determines the stability of the economic development of any nation."[167] BIPV is an avenue of consideration for reaching these goals.

A building and its BIPV system can only act as an auxiliary power source in its current form to the PDC, as the total BIPV kWh or kWp potential cannot exceed the total electrical load of 6,542,000 kWh/year. As of today, it is not possible to produce more energy through BIPV to match consumption; similar problems were faced by Westinghouse and Tesla when the transmission of electricity was at its infancy.

BIPV is an evolving technology which currently serves as a sub power supplier and represents a nascent building industry. Bridging the gap between gains in efficiency and adaptation, against the relationship between applications vs. full-scale integration are a major concern of public adoption. BIPV's future lies in its potential as a ubiquitous energy material that architecturally adapts and applies its energy duality (both passive and active) into built environment and its electrical infrastructure.

At the very beginning of this dissertation I started with a quote by the visionary builder Buckminster Fuller. I will also end with one. Fuller's tombstone reads, "Call me Trimtab." What a trimtab is is an aeronautical airfoil or adjustable tab on the back of a ship's rudder, which controls the entire ship or plane. It is smallest object that had the largest impact on its overall host. BIPV in its current power potential utilizes this philosophy. It is a small cog in the overall energy picture but engaged correctly in the right places within the building envelope it can have a considerable impact on the overall power system. This is BIPV's enduring legacy and attraction to architects when integrated into the building's for utilized efficiency, building energy autonomy and aesthetic exploration.

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[167] E. B. Ettah, "The Effect of Relative Humidity on the Efficiency of Solar Panels in Calabar, Nigeria", pg 8.

Bibliography

Adler, Anderson. *Green Building: Project Planning & Cost Estimating.* Hoboken: RSMeans, 2011, 3rd edition.

C., Mora, Frazier A.G., Longman R.J., Sanchez J.J., Kaiser L.R., Stender Y.O., Giuseffi L.M., Giambelluca T.W., Dacks R.S., Walton M.M., Anderson J.M., Ambrosino C.M., Tong E.J., Fernandez-Silva I. "The Projected Timing of Climate Departure from Recent Variability." *Nature* 502 (2013): 183-187.

Central Intelligence Agency. "The World Factbook - Country Comparison:: Population." Accessed August 24, 2014. https://www.cia.gov/library/publications/the-world-factbook/rankorder/2119rank.html.

Clark Construction Group, LLC."Caltrans District 7 Headquarters." Last modified 2014. http://www.clarkconstruction.com/our-work/projects/caltrans-district-7-headquarters.

Clean Technica. "Hawaii Residents Raise Serious Concerns About PGV, Geothermal Energy's Clean Energy Credentials." Last modified April 28, 2012. http://cleantechnica.com/2012/04/28/hawaii-residents-raise-serious-concerns-about-pgv-geothermal-energys-clean-energy-credentials/.

Council of Economic Advisers. "The Cost of Delaying Action To Stem Climate Change." Last modified July 2014. http://www.whitehouse.gov/sites/default/files/docs/the_cost_of_delaying_action_to_stem_climate_change.pdf.

Ettah, E. B., Udoimuk A.B. and Obiefuna, J.N., "The Effect of Relative Humidity on the Efficiency of Solar Panels in Calabar, Nigeria", Universal Journal of Management and Social Sciences, http://cprenet.com/uploads/archive/UJMSS_12-121.pdf

Energy Informative. "NREL Sets New World Record with Two-Junction Solar Cell." Last modified August 29, 2013. http://energyinformative.org/nrel-efficiency-record-two-junction-solar-cell.

Fairley, Peter "10 U.S. Cities Tackle Efficiency", The Big Issue, Architectural Record, McGraw Hill Construction, March 2014.

First Wind. "Clean Energy. Made Here." Last modified August 27, 2014. http://www.firstwind.com/.

Frechette III, Roger E. and Russell Gilchrist. 2008. *Towards Zero Energy: A Case Study of the Pearl River Tower, Guangzhou, China, March 3 - 5, 2008*. Dubai: CTBUH 8th World Congress.

Friedman, Thomas L. *Hot, Flat, and Crowded: Why We Need a Green Revolution-- and How it can Renew America*. New York: Farrar, Straus and Giroux, 2008.

