FOUNDATIONS FOR EVALUATING SOLAR PHOTOVOLTAIC ENERGY AS A VIABLE RESOURCE IN HAWAI'I: TECHNICAL, POLICY, AND BUSINESS INVESTIGATIONS

by

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Approved: ______________________________

Professor Gregory Bothun

Solar photovoltaic technology (PV) has great potential to facilitate a transition to sustainable energy generation in the state of Hawai'i. In addition, it may help alleviate high energy costs, due to competition with fossil fuels and financial incentives from the government meant to encourage adoption. I begin to explore the feasibility of PV as an energy resource in Hawai'i, from the standpoints of technical functionality and the political/economic/business landscape. To assess the former, I created a simulation of a PV system; I assess the simulation's accomplishments and areas for future improvement. To assess the latter, I observed the evolution of the business climate, through conversations with stakeholders and attention to current events. The results of both investigations can serve as a foundation for future research efforts relating to these issues.

Acknowledgements

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Finally, I would like to thank Miriam Alexis Castellon Jordan, for guiding me through the formal process of planning and completing my Thesis project.

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A Note on Spelling

The attentive reader will notice that I use two variants of spelling for words in the Hawaiian language. For example, at one point in the text I will write the word "Hawai'i," and one sentence later I will write "Hawaii."

The former spelling style is technically correct (Trapp), although it differs from the spelling style used in many of the references that I have consulted.

Out of respect for the people and culture of Hawai'i, I use the "Hawai'i" spelling style by default. Out of respect for the other giants on whose shoulders I stand, I use the "Hawaii" spelling style when quoting sources that use it.

1. Executive Summary

This Thesis attempted to examine the feasibility of PV installations in Hawai'i, and to provide the groundwork for future examinations. Hawai'i was chosen as a specific site of interest due to its burgeoning solar energy industry. As the cost of mostly imported fossil-fuel energy is very high (adding to a generally high cost of living), state and federal tax incentives make PV installation a lucrative possibility for families looking to save money, resulting in a robust and growing commercial infrastructure for the wide-scale deployment of PV.

In order to conduct such an assessment, a quantitative simulation of PV output was produced and tested. The model focused on the simulation of a single PV panel, by treating the panel as an electrical circuit whose relevant quantities could be determined from a datasheet. It was set up to assemble a differential equation for panel temperature with respect to time, assuming panel temperature to be the same as *p*-*n* junction temperature. The numerical solution for panel temperature would then be used to obtain the output power, efficiency, and other factors used to check the model's performance. (This order of steps is necessary, as temperature adversely affects panel efficiency.) The panel modeled was the SolarWorld Sunmodule SW 245 polycrystalline panel with a Version 2.5 Frame. The model's inputs came from data from instruments in Hawai'i operated by the National Renewable Energy Laboratory (NREL), correcting for an assumed panel tilt angle of 20° with respect to the horizontal, in addition to reflection by the panel (as described in Appendices E and F respectively).

The simulation thus produced did return sensible results for general trends in fill factor, short-circuit current, open-circuit voltage, and diode saturation current.

However, it predicted panel temperatures that were cozily in the range of ambient temperature variation. This is contrary to measured results. Correcting this problem thus presents itself as an avenue of possible development for future projects. Other future endeavors could attempt to adjust the code to accurately model connections to electrical grids or stand-alone systems, or to respond to the various environments within Hawai'i. The latter may be a critical variable, as changes in climate and season may affect radiative transfer, ground albedo (for irradiance that is reflected back form the ground), and the effects of wind, rain, and convection on panel heating/cooling.

In tandem with this research, I also had the good fortune to be able to speak with representatives of the solar business, solar consumer, and institutional stakeholder groups, while I simultaneously became more aware of current events related to solar power. I have gleaned what I perceive to be the intentions and attitudes held by each stakeholder regarding the other. These beliefs can create conflict: for example, on O'ahu, Hawaiian Electric Company's obligations to ensure product reliability and safety, and to prevent abuse of the system, have led it to support limits on state tax credits and to propose charging new residential installers for grid-connection studies. On the other hand, the PV industry sees these efforts as a threat to its customer base and its ability to do business, and customers see them as an obstacle to saving money on energy. I make the observation at the end of the main text that in instances in which stakeholders do not get along, the future viability of PV technology becomes uncertain. Furthermore, income inequality amongst customers could lead to a situation in which those who have more income benefit more from the solar industry. The mere existence of PV as an energy solution determines neither chances of success, nor the nature of its success.

This Thesis therefore provides analytical tools that can possibly be used as part of future research efforts, in order to better understand the technical and political feasibility of PV in Hawai'i.

2. Hawai'i's Energy Situation

2.1 Introduction

This chapter will discuss the practical motivation of this Thesis project, "Evaluation of solar photovoltaic energy as a viable resource in Hawai'i: technical, policy, and business perspectives." It describes the necessity of finding cheaper energy sources in for Hawai'i energy customers, and relates the progress of efforts to introduce sustainable energy sources, into Hawai'i's energy supply. Finally, it focuses on the potential of solar photovoltaic energy as a major resource with a well-developed commercial infrastructure.

This chapter lays the groundwork for future chapters that explore the technical feasibility of photovoltaic systems, and the favorability of the policy, economic, and business climates within Hawai'i toward their widespread adoption.

2.2 The Cost of Energy in Hawai'i

During a renewable energy-related trade show last year in Hawai'i, I walked to a booth that contained a display of Hawai'i's energy costs compared with costs in other parts of the country. I remember that the comparison was quite dramatic, although I do not remember precisely what the numbers were.

Indeed, official U.S. government figures back up the idea of such a disparity. Data from the U.S. Energy Information Agency states that "the people of Hawaii [*sic*] pay the highest electricity rates at 37 cents per kilowatt hour, triple the national average of 12 cents per kilowatt hour" (Murakami). This has very concrete effects for energy customers. As journalist Kery Murakami puts it, “[t]hat translates into bills that are two, three or even four times those in other states” (Murakami).

A 2009 study attempted to explain the high cost of electricity. Energy prices in Hawai’i were higher than on the Mainland: “more than twice the U.S. average” (Arent et al 1). The main culprit for this was the price of fossil fuels. Doug Arent et al of the National Renewable Energy Laboratory (NREL) notes that “[N]early 90% of [Hawai’i’s] primary energy resources [come] from oil” during 2009 (Arent et al 1). Thus, if oil suddenly became more expensive, so did the price of electricity (Arent et al 1-2). A 2014 article from the U.S. Energy Information Agency also makes this connection, noting that the proportion of energy generated from fossil sources is now down at 70%, although it remained near 90% through 2008 (Shear).

The expense of energy is compounded by other extreme everyday expenses. In fact, the U.S. Commerce Department Bureau of Economic Analysis judged Hawai’i to have the highest cost of living in the entire nation in June 2013 (Murakami). The cost is so high that people who “would be comfortably middle class” on the mainland end up “qualify[ing] for housing assistance on Oahu” (Murakami). Reducing the cost of electricity would therefore help alleviate a significant burden on Hawai’i residents. Arent et al conclude that renewable sources “are also cost competitive in most cases,” based on data from 2009 (Arent et al 5).

2.3 The Push for More Renewable Energy Sources

Powerful entities are attempting to implement a change from this picture to one more dominated by non-fossil-fuel sources. The state itself has adopted the Hawai’i

Clean Energy Initiative, a push to enable Hawai'i to survive on homegrown energy (Hawai'i Clean Energy Initiative, "About"). The Initiative's specific objectives are to "be more independent and less reliant on other economies," to "achieve greater security," to "help Hawai'i become more economically stable by keeping an estimated $6 billion in state that would otherwise go toward foreign oil investments," to "[e]stabli[sh] a new, green economic sector [that] will counter-balance [Hawai'i's] reliance on tourism and the military," and to "position Hawai'i as a worldwide leader in the clean energy category (…) that will attract more business and expertise to the region" (Hawai'i Clean Energy Initiative, "Hawai'i Is The Most") These objectives help to address economic, security, and scientific problems of fossil fuels (although not directly confronting the economic problems outlined above).

Many pro-fossil-fuel activists on the U.S. Mainland consider the virtues of such resources as natural gas as an easy way for the United States to achieve precisely these objectives (e.g. (Rosen)). However, because Hawai'i has no local fossil fuel extraction projects (Arent et al 1), methods involving such local extraction are out of the question. Instead, Hawai'i plans to achieve its goals through shifting the balance of Hawai'i's energy supply, so that "*70%*" of the state's energy comes from "*clean*" sources "*by 2030*" [italics in source] (Hawai'i Clean Energy Initiative, "Hawai'i Is The Most"). The specific breakdown that the Initiative aims for is as follows: "*30% from efficiency* measures, and *40% coming from locally generated renewable* sources" (Hawai'i Clean Energy Initiative, "Hawai'i Is The Most").

HEI serves five of the major islands: "Oahu, Maui, Hawaii Island, Lanai and Molokai" (Hawaiian Electric Industries, "About"). The other three major islands, Kaho'olawe, Kaua'i and Ni'ihau, are *not* served by HEI, but they are making progress toward increased adoption of renewable energy. Kaho'olawe had been used as a firing range for half a century, until it was "returned (…) to the state" (Guiterrez). Activists have been working "to (…) clean unexploded ordinance from the island" (Guiterrez). An additional piece of restoration, however, may come from the installation of renewable energy generating facilities on the island. The local government has approved "funds (…) to finance the construction and installation of a photovoltaic system to generate power for two volunteer huts located at a restored Navy base camp at Honokanai'a Bay" (Maui Now Staff).[1] Another island, Kaua'i operates under its own utility, the Kaua'i Island Utility Cooperative (KIUC). KIUC aims to have half of Kaua'i's energy come from renewable sources "by 2023 or sooner," and for "prices" to be "stabilize[d]," for Kaua'i to "be competitive with Hawaii's other islands and [to] disconnect electricity cost from volatile oil prices" (Kaua'i Island Utility Cooperative) - much along the lines of the stated objectives for the Hawai'i Clean Energy Initiative. Ni'ihau is radically different from the other islands (except perhaps Kaho'olawe), in that it is purely rural and traditional, with essentially "no electricity" whatsoever (Wachman). However, there has nonetheless been some penetration of solar power within Ni'ihau, as there is a school there that not only receives electricity, but does so through solar photovoltaic technology (Ni'ihau Cultural Heritage Foundation). It is clear, then, that there is a truly statewide push for renewable energy.

[1] One person wants to take installation even further. Derek "Kekaulike" Mar has proposed using "wind and solar power" technologies to make electricity and sell it elsewhere within Hawai'i, thereby making money for future restoration efforts (Guiterrez).

It is stated above that HEI administers Lana’i’s power system; however, it is worth mentioning Lana’i has recently transferred hands, from its previous owner David Murdock to Larry Ellison (“CEO of the business software firm Oracle”), who plans to make Lana’i run on solely on solar energy technology (NBC News staff and wire services).

2.4 Results Thus Far of Efforts to Green the State’s Power Supply: Opposition and Triumph

The efforts listed above all state specific objectives or achievements to be met. In order to evaluate these efforts, one must evaluate the ability of the organizations involved to meet these objectives.

The utilities’ efforts have not been entirely successful. Both HEI’s and KIUC’s plans have been met with resistance. The concerned group “Friends of Lana’i” opposes the wind farm that the company Castle & Cooke proposed to build on Lana’i. They cite concerns over damage to the ecosystem and environment and cultural sites, the nonexistent monetary rate of return for Lana’i and the low energy yield for O’ahu, and the fear that “[this] sets a precedent of using the Neighbor Islands as an industrial park for Oʻahu. Were this project to succeed, what would prevent Oʻahu from planting additional wind generators — or storing garbage — on Lānaʻi?” (Friends of Lana’i). Concerns over Kaua’i’s plan to include smart meter technology focused on “privacy,” “health,” employment, the environment, and the fear that consumers would be extorted via “opt out fees” (“Why Stop Smart Meters?”). In the context of smart metering, an op-out fee is a fee that one pays for not installing a smart meter (Henry). However, the cooperative’s members have voted *not* to get rid of these fees (Star-Advertiser staff).

Furthermore, the Hawai'i Clean Energy Initiative currently lists thirty-eight alternative energy generation projects throughout the state that it intends to pursue. These projects are based on Kaua'i, O'ahu, Maui, Moloka'i, and the island of Hawai'i, and utilize "[b]iofuel," "[b]iomass," "[g]eothermal," "[h]ydroelectric," "[o]cean," "[s]olar," "[w]aste-to-[e]nergy," and "[w]ind" sources ("Hawaii Renewable Energy Projects Directory").

2.5 The Potential of Photovoltaic Energy as a Viable Resource

One energy resource in particular seems to be promising. Photovoltaic, or PV, power relies on converting sunlight into electrical energy. (The mechanism by which this happens will be discussed in the next chapter.) Due to exposure to high levels of sunlight, Hawai'i has a high natural potential for PV power. In addition to purely technical promise, PV also enjoys support through official policy (at least for the time being) and a robust existing commercial infrastructure.

Currently, a tax incentive exists for PV installations, "intended to make solar competitive with current electricity prices and are matched by a federal tax credit that covers 30 percent of the system cost" (Cocke, "Hawaii's Booming") The precise amount of this tax credit had been "35 percent credit for the system's cost or a $5,000 refund, whichever is less" for residences and "35 percent or $500,000, whichever is less" for companies (Cocke, "Hawaii Tax Department"). Additionally, new single-family homes built in Hawai'i are required to have solar water heating ("Solar Water Heating Requirement for New Residential Construction").

A wide variety of companies are involved in Hawai'i's solar energy industry. Some are nationwide (e.g. SolarCity (SolarCity Corporation)) or multinational (e.g. ABB (ABB; Hawaii Solar Energy Association) but many of them are local (Hawaii Solar Energy Association). Many of these local companies operate on more than one island (e.g. Inter-Island Solar Supply (Hawaii Solar Energy Association; Inter-Island Solar Supply)).

PV technology is furthermore an active area of local academic research. The Hawai'i Natural Energy Institute, a research center at the University of Hawai'i, conducts empirical studies of sample "installations," incorporation of PV in built structures, the effects of attaching large PV installations to the electrical system, and the performance of an important device called an "inverter" (Hawaii Natural Energy Institute), about which more will be said in the next chapter.

There are, however, certain questions about PV technology, as applied to Hawai'i that should still be answered. Can PV actually provide sufficient energy to allow Hawai'i to meet the goals set out by the Hawai'i Clean Energy Initiative? Even if PV is technically capable, are the policy, economic, and business conditions favorable for its wide-scale adoption?

There is precedent for worrying about these issues. Nuclear fusion has long been touted as a clean energy source for the future, something that can provide a great deal of energy at very little environmental cost. Yet challenges related to the physics of fusion and the engineering of a fusion reactor have proven extraordinarily difficult to surmount, thus bursting many predictions of a fusion-fueled early twenty-first century (Sample). Nuclear *fission*, on the other hand, is a power resource that is demonstrated to be both and (when working properly) clean. However, high-profile disasters such as Three-Mile Island, Chernobyl, and Fukushima-Daiichi have turned much of the public against the option of fission (Holyk and Langer). If one is to say that PV is a viable energy resource for Hawai'i, one must be able to justify that on grounds of both feasibility and acceptability.

2.6 Conclusion

Solar PV technology appears to be very promising, as there is a vibrant industry within Hawai'i built around its distribution and installation, and because policy up to this date has been quite friendly toward PV's adoption.

In order to assess PV's future, though, one must be able to predict PV's performance as an energy generator, and its ability to survive in the real world of policy and commerce. In subsequent chapters I will work toward answering these questions, with Chapters 3 and 4 dedicated to the first one, and Chapter 5 to the second.

3. A Physical Description of PV Functionality

3.1 Introduction

Having laid out the challenges that Hawai'i's power customer's face, and possible means by which the situation may change, it is now time to begin discussing one of the potentially big players in the push to make the state more reliant on renewable energy. As mentioned in the previous chapter, solar photovoltaic (PV) technology appears to be a promising energy resource, thanks to government policy and the existence of a substantial industry in Hawai'i built around the selling, renting, and installation of PV systems.

Yet it is one thing to say that PV is promising from the penetration standpoint (i.e., the large number of people adopting it as an energy solution); it is another to state that PV can actually meet Hawai'i's energy needs. This question can most expediently be solved by building a computer simulation of a PV system installed in Hawai'i.

For this simulation to be accurate, it must faithfully take into account the physical and chemical principles that govern the operation of a PV system. I will describe these principles in this chapter. In the following chapter I will explain the construction of my simulation, and relate and interpret its results.

The reader should note that this chapter's treatment is mostly qualitative. While it discusses physical principles, it does so while invoking almost no equations. A more mathematical treatment of these subjects is given in the Appendices.

3.2 Physics of PV

We know that a photovoltaic (PV) system produces electricity when placed out in sunlight. This section hopes to illustrate just how this process works

What happens in a PV system is essentially the following. Sunlight carries energy with it. When this energy comes into contact with certain materials, it can enable electrons within the material, which may normally not be very mobile, to move around freely. These electrons can then be used to power devices that are connected to the PV system. In this way, energy from the sun is converted into useful energy for human life.

With this overview in mind, I will now explain the detailed physics behind PV technology.

3.2.1 The Photovoltaic Effect

Most of the time, the electrons in matter (like the material of a PV cell) are bound in some way to protons. This binding happens because electrons have a negative electrical charge, and protons have a positive electrical charge: opposite charges attract. The types of bonds that one sees in nature are fairly diverse (Silberberg 328-415), but it is safe to say that as long as no charge is added to or taken away from an object, there will be one electron for every one proton.

The photovoltaic effect demonstrates how this bond can be broken. As stated above, sunlight can make an electron move by giving it energy. This movement splits up the electron from its corresponding proton, leaving behind a positively-charged “vacancy” called a “hole,” an apt name because it denotes the lack of an electron (Nelson 44-46). The hole remains at a lower energy, and can be treated as an actual physical particle (Nelson 46). Since electricity derives from the movement of electrons, then it is desirable to let the photovoltaic effect energize many electrons, and then harvest these electrons to provide power (Nelson 11).

It turns out, though, that the photovoltaic effect needs *just the right amount of energy* to work. Light with too little energy will not do anything to the electron, and will instead end up as waste heat (Tiwari and Dubey 103-104). Light with more energy than what is required will work, but the excess energy will go to waste (Tiwari and Dubey 103-104). This is because an electron's energy can only be within certain *energy bands*, ranges of allowed energies with gaps in between (Nelson 42-44). Fig. 3.1 shows an example of such a scheme. Transitioning between energy bands is like climbing down stairs, from one elevation to another. Yet whereas a human can exist in intermediate heights between steps, an electron *cannot* exist between energy bands (Nelson 42-44). It would be like having to *teleport* between steps on a staircase. The amount of energy necessary to move an electron from one band, the "valence band," to the other, the "conduction band," is called the "bandgap energy" (Nelson 42-44).

One can use the bandgap energy to explain why semiconductors are so widely used in PV cells. A semiconductor's bandgap energy is between that of a metal and that of a nonmetal. A metal is a very good electrical conductor: electrons in a metal are easy to move and use. Correspondingly, the bandgap energy in a metal is lower than that in a semiconductor, and so one can get more electrons out of a metal than out of a semiconductor, from the same amount of light. The disadvantage of doing this is that the metal's electrons have less energy, since less is necessary to get them loose in the first place. (In fact, some electrons in a metal don't need to be kicked loose at all.) One

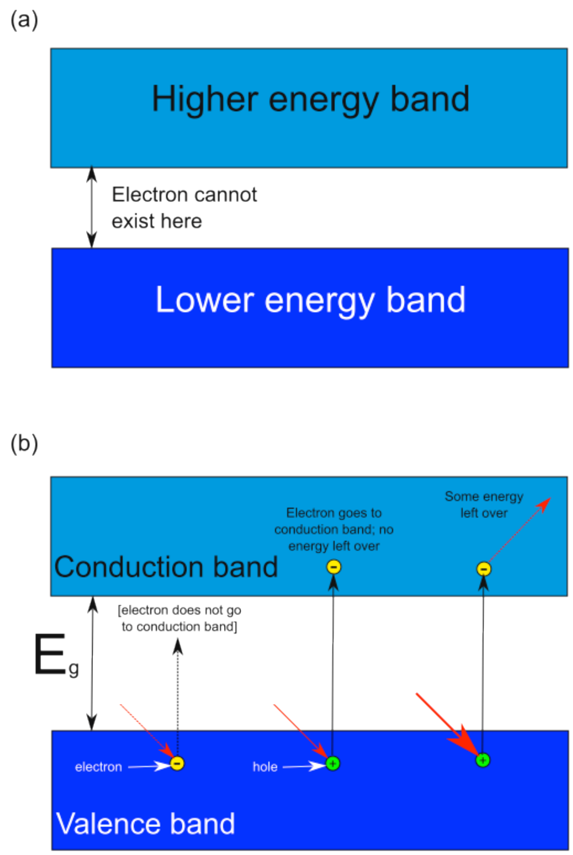


Fig. 3.1 A diagram of the photovoltaic effect, from the standpoint of energy bands

(a) An illustration of energy bands within a solid, in which one band represents ways that an electron can exist at a lower energy, and the other represents ways that it can exist at a higher energy. The two bands are separated by a gap, in which the electron cannot exist at all.

(b) A photon can loosen up an electron and sent it from the lower-energy band to the higher-energy band, if it has enough energy to do so. If it does not have enough energy, then the photon does not cross the bandgap E_g, and that photon remains in the cell as waste heat. If a photon has just the right amount of energy, then the electron will move upward, and no energy will be left over. If the photon has *more* than enough energy, then the electron will still move upward, but the energy that it did *not* use will stay in the cell as waste heat.

Parts (a) and (b) based on Figs. 2.6, 3.1, and 3.7 of Jenny Nelson, *The Physics of Solar Cells* (London: Imperial College Press, 2003; print; 29; 42; 51).

could alternatively use a nonmetal, which is a poor electrical conductor and which has a high bandgap energy compared with that of a semiconductor. The problem *here* is that while the electrons from a nonmetal would have more energy, there would be fewer of them. So a semiconductor presents a useful “middle ground” between electron number and electron energy (Nelson 42-44, Masters 453-455).

An additional problem presents itself. Electrons raised to the conduction band tend to want to fall back down to the valence band, or “recombin[e]” with their holes (Nelson 81). This cannot happen if the electrons are to be harvested. A solution is required.

3.2.2 The p-n Junction

It turns out that there is a way to turn a piece of semiconducting material into an object that produces either an excess of mobile electrons or holes when exposed to light. If we put such an electron-producer next to a hole-producer, the result will be a spatially-separated batch of electrons and holes, which is a desirable outcome.

As mentioned in §3.2.1, there are multiple ways to bond electrons and protons. One way is for the nucleus, the clump of protons at the center of each atom, to “shar[e]” electrons with another nucleus (Silberberg 330). This is the bonding scheme present in semiconductors (Nelson 42-44). (There are other possible bonding schemes, but those are beyond the scope of this paper.) One can consider silicon, which has four electrons around each nucleus, and can therefore share all of its electrons with other silicon atoms while accepting one electron from four other such atoms (Nelson 42-44)

Now, suppose one were to add in some phosphorous atoms. Phosphorous has five electrons that it can share, and it has room for three electrons from other atoms. A phosphorous atom surrounded by silicon atoms therefore has an extra electron. This electron is at a higher energy than the electrons near it, and so can be more easily raised into the conduction band. Physicists describe these sorts of additions as *doping*, and say that the substances added to the semiconductor are *impurities*. Specifically, a semiconductor doped in the way just described is *n-doped*, where the *n* stands for *negative* (i.e. the electron's charge) (Nelson 62-63).

On the other hand, suppose one were to add in some boron atoms. Boron is basically a flipped version of phosphorous: it has three electrons to share, and it can accept five from other atoms. This means that it ends up with one electron short, when surrounded by silicon atoms. Boron consequently has a hole, in the sense described in §3.2.1. This hole exists at a higher energy than its surrounding electrons, and, as with the electron, can easily be knocked loose. We call a material doped in this fashion a *p-doped* material, where the *p* stands for *positive* (i.e. the holes' charge) (Nelson 63-64).

If we put a *p*- and an *n*-doped material next to each other, we have a "*p-n* junction" (Nelson 145). If we expose this junction to light, we will end up with a device that produces a lot of current when hooked up to a (non-solar energy) source the correct way, and that will produce essentially no current when hooked up the wrong way. The junction is basically a "diode," an object that lets current through in one direction and not the other (Masters 458). [I mention this because in the wider world of electronics, the *p-n* junction diode is a valuable object (Masters 458).] In the following subsection we will explore just why this is the case.

3.2.2.1 The Depletion Region

When light strikes the *p-n* junction, the mobile electrons and holes are energized. However, it turns out that the "carriers" (the general term given to these entities) (Nelson 161) each want to move to the oppositely-doped material! That is, the electrons want to move to the *p*-doped side, and the holes to the *n*-doped side (Masters 458-460).

One can rationalize this in the following way. Suppose that one had water and sugar on opposite sides of a U-shaped flask, as in Fig. 3.2. There is a boundary between the sides of the flask, through which water can flow but sugar cannot. The water ends up flowing through the boundary until its pressure is the same on either side of the barrier [note: in chemistry, this process is properly termed "osmosis"] (Silberberg 503). This is a one-sided version of what happens across the boundary between the *p*- and *n*-doped sides. In reality, *both* electrons *and* holes act like water. However, we can just get the behavior on the other side of the junction by flipping the flask around. (We also have to allow for the fact that the carriers recombine after they diffuse (Nave), a fact for which the water analogy has no direct corollary.)

It turns out that this process, known as "diffus[ion]" (Masters 457), does not actually last until the concentrations of electrons and holes are the same on either side. After a certain period of time, new electrons diffusing in the *p*-doped region run into electrons that diffused across earlier. Similarly, the holes diffusing into the *n*-doped region run into the holes that got into the *n*-doped region earlier. If opposite charges

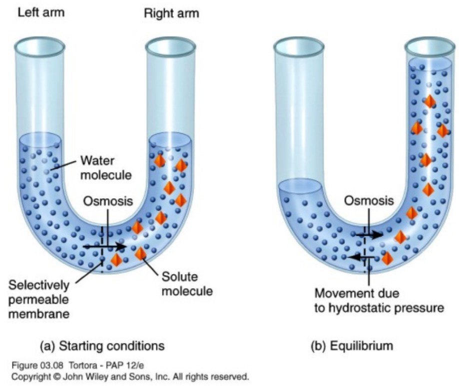


Fig. 3.2 An analogy between diffusion in the *p*-*n* junction and osmosis

A *U*-shaped flask contains water on one side of a barrier, and sugar on the other side. The barrier can let water through, but not sugar. Water tends to flow from its side into the sugar's side, to even out the "pressure" that it exerts (Wendy T.). Eventually, it reaches an "[e]quilibrium" state (Wendy T.). Similarly, electrons and holes diffuse across the boundary between the *p*- and *n*-doped semiconductors, in order to even out the concentration of these carriers on either side of the boundary. (Electrical repulsion eventually halts this process.)

Figure from Wendy T.; "Osmosis and Osmotic Pressure;" *Cell Physiology II (Chapter 3): Anatomy & Physiology 246 with Thomas at the University of Northern Colorado*; Study Blue, Inc., 13 Sept. 2011; Web; 26 May 2014; figure for "Osmosis and Osmotic Pressure;" JPEG file.

attract, then like charges repel, and so newer carriers are essentially prevented from diffusing across the junction (Masters 457; Nave).

This pushback limits the portion of the *p*- and *n*-doped regions that see electrons and holes coming in, to an area situated about the boundary. This area is termed the *depletion region* (Nave).

In order to get electricity out of the junction, we need to make electrons flow. In particular, they must be able to flow across the junction.

Let's say we have a pair of leads attached to an energy source. One lead has a positive charge, and one lead has a negative charge. What happens when an experimenter places these leads on the junction?

It turns out that the answer depends on the specific placement of the leads. If we place the positively-charged lead on the *n*-doped semiconductor, and the negatively-charged lead on the *p*-doped semiconductor, then the electrons will be attracted to the positive lead and the holes to the negative side. This will pull them away from the depletion region. Obviously, if carriers are traveling *away* from the depletion region, they are not traveling *through* it. This situation is termed "reverse bias" (Nave). The effect of reverse bias is displayed in Fig. 3.3 (a).

If, on the other hand, one were to connect the negative lead to the n-doped region and the positive lead to the p-doped region, then it the negative lead would repel the electrons, and the positive lead would repel the holes. This would push the carriers closer and closer to the depletion region. If the leads can push the carriers hard enough (i.e. if the energy source has enough energy), then carriers will start to cross the depletion region, as shown in Fig 3.3 (b). In this scenario, "forward bias" (Nave), one can generate electricity; whereas this is not really possible to do in reverse bias. Hence, the diode behavior of the p-n junction (Masters 458-460).

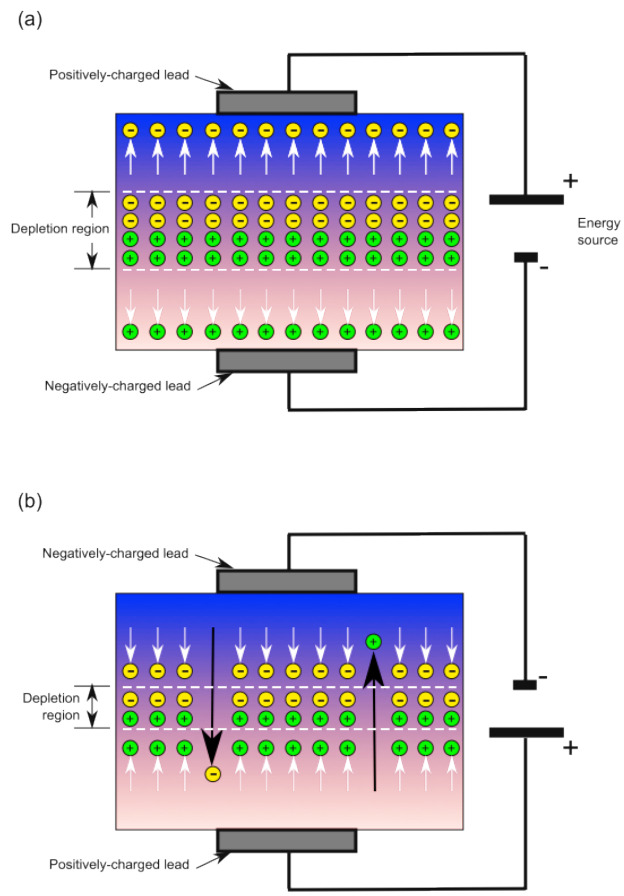


Fig 3.3 The effects of reverse and forward bias on a *p*-*n* junction.