Gaiddon, Bruno, Henk Kaan, and Donna Munro. *Photovoltaics in the Urban Environment Lessons Learnt From Large-Scale Projects.* London: Earthscan, 2009. http://public.eblib.com/choice/publicfullrecord.aspx?p=471073.

Global Village Institute for Appropriate Technology. "Solar Radiation Data." http://www.i4at.org/lib2/solarrad.htm.

Grondzik, Walter T. *Mechanical and Electrical Equipment For Buildings.* Hoboken, N.J.: Wiley, 2010.

Hawaii Department of Business, Economic Development and Tourism. "Hawaii Commercial Building Guidelines for Energy Efficiency." http://energy.hawaii.gov/wp-content/uploads/2011/10/CommercialBuildingsGuidelinesforEnergyEfficiency2004.pdf.

Hawaii Energy. "Solar Map Oahu." http://hawaiienergy.com/images/contractors/OahuSolarMap65f1.pdf.

"Hawaii Is Diverse, But Far From A Racial Paradise." Narrated by Liane Hansen. Weekend Editition. *NPR,* November 15, 2009. http://www.npr.org/templates/story/story.php?storyId=120431126.

Hawaii State Energy Office. "Hawaii Energy Statistics." Hawaii Energy Facts and Figures, November 2014 Edition. http://energy.hawaii.gov/resources/dashboard-statistics.

Hebert, Paul D.N. "Pacific Ocean." Last modified May 13, 2013. http://www.eoearth.org/view/article/155111/.

HECO. "Power Facts." Last modified September 2002. http://www.heco.com/vcmcontent/FileScan/PDFConvert/PowerFacts.pdf.

Henson, Jesse Wolf Corsi. "The Building Side of Building Integrated Photovoltaics." *SolarPro*, December/January 2010 Issue 3.1. http://solarprofessional.com/articles/products-equipment/modules/the-building-side-of-building-integrated-photovoltaics.

Howes, Craig and Jon Kamakawiwo'ole Osorio. *The Value of Hawai'i Knowing the Past, Shaping the Future.* Honolulu: University of Hawai'i Press, 2010.

Intergovernmental Panel on Climate Change. "Climate Change 2014: Impacts, Adaptation, and Vulnerability." Last modified March 31, 2014. http://ipcc-wg2.gov/AR5/.

Kaan, Henk, and Tjerk Reijenga. 2004. "Photovoltaics in an Architectural Context". *Progress in Photovoltaics: Research and Applications* 12, no. 6 (2004): 395-408.

Kind, Peter. *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electrical Business.* Washington, D.C.: Edison Electric Institute, 2013.

Krippner, Roland. “Solar Technology in Building Envelopes.” *Detail*, July 2012.

Kroh, Kiley. “74% Generation - Germany’s Record Renewables Day.” *Business Spectator,* May 15, 2014. http://www.businessspectator.com.au/article/2014/5/15/wind-power/74-generation-%E2%80%93-germanys-record-renewables-day.

Krymsky, Yan. *Responsive Skins An Exploration of Paratonic Surfaces in Architecture* (blog). https://yazdanistudioresearch.wordpress.com/2013/01/13/a-new-way-of-visualizing-solar-radiation/#more-1021.

Kuykendall, Ralph S. *The Hawaiian Kingdom, 1874-1893: The Kalakaua Dynasty*. Honolulu: University of Hawaii Press, 1967.

Lawrence Livermore National Laboratory and the Department of Energy. “Estimated U.S. Energy Use in 2013: ~97.4 Quads.” Flowcharts. https://flowcharts.llnl.gov/content/energy/energy_archive/energy_flow_2013/2013USEnergy.png.

Lazard. “Lazard’s Levelized Cost of Energy Analysis – Version 8.0.” Last modified September 2014. http://www.lazard.com/PDF/Levelized%20Cost%20of%20Energy%20-%20Version%208.0.pdf.

Lee Seung-Hwan and Lorenz Robert, “Development and valiadaiton of Model for 95%-Efficiency 220-W Wireless Power Transfer Over a 30-cm Air Gap”, IEEE, University of Wisconsin, Madison, November/December 2011.

Lovins, L. Hunter. “ Rethinking Production.” In *State of the World 2008*, edited by Linda Starke, 32-44. New York: W.W. Norton & Company, 2008.