(a)In reverse bias, positively-charged leads attract electrons in the *n*-doped region, and negatively-charged leads attract holes in the *p*-doped region. Consequentially, the carriers are farther away from the depletion zone, and are thus less able to form a current through it.

(b) In forward bias, negatively-charged leads push electrons toward the depletion zone, and positively-charged leads do the same with holes. The repulsive electric field from the leads can be strong enough to counteract diffusion to a degree, and allow current to flow through the depletion region.

Figures based on Fig. 8.14 and Fig. 8.17 of Gilbert M. Masters, *Renewable and Efficient Electric Photovoltaic Systems* (Hoboken, NJ: John Wiley & Sons, Inc., 2004; print, 457; 461).

3.2.3 An Electronics Simplification

The goal of this paper is to eventually model the functioning of a PV system. In order to assemble this model, one must have equations that a computer can use to calculate power output and other useful quantities. The problem with the mechanisms described above is that their equations are fairly complex and difficult to work with. It is therefore necessary to find a mathematically simpler model.

It turns out that such a model is possible, if one treats a PV system as an electrical circuit. A circuit is composed of multiple components connected together, with the objective of directing the flow and energy of electricity passing through them. The components are specialized, and have particular functions. Connecting them in particular ways causes electricity to be directed in a certain manner. Sometimes, current is made to flow across a *voltage difference*, which is basically a changeable difference between the current's energy just before and just after the diode.

In the equivalent circuit that we will use to model the PV system, we want to model the following aspects of its functionality:

1. The ability of a PV cell to generate charge carriers, as discussed in §3.3.
2. Electron and hole recombination.
3. The resistance to electrical flow found within connections between cells in a PV panel, between PV panels in a PV array, and between the system and the device it powers
4. The device being powered.

The result is the circuit model presented in Fig. 3.4 (a). I should, however, explain the current elements and connections used within this circuit. The symbols for these elements are explained in Fig. 3.4 (b) (i), with details given below:

1. The “current source” (Horowitz and Hill 9): This is a component that creates an electrical current (Horowitz and Hill 9). This corresponds to the flow of charge carriers across the depletion zone and into the wires connected to the device being powered.

2. The *diode*. This represents electron-hole recombination, which for purposes of this model is termed the “dark current” (Nelson 9-10). One can think of a diode as a gate that allows current to flow in one direction (the same as the arrow in the diode symbol), but not in the other. The diode represented here is *not* the same as the *p-n* junction. For one, the *p-n* junction should always be under forward bias, so the diode characteristics of the junction should not be relevant. Secondly, one can remember that recombination happens when electrons fall back down the bandgap energy, i.e. when they flow opposite to the direction required for power generation. The latter direction is represented by the arrow in the current generator. What the model therefore needs is a component that corresponds to downward-flowing recombination, and that simultaneously prevents upward-flowing recombination (because this doesn’t happen). In this manner, the diode is the electrical counterpart to a metaphor in language: it uses a figurative meaning – a directionality found in a *p-n* junction – to describe something in a non-literal manner.

3. The “resistor”: (Horowitz and Hill 4): The function of the resistor is to “safely dissipate” the “power” that a current carries when it flows through the resistor (Horowitz and Hill 5), i.e. to resist the transportation of power via current.

There is also the “load” which, simply put, is “[a]nything that uses electricity” (ABS Alaskan). This device provides the voltage difference that gives the current energy.

The different types of connections within the circuit, and their importance in electronics, are presented in Fig. 3.4 (b) (ii) and (iii).

This model allows one to succinctly describe the electrical output of a PV system in a succinct way. Fig. 3.4 (c) shows an “*I-V* curve” (alternately named “*I-V* diagram”), which plots the current produced by the cell as a function of the load’s voltage difference. This also allows us to describe the rate at which the panel produces energy, or the *power*: the power is the output current multiplied by the load voltage (Masters 7). Additionally, the relevant quantities in the circuit can easily be described

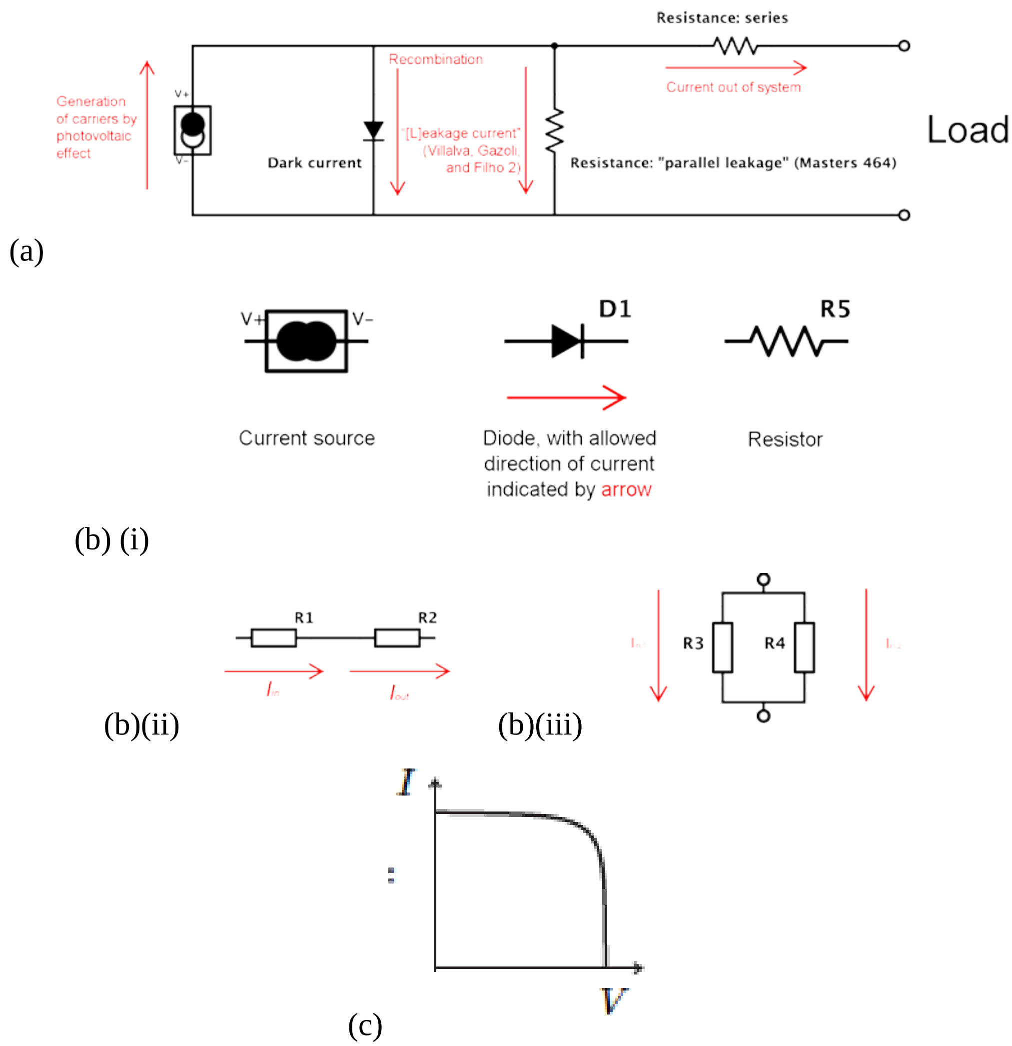


Fig 3.4 The circuit used to model PV systems in my simulation.

Circuit diagrams and elements for parts (a) and (b) generated by the author in DigiKey's Scheme-It open-source circuit-drawing software, and modified further using Adobe Acrobat Pro 9.3.4 and Adobe Photoshop Elements 8.0.

(a) A circuit diagram of this circuit. The components are labeled with the aspects of PV system function that they are supposed to model. Figure based on Fig. 1 of Villalva, Marcelo Gradella Villalva, Jonas Rafale Gazoli, and Ernesto Ruppert Filho, "Modelling and Curcuit-Based Simulation of Photovoltaic Arrays" (*10th Brazilian Power Electronics Conference (COBEP)* n.v. (2009): n.p; Web; 7 Jul 2013; 1). (The reader should note that this paper provides the foundation of my electrical approximation of the PV panel. This is discussed in greater depth in Appendix A.)

(b) An explanation of the elements shown in (a), and the connections between them. Part (i) defines the notation used in Part (a). Parts (ii) and (iii) explain the difference between series and parallel connections. Part (ii) shows two resistors hooked up in series. In this connection, the same amount of current $I_{in} = I_{out}$ goes through both resistors, and dissipates possibly differing amounts of power in each resistor. Part (iii) shows two resistors hooked up in parallel. In this connection, current I_{in} that enters the system eventually leaves as $I_{in} = I_{out}$. During transit, however, a portion I_3 goes through the resistor with resistance R3, and a portion I_4 goes through the resistor with resistance R4. These portions are not necessarily equal. They do, however, pass down the same difference in energy (albeit not dissipating the same amount of *power*, the *rate* at which energy is dissipated). Resistors need not be the only devices hooked up in this manner: note that in (a), the current source is hooked up "in parallel with a (…) diode" and a "parallel resist[or] (Masters 461, 464). This treatment is based on (Horowitz and Hill 2-7).

(Note that the current generator, diode, and parallel resistor are connected in parallel to the battery, while the series resistor is connected in series with it. Note also that while PV cells are typically connected in series within a panel, that panels are connected in parallel (Nelson 5)).

(c) The *I-V* curve of a solar cell, From Fig. 2 of Villalva, Marcelo Gradella Villalva, Jonas Rafale Gazoli, and Ernesto Ruppert Filho, "Modelling and Curcuit-Based Simulation of Photovoltaic Arrays" (*10th Brazilian Power Electronics Conference (COBEP)* n.v. (2009): n.p; Web; 7 Jul 2013; 3).

by a few measured values, which a PV manufacturer can provide (Villalva, Gazoli and Filho). One can therefore specify a system's electrical performance in a relatively compact manner.

3.2.3.4 A Note about the Maximum Power Produced by the Circuit

I should conclude §3.2 with a brief discussion of the maximum amount of power that the circuit can produce.

It turns out that at a specific temperature and under a specific amount of light, a PV system produces a maximum current $I_{\max}$ and maximum voltage $V_{\max}$ (Tiwari and Dubey 99). The maximum power produced by the panel, $P_{\max}$, is the product of these two quantities (Tiwari and Dubey 99):

$$P_{electrical,out,\max} = I_{\max} \times V_{\max}$$

We can also express this in terms of the "open-circuit voltage," the voltage difference present when no load is attached to the circuit's output, and the "short-circuit current," the current present when a load with no resistance is attached (Masters 461). If we represent the open-circuit voltage as V_{oc} and the short-circuit current as I_{sc}, then we can express the maximum power as

$$P_{electrical,out,\max} = FF \times I_{\max} \times V_{\max}$$

where *FF* denotes the "fill factor" (Tiwari and Dubey 98). This quantity measures the deviation of the actual maximum power point from its ideal value, $I_{\max} \times V_{\max}$.

3.3 Inverters

Yet the electrical characteristics of a PV system present a problem. The current that a system produces is called a *direct current* (DC current). Under the same conditions, it produces the same amount of current. It is more efficient, though, to transport current that *varies* over time, in a wave-like pattern termed *alternating current* (AC current); in fact, most electrical connections within the United States accept AC current (Lantero; Masters 51-53). We need to turn the DC output of the PV system into useable AC current. In order to do this, we use an *inverter*.

An inverter has other functions as well. It makes sure that a PV system outputs at maximum power throughout the day, although it will turn off if the system produces power, and not let the power increase past a certain amount. In addition, it prevents a phenomenon known as *islanding*, in which a part of the grid continues to produce electrical power, even after the rest of the grid has shut down. This presents a risk of electrocution to anyone who works on the grid (Masters 524).

The inverter's efficiency varies with the power produced by the PV system connected to it. For low values of power, the inverter efficiency is correspondingly low. As the power reaching the inverter goes up, the efficiency increases as well, to the point "inverters generally operate at greater than 90% over much of the range" (Vignola, Marvomatakis, and Krumsick 3). Other factors that affect inverter efficiency are the temperature of the inverter's surroundings, the temperature within the inverter, and the "size" of the system that the inverter serves (Vignola, Marvomatakis, and Krumsick 3,4,8). The first two factors negatively impact inverter efficiency as they increase. The third requires that any system be of just the right size to be hooked up to a particular inverter serves (Vignola, Marvomatakis, and Krumsick 3,4-6,8).

3.4 Organic Technologies as an Alternative to Semiconductor Technologies

The discussion above has pertained to *p-n* junctions made from doped semiconductors. Researchers are also attempting to create *p-n* junctions from "organic materials" (Nelson 137), where in this discussion, "organic" is defined as anything that “contain[s] carbon, [is] nearly always bonded to other carbons and hydrogen, and often to other elements” (Silberberg 571).

For any non-“crystalline” organic substance, it is significantly difficult to separate electrons from holes (Nelson 137). This separation really only happens at the boundary between the *p*- and *n*-doped materials. Recombination is also more of an issue for non-crystalline substances. One way around these concerns is to “blend” the doped materials, so that the boundary is spread throughout the junction itself (Nelson 137-138).

(For crystalline organic substances, electron and hole separation is easier to achieve (Nelson 137).)

3.5 Environmental Factors Affecting PV Performance

Obviously, PV systems are meant to respond to incoming sunlight. However, there are certain features of the local environment of the panel, and the environment of the Earth within the solar system, that affect the amount and the character of the sunlight incident on a PV system. Additionally, temperature can adversely affect PV system functionality. We will discuss each of these factors of system performance below.

3.5.1 Solar Irradiance

Irradiance is a measure of the amount of energy incident on a PV system or any surface on the Earth. It is the amount of power delivered, by sunlight or any source, per unit or surface area exposed to that power source. From now on, we will consider solar energy explicitly in terms of irradiance falling on a PV system.

Irradiance must travel to a system in a journey of three legs: from the sun to the top of Earth's atmosphere, through the atmosphere, and either directly into the panel or reflecting off of the ground. Each of these legs affects what the PV system sees coming in.

3.5.1.1 Effect of Earth's Rotation and Orbit

During the course of a day, the Earth completes a full rotation about its axis. For observers on the Earth, this creates the impression that the sun is moving across the sky, from the eastern part of the horizon to the western one. For ease of conception and computation, we will discuss the effect of time of day on irradiance in these anti-Copernican terms.

We consider the amount of sunlight incident perpendicular to a PV panel's surface, even though that PV panel may not necessarily rotate to follow the path of the sun. This makes sense, if one considers the following analogy. Suppose that one wants to kick a soccer ball. Common sense states, and Fig. 3.5 reiterates, that the way to get a ball to move the quickest is to kick it head-on. Kicking it at an angle will make it move slowly, or make it spin around, and is essentially equivalent to giving the ball a very weak head-on kick. Similarly, a PV panel is most efficient when the sun is shining directly over it, and irradiance coming in at an angle can be considered as weaker irradiance shining directly on the panel (Rensselaer Polytechnic Institute). Since irradiance travels with sunlight, the directionality of irradiance coming down on Earth's

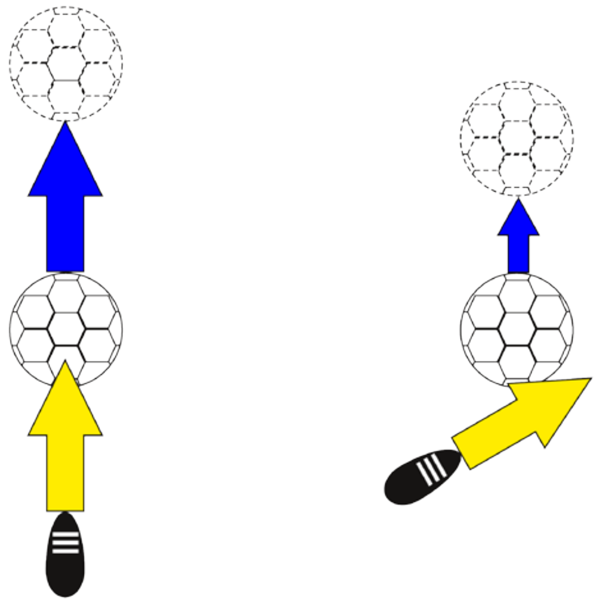


Fig 3.5 Comparison of a head-on kick to a glancing kick.

The head-on kick provides the ball with more energy in the forward direction, whereas the glancing kick provides a negligible amount. Similarly, irradiance from directly above a panel imparts more energy than irradiance coming from a different direction.

surface changes with the position of the sun, and therefore the amount of irradiance considered incident on the panel changes with the time of day as well.

The Earth does not only move about its axis. It also rotates about the sun in an elliptical orbit. This means that its distance from the sun changes throughout the year. Correspondingly, in our easier Earth-centric viewpoint, the sun's path through the sky changes throughout the year. One can illustrate this change by taking a photo of the Sun's position during the same time each day of the year, and overlapping the photographs on top of one another. This results in the creation of a shape called an *analemma*, resulting from Earth's elliptical orbit. An example of an analemma is provided in Fig. 3.6.

Fig 3.6 An analemma.

Photograph by Vasilij Rumyantsev, “Analemma,” from Robert Nemiroff and Jerry Bonnell; “Astronomy Picture of the Day: 2002 July 9;” *Astronomy Picture of the Day*; National Atmospheric and Space Administration, 9 July 2002; Web; 20 Apr. 2014. JPEG file.

As with the daily variations in the sun’s position, the yearly variations also influence the direction of the irradiance incident on the panel, so that the daily irradiance profile from one time of year is different from that of a different time.

3.5.1.2 Radiative Transfer through the Earth’s Atmosphere

If we factor in the time of day and time of year to the irradiance leaving the sun, then we obtain the amount of irradiance that *would* hit the Earth, *were there no atmosphere*. Yet we do, in fact, have an atmosphere; this fact presents another element that affects incoming irradiance.

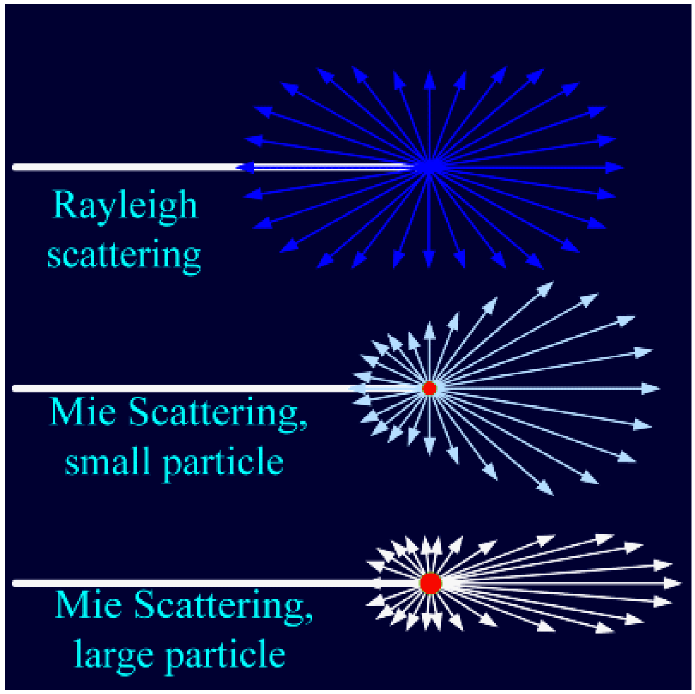
Within the atmosphere are essentially three types of particles that are relevant for our purposes: “gases,” “cloud drops,” and “aerosols” (Jacobson 279). Each of these particles interacts with irradiance in different ways.

When irradiance is incident on a particle, some of it is *absorbed*, and therefore unable to reach the surface of the Earth. Different particles absorb different amounts of light. Very large particles are extremely good absorbers (Jacobson 275).

The rest of the irradiance is *scattered*, altered in direction. If light hits an object that is a lot bigger than the light’s wavelength, then the light is “scatter[ed] according to the laws of geometric optics” (Michaelson). On the other hand, if the object is smaller than this, the resulting direction for the scattered light is not as clean. If the light hits an object that is about as big as the light’s wavelength, then the light is “Mie scatter[ed]” (Michaelson) In Mie scattering, light is scattered in all directions, but *most* of the light is scattered “forward,” i.e. in and near the direction of the incident irradiance (Salby 213-216). If the light hits an object that is much smaller than the light’s wavelength, then the light is “Rayleigh scatter[ed]”. In this case, the light is still scattered in all directions, but mainly *forward* and *backward* scattered. (In *backward* scattering, light is scattered in and near the direction *from which it came*.) The different types of scattering are demonstrated visually in Fig. 3.7.

One should note that the type of scattering that takes place is dependent upon the size of the scatterer compared with the particle’s wavelength. Sunlight has multiple wavelengths, most of which are in the visible range, but which also contain larger wavelengths and smaller ones as well, as shown in Fig. 3.8(a). Not all of these wavelengths will be affected equally. For example, the sky is blue because air particles scatter more blue light in multiple directions than they do redder light (Salby 213-216). On the other hand, clouds are white because water particles in clouds scatter all visible wavelengths pretty well; these wavelengths blend to create white light.

In fact, absorption is also dependent on wavelength. Different atmospheric constituents absorb different wavelengths of light. As sunlight passes through these absorbers, different portions of it are taken out of the running, so that what is incident on the ground is not the same light that left the sun, but is missing chunks within certain wavelength ranges. These chunks are referred to as "absorption band[s]" (Salby 216-217). Their effect is illustrated in Fig. 3.8(b). Note that, in the figure, there is a



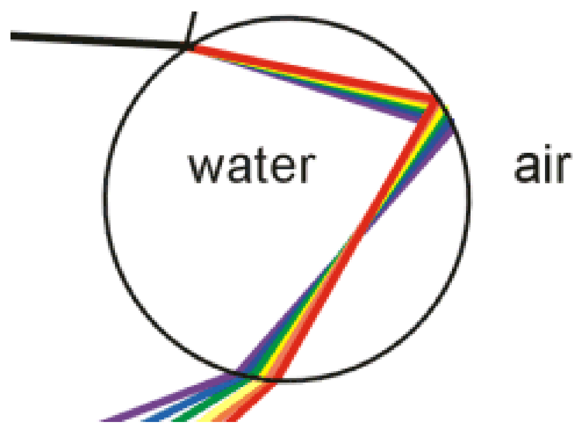
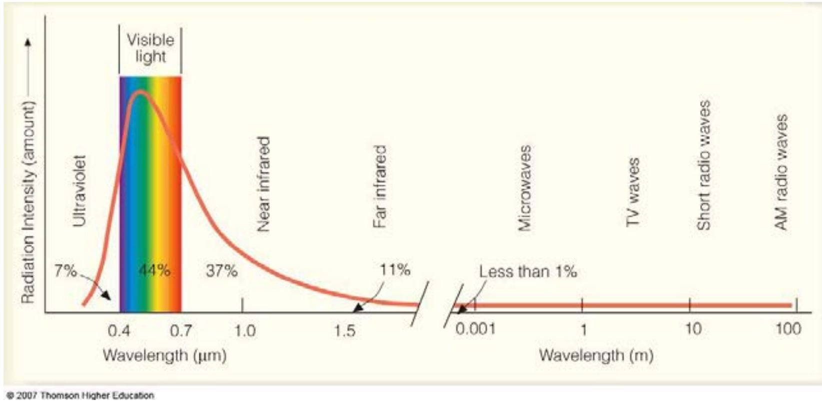


Fig 3.7 Different types of scattering.

Rayleigh and Mie scattering images: Untitled from Rich Watkins and Joe Vallandingham; “Rayleigh Scattering;” *Rayleigh Scattering*; Rowan University, 2008; Web; 5 Jun. 2014; GIF file. Geometric scattering image: Rebecca McDowell, [untitled], from Rebecca McDowell; “Total Internal Reflection;” *How Rainbows Happen*; Rebecca McDowell, n.d; Web; 22 May 2014; JPEG file.

(a)



(b)

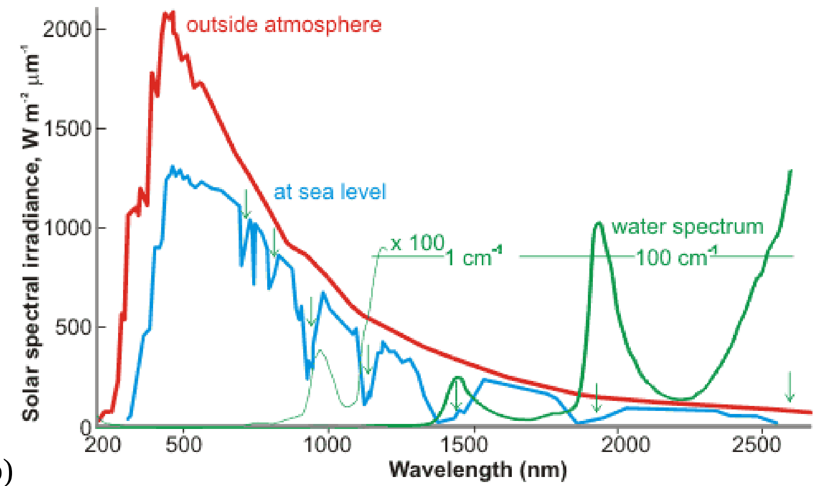


Fig 3.8 Solar spectrum

(a) Spectrum of sunlight, approximated, including the visible region. Image: "Radiation curve for the Sun – a closer look," from Nolan Atkins; "Chapter 2 – Energy: Warming the Earth and the Atmosphere;" *Lyndon State College Survey of Meteorology*; Lyndon State College, 13 Sept. 2006; Web; 20 Apr. 2014; JPEG file. Note the variation of intensity with wavelength.

(b) Effect of absorption bands on the solar spectrum that reaches the ground. Note the relatively uninterrupted region from the wavelengths 300 nm to 1100 nm. Image: Untitled, from Martin Chaplin; "Water Absorption Spectrum;" *Water Structure and Science*; London South Bank University, 18 May 2014; Web; 22 May 2014; Document; <http://www1.lsbu.ac.uk/water/vibrat.html>; Creative Commons Attribution-Noncommercial-No Derivative Works 2.0 UK: England & Wales License.

relatively intact portion of the spectrum between the wavelength values of 300 nm and 1100 nm.

It turns out that these effects do not only affect the amount of *incident* energy on a PV panel. An electron being knocked loose in the photovoltaic effect can *only* absorb energy in chunks called *photons*. Each chunk's energy is equal to (Nelson 8)

$$E_{photon} = \frac{hc}{\lambda}$$

where λ is the wavelength, c is the speed of light, and h is a constant called Planck's constant. As can be seen in Fig. 3.9, the amount of energy in a packet from light with a longer wavelength is *lower* than the amount coming from a packet attributable to a shorter wavelength. Remember that the electron needs a certain amount of energy to cross the gap between the valence and conduction bands, in order to be able to move. So if certain wavelengths reach the panel more than others, or if certain wavelengths disappear form the incident light altogether, than this will alter the amount of energy from the sun that an electron can actually use and convert into electrical energy.

(One other effect that has gone unstated is *emission*, in which particles emit infrared radiation. This is something that they do whether or not they are exposed to light. In fact, all objects do it: the spectrum of the light is temperature dependent. This phenomenon is insignificant, though, in comparison with the others discussed above (Jacobson 284).)

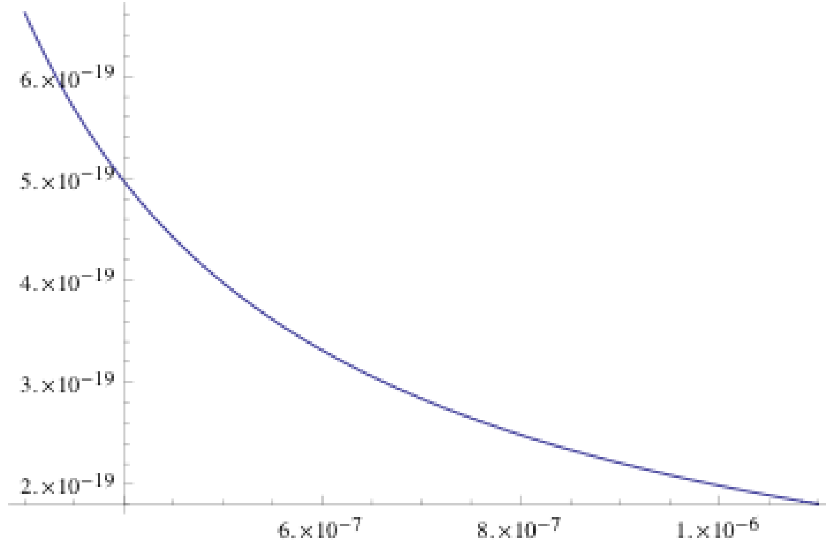


Fig 3.9 Graph showing the dependence of photon energy on wavelength, with wavelength on the horizontal axis and photon energy on the vertical axis.

Note that increasing the wavelength decreases the photon energy. Plotted by the author on Mathematica.

3.5.1.3 Interactions with the Ground

Once light hits the ground, it can be reflected back up into the atmosphere. All objects have a particular "albedo," a fraction of light they receive that they reflect back. Some objects, like snow, are very reflective; others, like grass, are somewhat reflective, but not as much (Jacobson 255-256).