Montgomery, James. “SunPower Tops in Mono C-Si Cell Efficiency.” *Renewable Energy World,* March 29, 2012. http://www.renewableenergyworld.com/rea/news/article/2012/03/sun power-tops-in-mono-c-si-solar-cell-efficiency.

Morphopedia. “Caltrans District 7 Headquarters.” Last modified April 5, 2012. http://morphopedia.com/projects/caltrans-district-7-headquarters.

National Renewable Energy Laboratory (U.S.). 2011. “HCEI road map.” Golden, CO: U.S. Dept.of Energy, National Renewable Energy Laboratory. http://purl.fdlp.gov/GPO/gpo13682.

Oakley, David*. Tropical Houses: A Guide To Their Design.* London: Batsford, 1961.

O’Connor, Jennifer. “Survey on actual service lives for North American buildings.” Presented at Woodframe Housing Durability and Disaster Issues conference, Las Vegas, October 2004. http://www.woodworks.org/wp-content/uploads/2012/02/fpi-survey-actual-service-lives.pdf.

Olgyay, Aladar, and Victor Olgyay. *Solar Control & Shading Devices*. Princeton: Princeton University Press,1957.

Ormat Technologies Inc.“Puna.” Last modified 2015. http://www.ormat.com/case-studies/puna-geothermal-venture-hawaii.

Pacific Office Properties. “Pacific Davies Center.” Accessed February 2, 2015. http://www.pacificofficeproperties.com/p_honolulu_2.htm#.

Pagliaro, Mario, Giovanni Palmisano, and Rosaria Ciriminna. *Flexible Solar Cells.* Weinheim: Wiley-VCH, 2008.

Pawlyn, Michael. *Biomimicry in Architecture.* London: Riba Publishing, 2011.

Reilly, Steve. “Bracing for a Big Power Grid Attack: ‘One is Too Many.’” USA Today, March 24, 2015.

Renewable Fuels Association. “World Fuel Ethanol Production.” Last modified 2015. http://ethanolrfa.org/pages/World-Fuel-Ethanol-Production.

Reuters. “Last Year Was Earth's Hottest On Record, U.S. Scientists Say.” Accessed January 16, 2015. http://in.reuters.com/article/2015/01/16/earth-climate-idINL1N0UV17420150116

Roaf, Susan. “BIPV: High on the Agenda for Survival.” Paper presented at the 14th Sede Boqer Symposium on Solar Electricity Production, February 19-20, 2007.

Roberts, Simon, and Nicolò Guariento. *Building Integrated Photovoltaics: A Handbook*. Basel: Birkhäuser, 2009. http://public.eblib.com/choice/publicfullrecord.aspx?p=511239.

Roth, Leland M. *Understanding Architecture: Its Elements, History, and Meaning.* New York: Icon Editions, 1993.

SANYO Energy U.S.A. Corp. “Bifacial Photovoltaic Module.” Last modified September 1, 2008. https://www.hepn.com/assets/files/renewables/rushshelby_sanyo.pdf.

Shockley, William, and Hans J. Queisser. 1961. "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells". *Journal of Applied Physics* 32, no. 3 (1961): 510.

Smith, Adrian D. and Gordon Gill, *Towards Zero Carbon: The Chicago Central Area DeCarbonization Plan.* Mulgrave: Images Publishing, 2011.

Smith, Kristine. “Northumbria Is Solar Panel Test Ground.” *Construction News,* January 19, 1995. http://www.cnplus.co.uk/news/northumbria-is-solar-panel-test-ground/953402.arti lc.

Solar Energy Research Institute of Singapore. “Annual Report 2013.” http://www.seris.sg/Seris/Publications/AnnualReport.html.

Solar Insolation.Org. “Solar Insolation.” Last modified January 15, 2012. http://solarinsolation.org/.

Solemma. “DIVA-for-Rhino.” http://www.solemma.net/DIVA-for-Rhino/DIVA-for-Rhino.html.

Stack Exchange: Physics. “PV Cell For Invisible Spectrum Only.” Accessed February 5, 2015. http://physics.stackexchange.com/questions/31215/pv-cell-for-invisible-spectrum-only.

Stang, Alanna and Christopher Hawthorne. *The Green House: New Directions in Sustainable Architecture.* New York: Princeton Architectural Press, 2005, 160.