The main importance of the ground's albedo is that any light reflected by the ground goes back into the sky. Some of this can be scattered down again. This process is illustrated in Fig. 3.10. (In fact, the sky has its own albedo, which is involved in sending a portion of the light reflected from the ground back down again (Wong and

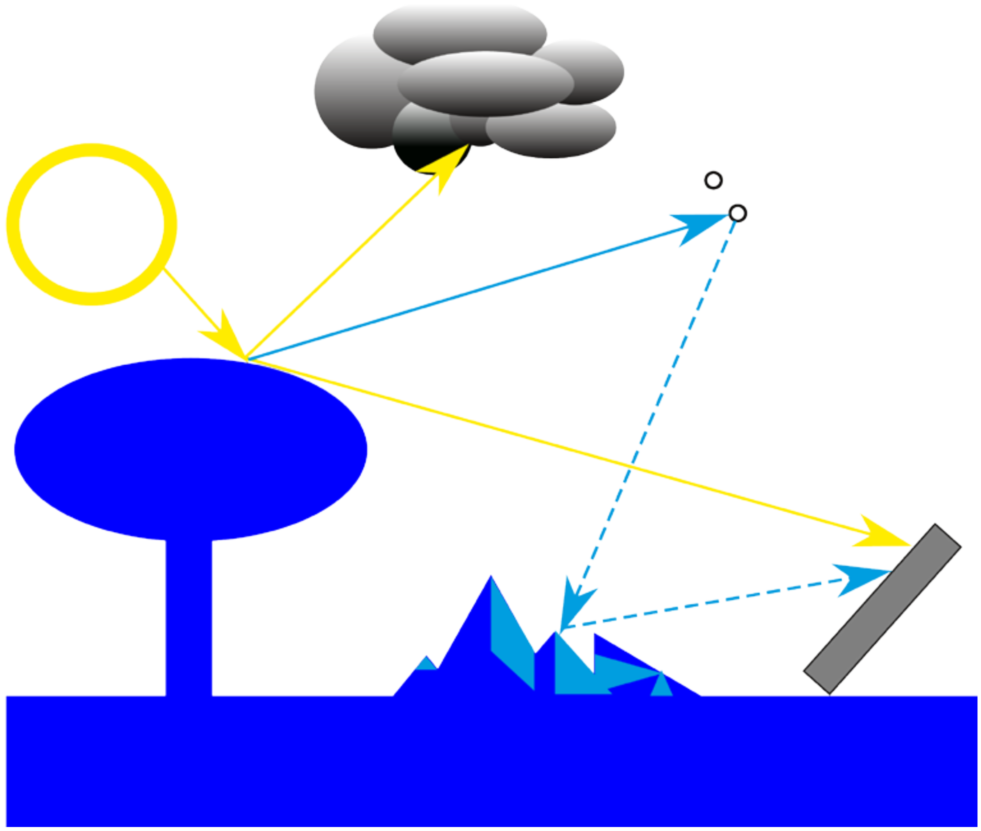


Fig 3.10 Interactions of irradiance with the ground and the atmosphere.

Due to the ground's albedo, some of the sunlight that is incident on the ground is reflected back into the sky, which can send the light back to the ground again. The tilted rectangular shape on the far right is a PV panel in profile. Guided by Figure 2.11 of Frank Vignola, Joseph Michalsky, and Michael Stoffel, *Solar and Infrared Radiation Measurements* (Boca Raton: Taylor & Francis Group, LLC, 2012; Google Books Preview; 21 May 2014; Energy and the Environ.; 23).

Chow 198).) This can allow scattering and absorption to take place once again, altering the character of the light incident on the PV panel even further.

This consequentially places a certain importance upon the location in which panels are installed. The albedo of a suburban is different from that of an urban environment, which is in turn different from that of a rainforest environment. All three of these place types, and more, are found within Hawai’i. One should therefore take care to account for differing ground albedoes within the state, if one truly aims to obtain a statewide assessment of PV technology (as is the aim of this Thesis). This problem is discussed in more detail in the next chapter.

3.5.1.4 Directionality of Panel

In the Northern Hemisphere, the sun appears to travel a path in the southern portion of the sky. As Hawai’i is in the Northern Hemisphere, solar panels installed there should therefore face south, in order to increase their efficiency (Duffie and Beckman 16).

3.5.2 Temperature

The temperature of a panel plays an important role in the panel’s ability to convert from solar irradiance to electrical energy. Increased temperatures make panels less efficient

The reason for this is the following: the dark current grows (i.e., more electrons are recombining with holes more quickly), therefore decreasing the open-circuit voltage (Nelson 173).

The energy entering and leaving the panel affects the panel’s temperature. From everyday experience, we know that laptops get hot when their batteries charge, and we get hot when we stand out in the sun. In both of these cases, energy is placed into an object: from the charger to the laptop, and from the sun to particles in our bodies that also move, in response to sunlight. In all of these cases, the addition of energy causes an increase in temperature. We can reverse this picture by, say, stepping into a gigantic refrigerator: energy leaves our bodies, and our temperatures decrease. So, if we put energy into something, its temperature increases; and if we take energy away from something, its temperature decreases. So if we know how much energy comes in or goes out over time from which source acting on a PV panel, and add everything together, then we'll see how the temperature of the panel evolves.

The following is a brief summary of all of the effects that add/subtract energy from a panel, and that therefore affect the panel's temperature. **This list will become important in the next chapter.** Obviously, irradiance adds energy, and electrical power production takes it away. PV panels have a certain non-zero reflectance, and so lose some of the solar energy that is incident on them by default. Also, as mentioned earlier, any solar energy incident on the panel that is *not* used to free up an electron turns into waste heat. This waste heat stays inside the panel. Another source of heat is the dissipation by resistors: the heat that is dissipated stays in the panel. There is the temperature of the surrounding environment. Possibly, there is conduction to the surrounding environment, if the panel is mounted using a conductive material. Rain and wind can cool the panel (or heat it up, if the water or wind is hotter than the panel). Finally, an agent that can heat *and* cool the panel is the radiation I discussed earlier, that takes place for all objects and whose spectrum is temperature dependent. This radiation is termed *thermal* or *blackbody radiation*, and is emitted *by* the panel *to* its surroundings, and *to* the panel *by* its surroundings. Whether this radiation causes an overall decrease, increase, or neither in panel temperature must be evaluated based on the particular case being studied.

3.6 Conclusion

A PV panel woks by converting energy from solar irradiance into electrical energy, by using the former to free up an electron and allow it to flow (once the cell is connected correctly). The panel's performance can be affected by many factors, not just the amount of irradiance incident on the panel.

In the next chapter, we will examine how to create a simulation that revolves around the temperature of the panel and the phenomena that change it. It is therefore important to keep the lessons from this chapter in mind, as we discuss the creation of a model based on the performance of a PV system, by imagining the system as an electrical circuit subject to effects from its environment.

4. Description and Explanation of the Simulation of Photovoltaic System Functionality

4.1 Introduction

In the previous chapter, we discussed how PV systems work, and how their environments influence their functionality. In order to assess whether PV is a capable technology for handling Hawai'i's energy needs, it is necessary to predict the performance of PV systems within Hawai'i's diverse geography and weather. In order to do this, I have created a computer model of a PV system and of the factors that affect it.

In this chapter, I will discuss the mathematical approach to the simulation, and how it takes account of differing environmental characteristics found across the state of Hawai'i. Following brief notes on the simulation's development, I will then describe what the simulation has accomplished, along with possible future avenues of development.

4.2 Review of Temperature's Importance

As we noted at the end of the last section, the efficiency of a PV system at generating power is dependent on the temperature of the system. As a system becomes hotter, its efficiency drops, due to an increase in bandgap energy and resistive heating.

If we want to make accurate predictions about the performance of PV cells, we therefore need to give temperature a very prominent role in our considerations. In fact, to some degree, this is easy to do. If we know how much energy comes in or goes out over time from which source acting on a PV panel, and add everything together, then we'll see how the temperature of the panel evolves. This, in turn, will give us a sense of how the power output by the panel changes over a period of time; say, throughout a whole day.

4.3 What Nature Actually Provides

The problem is that the effects influencing the panel's energy are not described in terms of how much *energy* enters a panel, but rather the *rate* at which it enters. We call this rate *power*. Instead of providing us with a way to add up energies and get the change in temperature, the available equations provide a way to add up powers and get the *rate* of temperature change – how much it changes per unit time.

I will illustrate this situation with an analogy. Suppose we want to see how much water comes out of a hose. We don't have a graduating cylinder or a bucket or anything else that we can use immediately to give us a straight answer immediately. And we can't really just turn water *on*, we have to figure out *how much* to turn it on. Twisting the knob more or less makes the water come out faster or slower. It increases or decreases the rate at which water leaves the hose. We can add more positive twist and make it come out faster, or we can add more negative twist and make it come out slower. But in the end, we are left with the *rate* at which water comes out, *not* the actual amount that comes out.

This is also true of power. If energy enters the cell *faster*, i.e. if the *power* entering the cell is large, then the cell's temperature will increase very quickly. If it enters the cell more slowly, then the power entering is lower, and the cell's temperature increases more slowly. Finally, if energy is taken *away* from the cell, then we are putting in *negative power* (i.e. subtracting power), and the temperature *decreases* at some rate.

4.4 Working With Change: Differential Equations

4.4.1 Explanation of the derivative

A differential equation, as the term might indicate, is something that describes how to combine certain quantities to get a different quantity. But what do we mean by *differential?*

Well, the word "differential" sounds an awful like "difference," which is what happens when you subtract one quantity from another. Once could also define the difference to be the *change* between one of the quantities involved in this subtraction, and the other one. So somehow, differential equations have to involve change.

Let's proceed to an example. Suppose I am walking down a hill. I can say that with each step, I am walking down a certain distance in the vertical direction. Since I am coming down a hill with a *slope*, though, this change in the vertical is also going to be accompanied by a change in the horizontal, though, as can be seen in Fig. 4.1 (a). I could say that the *rate of change* of my vertical position is

$$\frac{\Delta height}{\Delta width}$$

where $\Delta height$ is the distance that I come down vertically, and $\Delta width$ is the corresponding distance that I cross horizontally. In fact, if I were to draw a line between

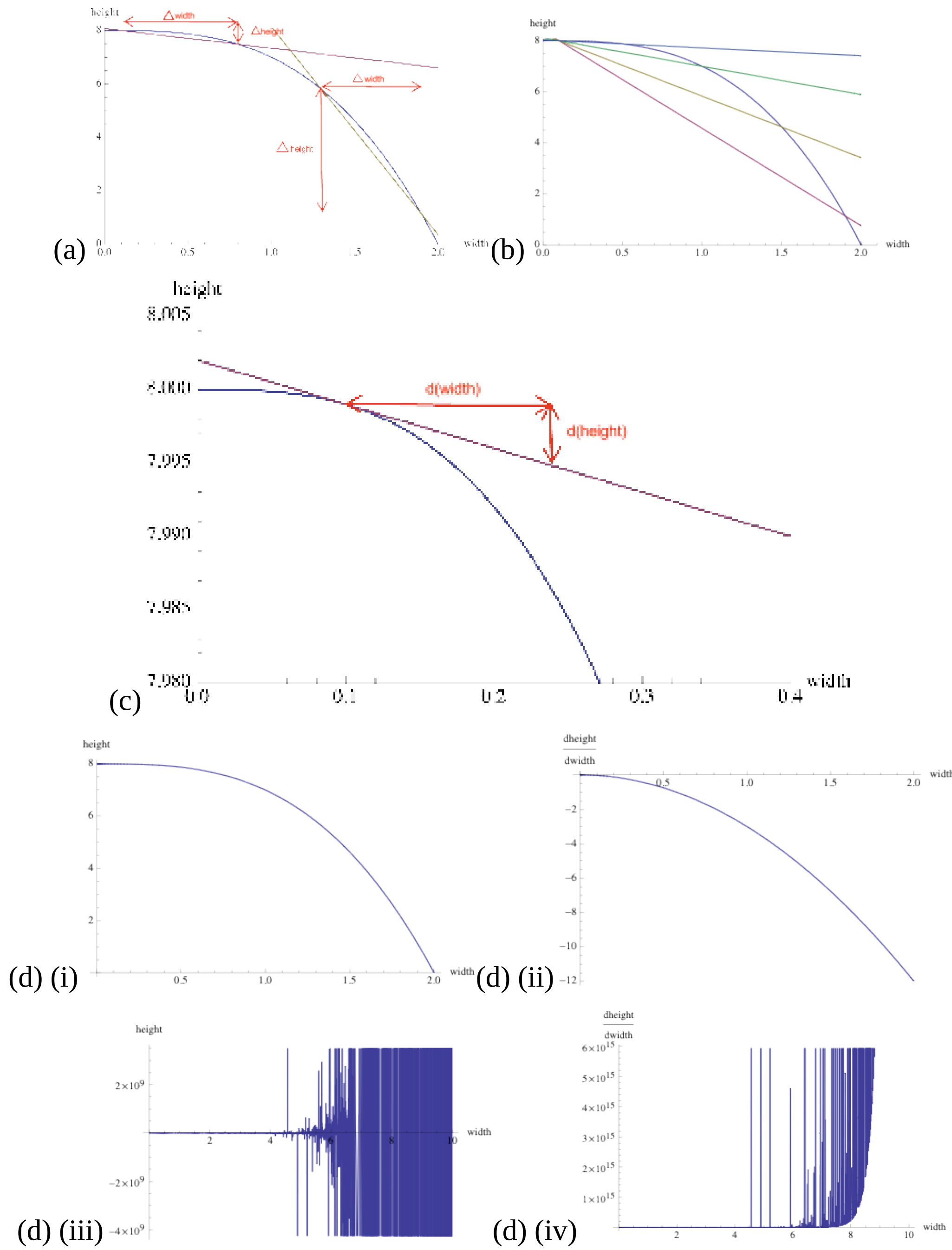


Fig 4.1 A motivating analogy, for the concept of *instantaneous* rates of change and for equations involving these rates.

(a) When a person walks down a hill by taking a step forward, he/she travels downward at a rate of $\frac{\Delta height}{\Delta width}$. This quotient is also the slope of a line through the starting and ending point of this step, a line that cuts through the curve of the hill. (Since the hill looks different at different points, this slope is also different at different points, as illustrated by the presence of two steps in this figure.)

(b) If I look at this slope when I decrease the width of the steps, I end up with a line whose slope is equal to $\frac{d(height)}{d(width)}$, which can also be termed *height*'(*width*). The corresponding line is *tangent* to the hill: it passes through only one point on the hill, and not any of the ones nearby, unlike the lines shown in Fig. 4.2.a. Thus, we say that $\frac{d(height)}{d(width)}$ is the *instantaneous rate of descent at the point where the line crosses the hill*. (Note: the notation $\lim_{\Delta width \to 0}\left(\frac{\Delta height}{\Delta width}\right) = \frac{d(height)}{d(width)}$ simple means that when I decrease the step width to zero, the slope of the line approaches the limit $\frac{d(height)}{d(width)}$.)

(c) The quotient notation of this slope is no accident: it implies that when moving at the point of intersection, one travels an infinitesimally small (but nonzero) width *d*(*width*), causing an infinitesimally small (not nonzero) drop in height *d*(*height*).

(d) [Parts (i)-(iv)] I can plot the slope of the tangent line, the *derivative*, at each point on the hill as a function of width. For the hill shape that I have chosen (i), the result is a also a hill (ii), albeit one with negative values. The hill was created from the simple function $height = 8 - width^3$; the derivative is also given by a simple function, $\frac{d(height)}{d(width)} = -3 \times width^2$. However, to describe the derivative of more complicated terrain, as in (iii), it is often better (and easier) to use a purely mathematical approach. This is because the derivative (iv) of a complicated terrain can itself be complicated.

Graphs generated in Wolfram Mathematica 9.0.1, and modified in Adobe Acrobat Pro 9.3.4 and Adobe Photoshop Elements 8.0.

where I was at the start of my step and where I was at the end, this line would have a *slope* given by the ratio above.