Strong, Steve. Building Integrated Photovoltaics (BIPV), Solar Design Associates, Whole Building Design Guide, Last Modified December 27, 2011. http://www.wbdg.org/resources/bipv.php

“The Future of Amphibious Warfare; War Games.” YouTube video, 13:10. Posted by “Vice News,” September 2, 2014. https://www.youtube.com/watch?v=P5f-Bt3DXfU&list= UUZaT_X_mc0BIdjXOlfhqWQ&src_vid =bYG1qccSUAw&fea ture=iv&annotation_id=annotation_4190727581.

The Weather Channel. “New Solar Plants are Incinerating Birds.” Last modified August 18, 2014. http://www.weather.com/news/solar-plants-birds-20140818.

Triple Pundit. “Tidal Power: Pros and Cons.” Last modified June 1, 2012. http://www.triplepundit.com/2012/06/tidal-power-pros-cons/.

UHERO Hawaii. “UHERO: Tax Credit Incentives for Residential Solar Photovoltaic in Hawai’i.” *A*ccessed January 22, 2015. http://www.uhero.hawaii.edu/assets/UHERO-PolicyBrief-SolarTax.pdf.

UH News. “Study in Nature Reveals Urgent New Time Frame for Climate Change.” Last modified October 9, 2013. http://www.hawaii.edu/news/2013/10/09/study-in-nature-reveals-urgent-new-time-frame-for-climate-change/.

United Nations. 1982. World Population Prospects. New York: United Nations Department of International, Economic and Social Affairs. http://esa.un.org/wpp/. (YEAR 1982???)

UNSW Australia. “UNSW Researchers Set World Record in Solar Energy Efficiency.” Accessed December 15, 2014. http://newsroom.unsw.edu.au/news/science-technology/unsw-re searchers-set-world-record-solar-energy-efficiency.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. *Building-Integrated Photovoltaics (BIPV) in the Residential Sector: An Analysis Of Installed Rooftop System Prices,* by Ted James, Alan Goodrich, Michael Woodhouse, Robert Margolis, and Sean Ong.

Technical Report November 2011, National Renewable Energy Laboratory. Golden, Colorado, 2011. http://purl.fdlp.gov/GPO/gpo16397.

U.S. Department of Energy, Office of Science and Technical Information. *The Silicon Solar Cell Turns 50,* by John Perlin. National Renewable Energy Laboratory. Golden, Colorado, 2004. http://www.osti.gov/servlets/purl/15009471-Jg9qgS/native/.

U.S. Energy Information Administration. "AEO2014 Early Release Overview." Analysis and Projections. http://www.eia.gov/forecasts/aeo/er/index.cfm.

U.S. Energy Information Administration. "Electric Power Monthly." Data for November 2014. http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a.

U.S. Energy Information Administration. "How Much Electricity is Lost in Transmission and Distribution in the United States?" Frequently Asked Questions. http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3.

U.S. Environmental Protection Agency. "Heat Island Effect." Last modified July 31, 2014. http://www.epa.gov/heatisland/.

U.S. Global Change Research Program. "National Climate Assessment 2014." http://nca2014.globalchange.gov/.

U.S. Green Building Council. "LEED." Accessed September 4, 2014. http://www.usgbc.org/leed.

Washington Post. "World's Population Unlikely to Level Off Anytime Soon — May Hit 12 Billion by 2100." Accessed September 22, 2014. http://www.washingtonpost.com/national/health-science/worlds-population-unlikely-to-level-off-anytime-soon-may-hit-12-billion-by-2100/2014/09/22/aa6689a0-3f68-11e4-9587-5dafd96295f0_story.html.

Wei Lai Jian Zhu Za Zhi She. Chui Zhi Mi Du. *Vertical Density 2. [The Need For Tall Buildings in the City]* 2, 2. Dalian: Dalian Li Gong Da Xue Chu Ban She, 2012.

World Health Organization Western Pacific Region. "Tobacco in China." WHO Representative Office China. Accessed May 10, 2014. http://www.wpro.who.int/china/mediacentre/factsheets/tobacco/en/.

Zomer, Clarissa, André Nobre, Pablo Cassatella, Thomas Reindl, and Ricardo Rüther. "The Balance Between Aesthetics and Performance in Building-Integrated Photovoltaics in the Tropics". *Progress in Photovoltaics: Research and Applications* 22, no.7 (2014): 744-756. http://onlinelibrary.wiley.com/doi/10.1002/pip.2430/full.