Now, imagine that I take smaller and smaller steps. This corresponds to smaller horizontal distances $\Delta width$ traveled, and starting and ending points that are closer together. What happens if I shrink my step size progressively to zero, as in Fig. 4.1. b-c? What happens to the ratio of $\Delta height$ to $\Delta width$? What happens to the line between my starting and ending points?

Let's answer the second question first. As we move the starting points closer and closer, the line between them cuts through less of the hill. If we moved the starting and ending points so that they were *right on top of* each other, then the line would go through *just that point*, and not cut through the hill at all. The line is *tangent* to the curve of the hill. This line has a slope, which we will denote as

$$\frac{d(height)}{d(width)}$$

This looks like our first expression for the slope of a line between start and end. But for the first quotient, the numerator and denominator were the changes in vertical and horizontal distances between these two points? What about here?

What we conclude is that the slope of the tangent line represents an *instantaneous rate of change* at a *single* point on the hill, the rate of descent *at that particular point*. We call this slope the *derivative*, and its numerator and denominator the *differentials of height and width*, respectively: the infinitesimal but nonzero *differences* in height and width crossed at that point. The branch of mathematics that deals with these concepts is *calculus*.

We can, if we want to, graph the derivative as a function of width, which we do in Fig. 4.1 d. In fact, the power of calculus comes in part from the ability of humans to represent derivatives as mathematical functions, of one or more than one variables.

4.4.2 Differential equations

This ability enables us to write equations for, or involving, derivatives. These equations can describe how to assemble a derivative from many quantities; or how to take one derivative, manipulate it, and turn it into another derivative; or explore many other possible relationships. We call these *differential equations*. They provide an important shorthand in mathematics and the sciences, as they allow quantities to be described through their rates alone.

In particular, using the power put into/taken away from the cell by each natural effect, I am able to write a differential equation for the rate of change of the PV system's temperature over time.

4.4.3 Solving differential equations

Yet, as in the case of PV panels, investigators frequently need to know the quantities *themselves*, and not just their rates of change. We want to turn the derivatives of functions into the original functions. This is necessary in order to understand how *temperature*, and not *temperature's derivative*, affects the power output of a PV system. (The equations for power output are in terms of temperature only, which is why we have to solve this problem.)

There are two main approaches to this problem. The first is to use an extensive tool kit developed in calculus to solve for the original quantities symbolically, like how one would perform algebra by manipulating symbols and variables. This method will not be covered here, although it does take up a great deal of instructional time during courses in differential equations. The differential equation for panel temperature is not an equation that can be solved this way. Instead, it must be solved approximately, with a set of techniques dubbed *numerical methods*.

In their essence, numerical methods retrace the steps taken in the hill example. We start out with the height of the hill at a certain width. We call this our "initial condition" or boundary condition (Boyce and DiPrima 12). We then draw the tangent line to the hill at that point, out until it is a particular distance away from the starting point, in terms of width. We then draw another line, the one tangent to *this* point, according to the differential equation. We let this line continue out for a distance in width, stop, and repeat. Eventually, as in Fig. 4.2, we end up with a shape that looks like the original shape. Note, however, that this is an *approximate* method, and that "errors" are possible (Boyce and DiPrima 448-449). There are many possible variants of this general technique (Boyce and DiPrima 454-470), which are beyond the scope of this section to cover.

The simulation that I designed solves for temperature as a function of time, by starting with a differential equation for the temperature, and information about the temperature at the start of the time period over which I am solving (daylight), through the overall simulation design illustrated in Fig. 4.3. Through numerical solution of this

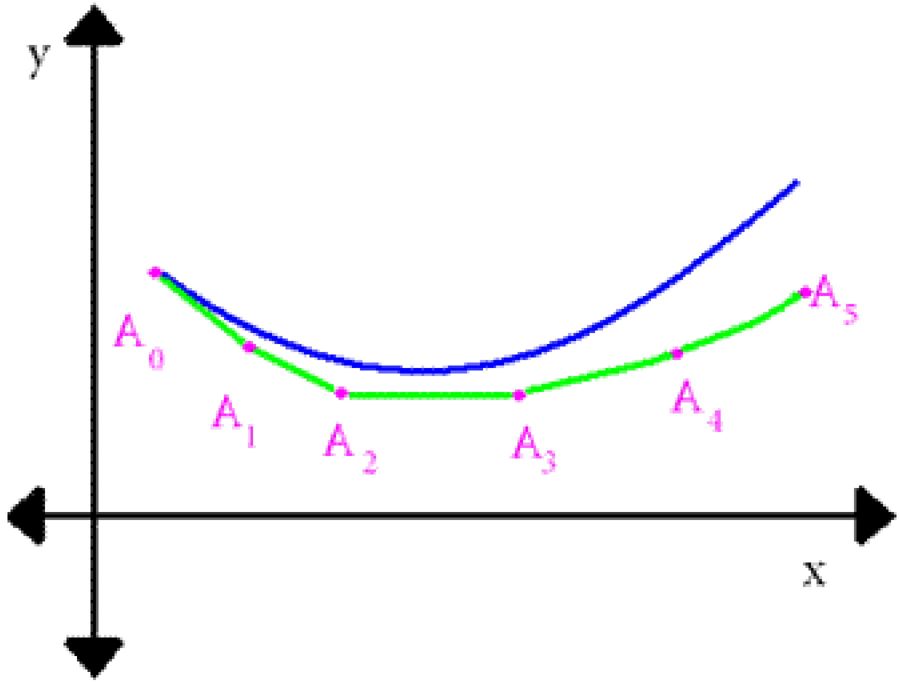


Fig 4.2 An example of the outcome of numerically solving a differential equation (illustrated by the joined line segments), to approximate the actual solution (the smooth curve).

Note the error between the numerical solution and the actual solution. Unfortunately, due to the complexity of some differential equations, we are stuck using numerical solutions. Image: Untitled from Math Scoop, "Euler's Method;" *Math Scoop;* Math Scoop, 2010; Web; 20 Apr. 2014; PNG file.

differential equation, I am able to understand how PV system temperature varies across the day.

4.5 Brief Summary of Simulation Development Process

In order to put the simulation together as efficiently as possible, I built it in two major steps. During the first step, I created a simplified version of the simulation, which took account only of incident irradiance on a clear day, resistive heating, photon waste

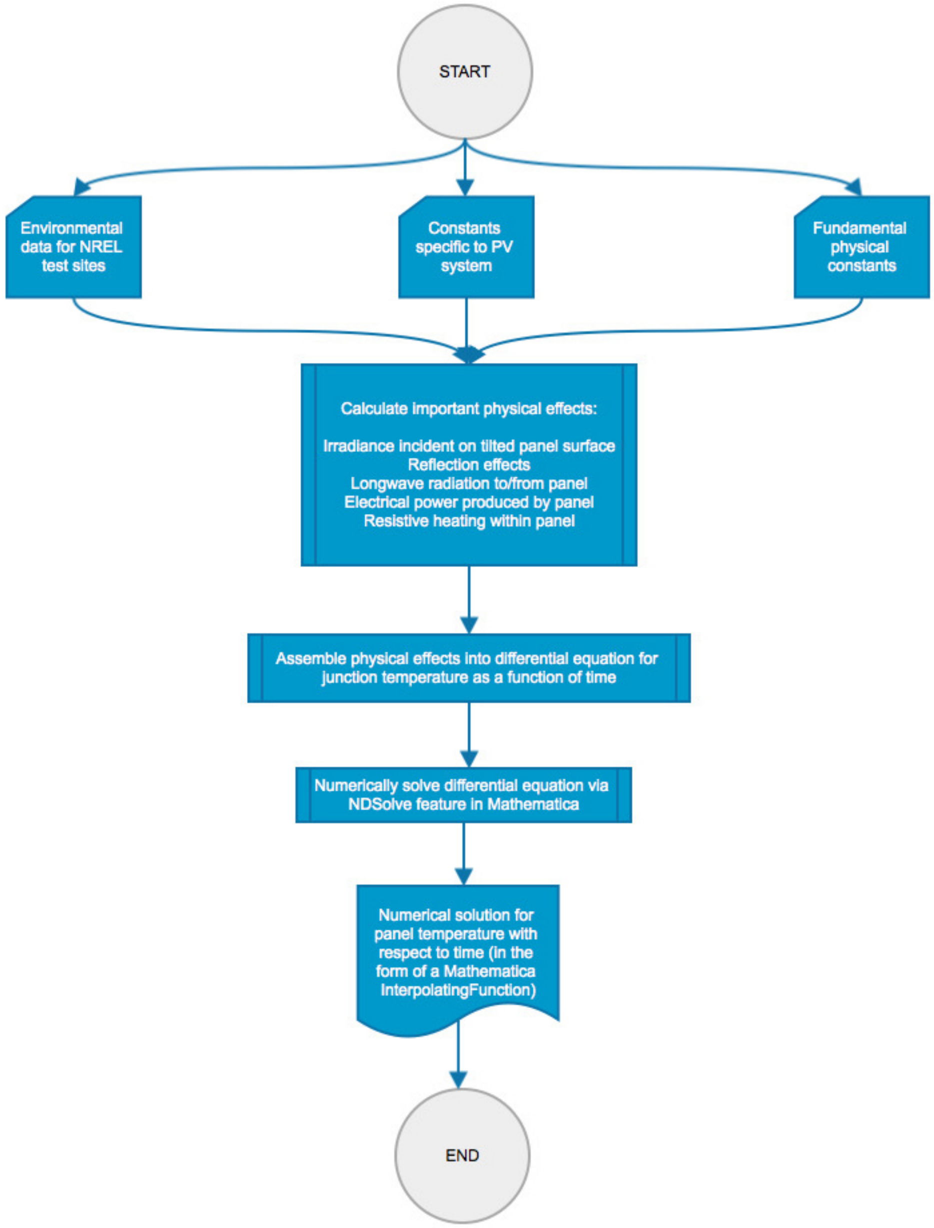


Fig 4.3 A flowchart showing the quantities and calculations involved in the simulation.

Input and outputs are written inside parallelograms, and complex calculations are written in rectangles with doubly-thick vertical sides.

heat, and electrical power production. Simplifications were made not only in the number of factors considered, but also in the equations used for the included factors. The second step, by contrast, featured the creation of a more complete program, taking into account all of the factors listed in Chapter 3.

My rationale for this sequence was as follows. Computer programming of all kinds generally involves a process of extensive error detection and removal. Based on my own prior experience, I knew that debugging could be quite a length process. I decided therefore to build a simple simulation that would be relatively easy to debug, and deal with the difficulties presented by its equations before moving onto a more complex simulation with more equations. I felt that this would be more efficient than trying to hunt for and fix everything at the end, and it would leave a greater chance of errors actually being found.

Flowchart diagrams of these simulation drafts are shown in Fig. 4.4.

4.6 Some Notes on the Programming Language Used to Write the Simulation

Simulations and other programs are written in *programming languages*, which serve to enable humans to write instructions for computers in an explicit and consistent manner (Schneider, Wiengart, and Perlman 2). There are many such languages in existence, but the one that I chose for my simulation is Mathematica 9.0.1. My reason for choosing this language, as opposed to a potentially more versatile one, comes down to familiarity and the existence of pre-defined calculations within Mathematica that can carry out complex calculations far more quickly than an unaided human could. For

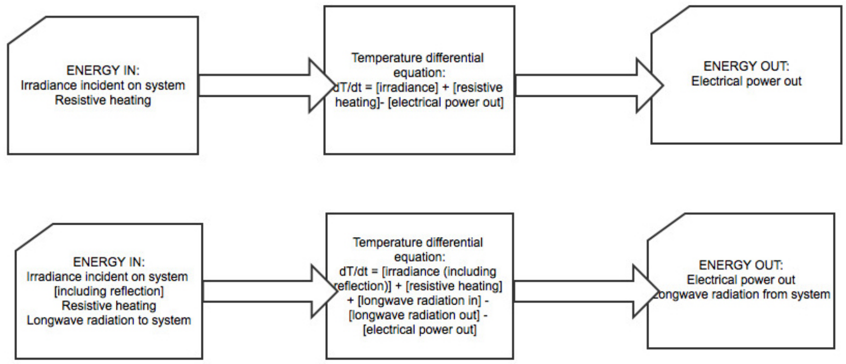


Fig 4.4 Diagrams illustrating the simplified and full versions of the simulation.

(a)The simplified simulation takes into account irradiance and resistive heating as phenomena that add energy (and power) to the PV system, and reflection by the system and electricity generated as phenomena that subtract energy (and power) to the PV system. These are the effects taken account of in the differential equation. The equations involved will have some simplifications. In a further simplification, this version is meant to model only a single PV cell.

(b)The full simulation takes into account the phenomena included in the simplified version, as well as longwave radiation to and from the panel (respectively as energy/power in and out). The equations will appear in this model in their full complexity. This version can model a cell, a panel, or a collection of panels. This version will also take into account cutoffs and caps imposed by inverters, as discussed in Chapter 3, as well as inverter efficiency.

instance, one of these packages enables the numeric solution of differential equations, using many possible methods and step sizes (Wolfram).

4.7 Accomplishments of the Simulation, and Notes on Some Problems

Our task is therefore to figure out how to translate combined power from all effects that the panel sees into temperature, and then to translate temperature into the power out of the panel.

I have constructed a simulation that factors in the power inputs and outputs given in Fig. 4.4 (b). It examines the effect of irradiance, resistive heating, and longwave radiation to the panel as additive inputs, and electrical power production and longwave radiation from the cell as subtractive inputs. The simulation begins with measured data for irradiance and temperature from an entire day, translates this data into a differential equation, solves the differential equation for temperature, and then uses the result to characterize the electrical output of a PV panel.

The panel that I chose to model is a SolarWorld Sunmodule SW 245 polycrystalline panel, with a Version 2.5 frame. I should also note that the model took account of reflection by the panel; this treatment is discussed further in Appendix F.

The simulation that I constructed puts out a numerical solution for the PV panel temperature as a function of time of day, over the course of a pre-selected day. The solution interpolates the temperature's behavior within the points obtained through numerical solution methods. A plot of such a solution is shown in Fig. 4.5 (a).

This simulation was also able to turn this temperature solution into electrical outputs that look partially reasonable. As can be seen in the remainder of Fig. 4.5, the fill factor, open-circuit voltage, and efficiency drop, and the short-circuit current and saturation current increase, as temperature increases. This is how these quantities should behave (Nelson 173). In addition, the maximum power that the panel can produce (which is what an inverter would allow to leave the panel) approximately follows the irradiance incident on the panel. From these general standpoints, the simulation is a success.

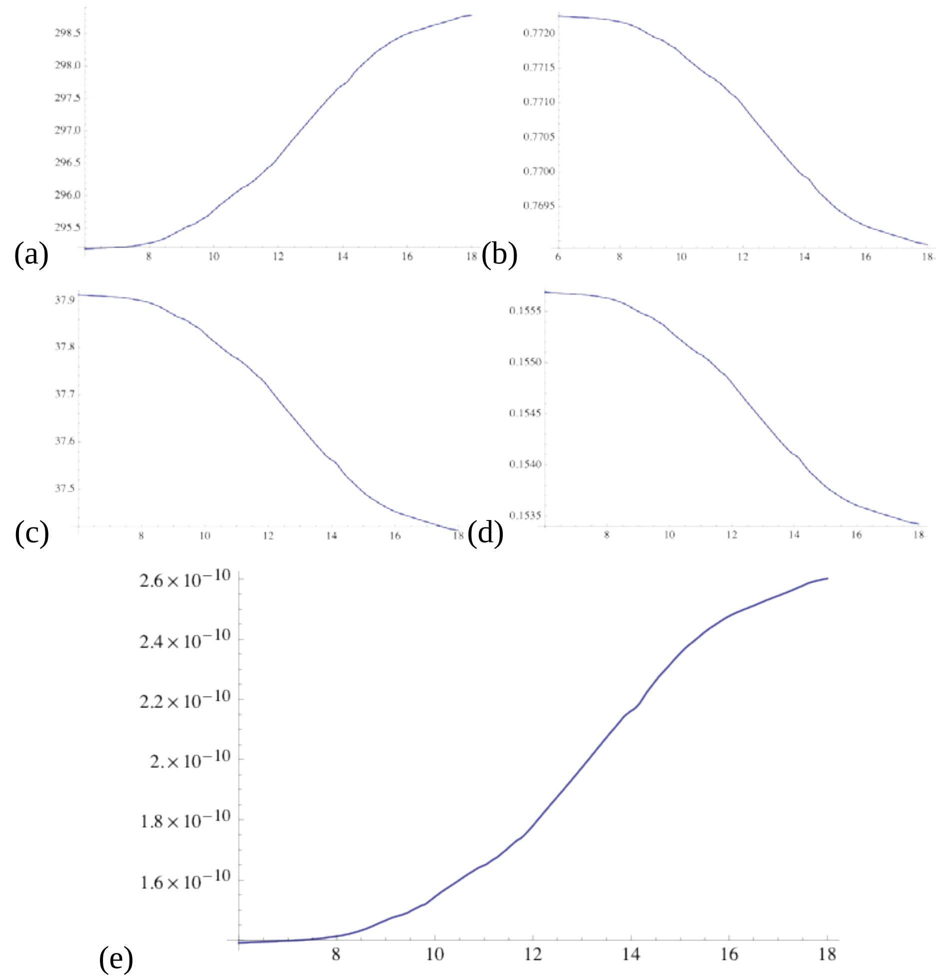


Fig 4.5 Examples of the code's accomplishments thus far.

All images created in Wolfram Mathematica 9.0.1 by the author, from NREL data for February 15, 2011, from the Kalaeloa Solar Resource & Meteorological Assessment Project (National Renewable Energy Laboratory, "20110215.csv").

(a)A plot of the numerical solution for the temperature of a PV panel versus time of day, obtained by my model. The solution takes the form of an InterpolatingFunction in Mathematica.

(b)A plot of the fill factor versus time of day, obtained from the numerical temperature solution

(c)A plot of the open-circuit voltage versus time of day, obtained from the numerical temperature solution

(d)A plot of the panel's efficiency, obtained from the numerical temperature solution.

(e)A plot of the saturation current, obtained from the numerical temperature solution.

For an explanation as to how the fill factor, open-circuit voltage, efficiency, short-circuit current, and saturation current were obtained from the numerical solution, the reader is directed to Appendix C.

Yet the simulation is not without problems. For one, the panel's temperature is nested neatly within the air temperature. It would be more realistic if the panel were substantially hotter than the air temperature (Mattei et al). The simulation is also really just a beginning step in understanding the technical performance of PV systems in Hawai'i. A truly comprehensive simulation should account more completely for inverter effects, for battery efficiency, and for issues with connection to and transmission over the grid (Masters 16-20, 521-584).

I will therefore discuss some possible future directions toward improving the code, beginning with fixing the apparent problem with the panel temperature, and ending with a discussion of adapting the code to additional realities of power production.

4.8 Adjusting the panel temperature

There are easy ways to check the code for additional errors: looking at units, checking the values being plugged in, looking for sign errors, etc. However, I think that any further improvement of the code should also take into account the possibility of missing effects.

One effect that I did *not* take into account was heating by reflection. A PV cell is covered in electrical contacts that are meant to receive the electrons that are freed up during the photovoltaic effect. These contacts can also reflect incoming light. The contacts lie underneath protective glass, which can reflect light from the contact back onto the cell. This extra energy heats the cell up (Vignola).

A very obvious route to future modification of the code would be to read through the literature to see if, and how, others have dealt with this problem. It seems like a sensible place to start, as it is an effect that my code does not include that can potentially contribute to extra heating.

In particular, I briefly discuss in Appendix C.1 a linear approximation that I adopted for the open-circuit voltage with respect to panel temperature. This approximation is a simplified version of an existing equation. One problem may therefore be that this simplification threw away too much physically important information.

4.9 Making the Code More Realistic

4.9.1 Connection to the Grid (Or Not)

Most PV systems that are put to practical use are connected to inverters. As discussed in the previous chapter, inverters contain particular cutoff points that ensure the safety of the grid, by making sure that a PV system does not produce too much power. One must also consider inverter efficiency. Both of these aspects are things that could be added to my simulation.

There are additional technical issues to consider, depending on whether the PV system is connected to the grid or is "[a] stand-alone system" (Masters 550). The utilities who administer grids choose to transport current at particular voltage differences – for Hawaiian Electric Industries, this is "138-kV" [sic] (Hawaiian Energy Industries, "Power delivery"). Additionally, power is lost as it travels along long wires, like those which would be found in a power grid (Masters 16-20). A stand-alone system is not free of difficulties either. Such systems frequently make use of batteries, which have their own issues relating to efficiency and storage (Masters 550-584).

4.9.2 Taking the Environment Into Consideration

Hawai'i is a diverse location. This diversity presents variables that can conceivably affect the functioning of a PV panel. In order for a quantitative study to be *truly* comprehensive, it must take account of *all* (or at least *most*) of these variables.

These variables consist of *daily temporal variables* (i.e. the time of day), *long-term temporal variables* (i.e. seasonal variation throughout the year), and *long-range locational variables* (i.e. different regions of the state with distinct climates and terrains). In the following sub-sections I will discuss the rationale for choosing to examine these three broad factors.

It would be ideal to simulate the effects of all of these conditions, based on existing data. Unfortunately, data on irradiance, wind, rain, and temperature are only accessible for a few locations within Hawai'i. These are all sites of measurements conducted by the National Renewable Energy Laboratory (NREL). The particular sites are two sets of instruments at Kalaeloa on O'ahu, one at La Ola on Lana'i, and one in

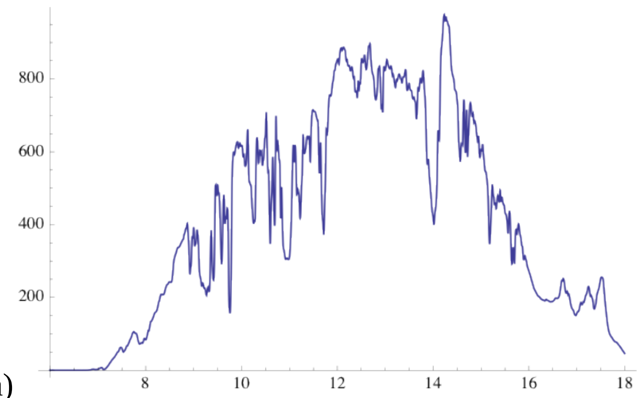
Kailua-Kona on the island of Hawai'i. While these sites have data taken all day for one-year periods and thus account very well for the temporal variables, they are representative of only a narrow range of locations, and so are probably not able to account for spatial variation.

It may be possible to make educated guesses as to what performance in different terrains would look like. There are calculational tools that enable these types of guesses. However, this would venture outside the comfort provided by NREL's data.

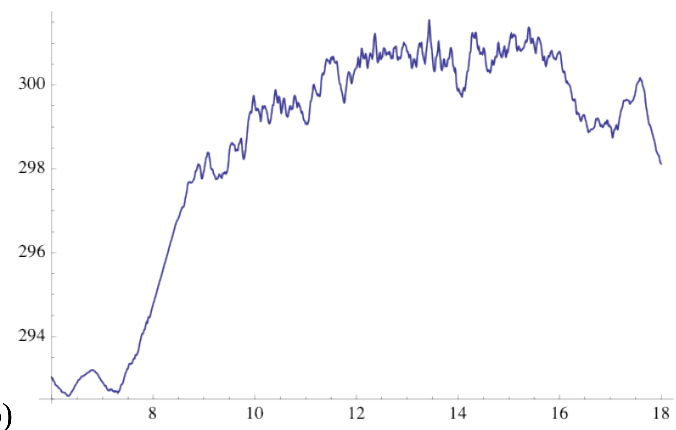
4.9.2.1 Time of Day

It seems fairly obvious that time of day would influence the performance of a PV panel. One can graph the global horizontal irradiance taken on a particular day at one of the sites at Kalaeloa, as is done in Fig. 4.6 (a), and observe the general bell-shape of the irradiance as it increases during the morning and drops back down during the afternoon. (The jaggedness is probably caused by cloud cover.)

The temperature of the environment, as represented by NREL's air temperature data also varies during the day. This variation may affect the nature of the temperature differential equation, through changes in the longwave radiation that reaches the PV panel from the sky. (The connection between air temperature and sky longwave radiation is discussed in more mathematical detail in Appendix G.) One such instance of air temperature variation is shown in Fig. 4.6 (b).



(a)



(b)

Fig 4.6 Variation of irradiance and temperature within each day, from the same date and site as featured in Fig. 4.5 (NREL, “20110215.csv”).

Plots generated in Wolfram Mathematica 9.0.1 by the author.

(a)Irradiance data points (in Wm^{-2}) paired with time (in hour-fraction units).

(b)Air temperature data points (in degrees Kelvin) paired with time (in hour-fraction units).

4.9.2.2 Time of Year

Unlike in the mainland United States, Hawai’i has essentially *two* seasons. According to the National Oceanic and Atmospheric Administration (NOAA), these seasons cut the year into two seasons: a cool, rainy one from May to October, and a hot, dry one from October to April (National Weather Service Honolulu Forecast Office).

Cloud cover, with all of its associated effects on radiative transfer, varies throughout the year. The nature of the sunlight falling on the panel is therefore not necessarily the same at two given times of the year. This makes it necessary to have data from throughout the year, at each individual site.

4.9.2.3 Location

As mentioned in the last chapter, the ground can reflect light into the PV panel *and* back into the air as well, adding to the effects of radiative transfer in the atmosphere. The fundamental quantity for this process is the “albedo” of the ground, the amount of light that is reflected (Jacobson 14).

Changes in terrain can change the albedo of the ground. Joseph R. Morgan identifies five different types of terrain: “Rain Forest,” “Dry Forest,” “Arid Scrub,” “Upland Scrub,” and “Strand Vegetation” (Morgan 43-45). I have added my own classifications, based on my own experience as a longtime Hawai’i resident: Urban, Suburban, and Beach/Shorefront.

Changing location also changes climate, in a similar fashion as changing the time of year. One can identify seven major climate areas within Hawai’i: “Windward Lowlands,” “Leeward Lowlands,” “Interior Lowlands,” “Kona Coast,” “Rainy Windward Mountains,” “Lower Leeward Mountains,” and “High Mountains” (Morgan 29). So location is just as important a variable as time, with respect to its ability to change weather conditions

In fact, two weather conditions that should probably be taken into greater account are rain and wind. Both of these may be able to cool PV panels. Some exiting simulations (Koech et al) incorporate the latter. Adding these phenomena could bring forth a more accurate picture of climate's effect on panel temperature and functionality.

4.10 Conclusions

It is possible to model the functioning of a PV panel through generating and solving a differential equation for the panel's temperature with respect to time. While my model produces the correct general trends in output power and its associated quantities, though, it is not accurate with regard to the total power increase over the course of a day.

There may be avenues for improvement in future endeavors. Such avenues could not only correct the aforementioned inaccuracy, but also make the existing code compatible with realistic electrical generation schemes. As a result, the code could become a powerful tool for predicting PV panel performance in the future.

5. Real-Life Issues with PV Implementation: Policy, Economics, and Business

5.1 Introduction

Having explored the technical capabilities of PV systems, it is now time to return to where the project, by looking at the future of solar energy in the state of Hawai'i.

From Chapter 2, the reader may understand that solar has a great deal of economic promise in Hawai'i. The preceding two chapters may lead to a glimpse of its physical promise as a power generator. But conditions that are favorable in theory do not always play out in a favorable way. Here, we return to the example of fusion, brought up in Chapter 2. We must consider whether the technical, commercial, and green political advantages identified in Chapter 2 are really that helpful for the solar industry.

What follows is a summary gleaned from reading current events related to Hawai'i's solar industry over the last two years, paired with conversations with figures in business, the government, and the public. This summary presents the main lessons that I have learned about the current state of solar energy in Hawai'i, and its possible future state. This is not a detailed report, although when details are necessary, they are brought in.

In addition to summarizing my findings, this chapter also aims to develop a framework that can be used to analyze the conflict between the local PV industry's stakeholders. This framework has been developed in detail with regards to a conflict involving the Hawaiian Electric Company (HECO), HEI's O'ahu subsidiary [ref]. Yet I would like to postulate that the essence of this framework is generalizable to any stakeholder conflict, as it is built from insights gained into the apparent intents and perceptions that each stakeholder holds toward the other.

Finally, I will note that the readings and conversations that led to these conclusions can be found in the Bibliography.

5.2 The Main Stakeholders in the Solar Industry and Their Interests

There are three main groups that stand to gain and/or lost something within the solar industry. The first group is the industry itself; that is to say, the companies involved in distributing and installing PV systems. Secondly, there are the customers that the solar industry seeks to serve. Last but not least are the institutions charged with transitioning Hawai'i to a situation in which a significant amount of its power comes from renewable energy.

Each of these stakeholders has its own desires for what the future wants to be, and motivations for pursuing this future. At times, the stakeholders' interests are perfectly aligned, and the three groups work in synergy. Other times, this is not the case. These interests are summarized in Fig. 5.1, and are explained in detail below.

Businesses within the industry want to stay in business. Representatives of multiple companies, including senior executives, have repeatedly told me that in order to stay in business, they need people to continue to buy their products. They do not want anything to happen that would cause business to decline.

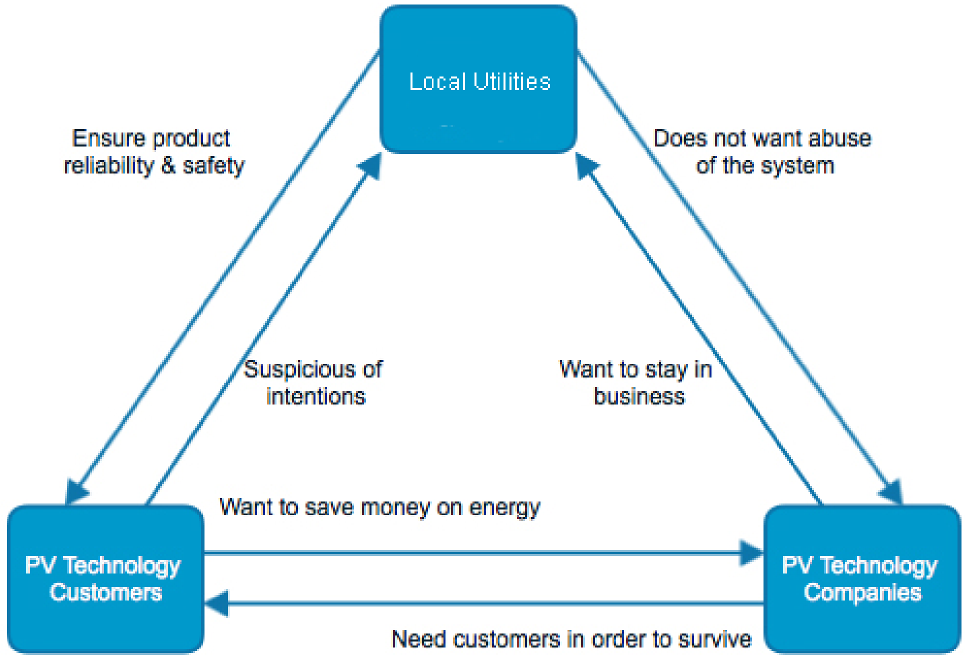


Fig. 5.1 A diagram illustrating the relationships between local utilities, PV technology companies, and PV technology consumers.

The potential institutional customers with whom I have spoken have had somewhat more idealistic concerns. They believe in helping a movement that is ultimately good for the planet. Their desires are driven by a belief in what is right.

I have also read news profiles of residential customers, who are motivated in part by a desire to do good, but also by a desire for reprieve from the high electricity costs discussed in Chapter 2. The state government formerly offered generous tax credits for individuals who had installed solar power (Yonan, "State unveils"). The original credits functioned alongside credits from the federal government. Residents feel that solar power should alleviate expenses.

The utilities who oversee net-metering and other aspects of the grid are officially driven to prevent disasters related to “grid instability,” when a single blip in a power grid can cause far-reaching effects within that grid. An incident in Germany illustrates the hazards of grid instability. A factory powered entirely by PV sustained “12,300” in “damage” after an extremely short change in the output of its power source (Schröder). Utilities are also bound by the state government’s mandate to facilitate increased adoption of renewable energy sources. Hawaiian Electric Industries (HEI), which provides power to five islands (Oahu, Maui, Hawaii Island, Lanai and Molokai), is also a private business. Just as solar companies feel the need to ensure their corporate survival, it would not be unimaginable if HEI were to feel the same way about its own operations: in fact, one of its subsidiaries, Hawaiian Electric Company (Hawaiian Electric Industries, “about”), has recently expressed its fear that the expansion of the solar energy industry may force it out of existence (Thomson).

5.3 Present Conflicts Between Stakeholders

As mentioned above, when the stakeholders’ interests align, then the energy industry is very productive. Discord can create chaos.

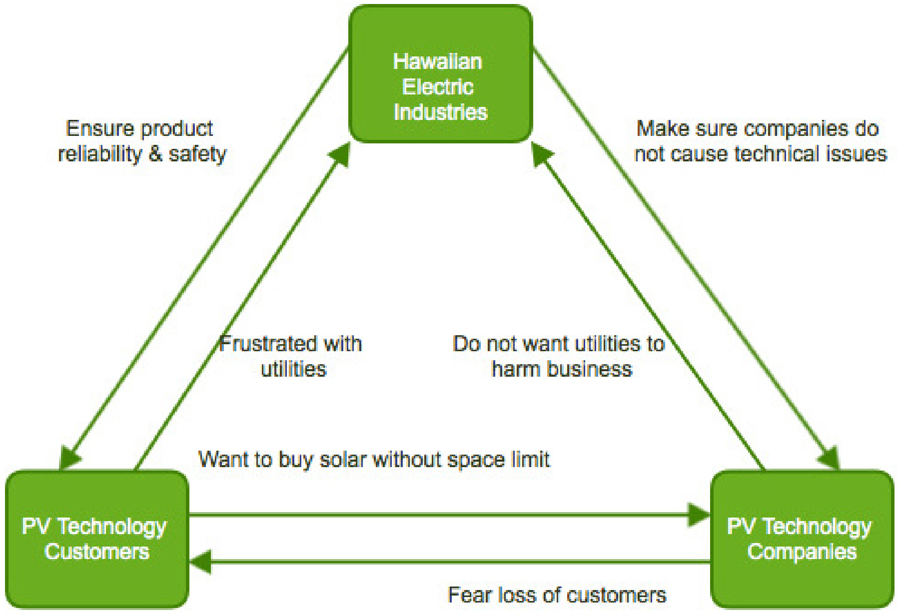
On Kaua’i, this conflict has become manifest in the opposition to smart meters described in Chapter 2, in which opponents felt that utilities ignored their desires for good health and privacy. Meanwhile, Hawai’i Energy Industries is having its own set of conflicts. In order to prevent grid instability, it proposed that new customers pay money to conduct new studies to check the robustness of the grid (Cocke, “Want Soar Panels?”). This ran afoul of both customers, who wanted to save money through installing PV systems (Yonan, “Solar saturation proves costly”), and of solar businesses, who (according to the representatives I got to speak with), were concerned about their market shrinking as customers move away from installing solar. A similar furor broke out over a proposed (and ultimately accepted) curtailment of tax benefits, for the same reasons (Yonan, “Solar squeeze”). These actions and reactions are outgrowths of the general attitudes described earlier, and can similarly be depicted diagrammatically in Fig 4.2.

It is worth noting that the first conflict may have been resolved: HECO lifted its cap on new installations, in exchange for new rules governing installation procedure (Yonan, “More homes”). However, this does serve to let us know that PV’s technical feasibility is not determinant of its success. When stakeholders decided to fight over whether PV will be widely adopted, the future of PV became less clear.

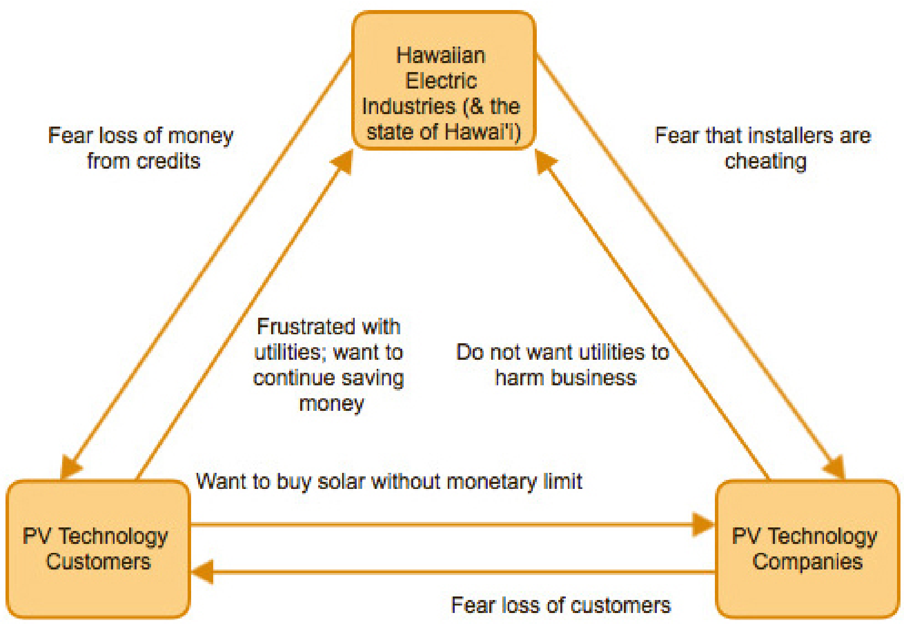
5.4 A Future Conflict?

One should also note that even if PV continues to thrive as a viable technology, the character of its implementation is not necessarily clear.

I was able to speak with a bookstore owner based out of O’ahu. He expressed a desire to install a PV system, since it was, after all, the right thing to do. However, both balked at the expense of the venture involved. The bookstore owner said that in order to install the right amount of PV technology, he would have to put more stress on finances that are already under a great deal of pressure (Percy).



(a)



(b)

Fig 5.2 Diagrams of conflicts involving Hawaiian Electric Industries, using the framework illustrated in Fig 4.1 to illustrate the stakeholders' mutual intents and suspicions.

(a) Summary of the conflict over grid instability.

(b) Summary of the conflict over tax credits.

Meanwhile, one can go on the Internet and find photographs of large business' rooftops drenched in solar panels. Sunetric, a local company, displays such photographs for past customers including Honda Windward, King Windward Nissan, and Wilcox Memorial Hospital (Sunetric).

It seems that within the consumer stakeholder group, there may be at least two additional sub-groups, consisting of those with more income and those with less. If the aforementioned disparity is any indication, then there may be an additional class of conflicts yet to come, as the positive impacts of PV benefit customers unevenly, despite any intent to save or do good for the world.

5.5 Conclusion

As with Chapters 3 and 4, Chapter 5 set out to develop a model of sorts to describe an aspect of the solar PV industry in Hawai'i. Yet whereas the quantitative simulation focused on building a differential equation to predict PV performance, the above discussion sought to synthesize a series of (arguably) semi-mechanistic relationships between stakeholders. The predictable and generalizable nature of these relationships serves as a springboard from which to describe conflicts as events that are, basically, predictable. In a way, this framework serves as the counterpart to the quantitative model, which sought to derive the functionality of a PV panel from datasheet values and irradiance data.

The reader would be correct in noting that this framework depends on *human opinion*. Unlike the laws of physics (and their approximations), preferences can change in response to anything at all. The framework's accuracy therefore depends on the attitudes of stakeholders during a particular snapshot in time, i.e. the early 2010s. It would not be crazy to speculate that the framework might not work at all in another ten years, as stakeholders' desires and beliefs change. The framework *should* be modified, according to these changes, in order to remain accurate.

However, for the here and now, the framework appears to be an accurate descriptor of the current conflicts relating to the PV industry within Hawai'i, and may therefore be able to serve as a tool for future analysis.

6. Summary and Final Conclusions

6.1 Introduction

Having described a parallel set of efforts, we now end with a discussion of what has been accomplished and what can be done for further improvement. The aim of this chapter is to situate the Thesis project as a possible starting point for future research toward understanding the future possibilities within Hawai'i's solar energy industry.

6.2 Overview of quantitative simulation

6.2.1. Summary of Approach

In order to understand the technical potential of PV technology, I sought to create a simulation to predict the performance of a PV panel. The simulation's conceptual starting point was to treat the panel as an electrical circuit, as this would not only be relatively simple from the mathematical standpoint, but would also allow me to directly use datasheet values for a given PV panel (following the treatment from Villalva, Gazoli, and Filho.)

The simulation was written in Wolfram Mathematica 9.0.1. I intended for it to assemble a differential equation for the panel temperature with respect to time, taking into account irradiance incident on the panel (including reflective losses and panel tilt), resistive heating, and lonwave radiation to the panel as additive inputs; and electrical power generated by the panel, and longwave radiation from the panel as subtractive inputs. My irradiance input came from NREL data from its Kalaeloa Solar Resource & Meteorological Assessment Project.

It is worth noting that I made many approximations in order to simplify the simulation. These approximations are discussed in detail in the Appendices.

6.2.2 Results and possible areas for improvement

The simulation did produce quantitative results that behaved, in general terms, as they should. As the panel's simulated temperature increases, its diode saturation current (from the circuit model) increases, while its fill factor, open-circuit voltage, and efficiency decrease. This behavior is consistent with what is known about the physical mechanisms of PV panels.

On the other hand, the total temperature increases seen were far too low to be physically accurate. This implies that there is something wrong with the simulation. This may have been due to some of the aforementioned simplifications, and one course of action may be to review the literature once again, in order to understand how others have surmounted or sidestepped this difficulty.

Alongside these concerns, the simulation needs to be made more realistic, to accurately model grid connection or connection with stand-alone systems. In addition, the simulation might be expanded to account for climate and terrain, as these may affect radiative transfer, ground-reflected irradiance, convective heat transfer, and any thermal effects that come from rain. (For these same reasons, the time of year should also be a variable, as these factors vary in intensity as seasons change.)

6.3 Overview of Policy/Economics/Business Framework

By coupling conversations with stakeholders alongside studious attention to current events, I was able to synthesize a model that appears to describe current interactions and conflicts between the solar industry's major stakeholder groups. These groups are the industry itself, the industry's customers, and the government/utilities.

The model is based upon the apparent intents and attitudes of each group, especially with regard to dealings with other groups. It provides a concise tool to analyze relations between stakeholder groups. For example, Hawaiian Electric Industries' fears over consumer safety and satisfaction led it to take measures to prevent grid instability; in turn, solar companies fought back for fear of losing their business (and therefore their existence), and customers fought back to retain their right to relatively cheap PV power.

This framework's accurate simplicity appears to make it a compelling tool for future analysis; however, it may need to be updated depending on how the stakeholder groups' intents and attitudes change with time.

6.4 Final Conclusions

It appears, then, that although the tools this Thesis produced are not perfect, that they do provide a gateway to further research efforts. Many possible future improvements are obvious, and could be carried out within the realm of possibility. Furthermore, it is the overall *simplicity* of the tools, in concept and (to a degree) in use, that give them the greatest potential. Properly polished, they may allow researchers to cut through tangles of facts and opinions, in order to obtain hard (or at least clear) predictions.

I hope to continue this work, as a graduate student or in some other capacity, to further develop the products presented herein. And if I am not able to do so, I hope that the reader may be motivated to continue this work.

Appendices

Note to the reader: These appendices contain material explaining the quantitative details of the simulation used to model PV temperature and functionality; i.e. the derivations of the components of the temperature differential equation. These sections contain content that assume basic and/or intermediate mathematical acquaintance with calculus quantum mechanics, analog electronics, thermodynamics, and fluid mechanics.

Appendix A: Analog Electronics Treatment of PV Systems

As discussed in §3.4, the model that I use treats a PV system as a current generator in parallel with a diode in parallel with a parallel resistance; in addition, a series resistance lies between the parallel resistor and the voltage to which the circuit is connected. The components of the circuit represent steps in photovoltaic energy conversion: the current source provides the photocurrent in response to incident irradiance, the diode allows dark current to flow in the opposite direction, the series resistance impedes the flow of current between cells (and panels connected in series), and the parallel resistance impedes the flow of current between panels connected in series (Tiwari and Dubey 465, Villalva, Gazoli, and Filho 1-2).

The circuit model I programmed is closely based on the one presented in Villalva, Gazoli, and Filho in their conference paper, "Modeling and circuit-based simulation of photovoltaic arrays," which provides both an explicit quantitative circuit model (whose circuit design is the one that I used in my simulation and have summarized above) and an explicit correspondence between "datasheet" values and relevant quantities within the circuit (Villalva, Gazoli, and Filho, abstract). The latter feature served as a great benefit to my simulation.

The circuit diagram for this model is reproduced in Fig. A.1. The equations describing the electrical quantities within the circuit are given below. The *I-V* equation is given by (Villalva, Gazoli, and Filho 2)

$$I = I_{pv} - I_0\left[\exp\left(\frac{V + R_s I}{V_t a}\right) - 1\right] - \frac{V + R_s I}{R_p}$$

where I_{pv} is the photocurrent, I_0 is the diode saturation current, V is the voltage to which the circuit is connected, R_s is the series resistance, R_p is the parallel resistance, a is the "diode ideality constant" (Villalva, Gazoli, and Filho 2), and

$$V_t = \frac{N_s k_B T}{q}$$

is the thermal voltage. In the last equation, N_s is the number of "cells connected in series" (Villalva, Gazoli, and Filho 2), k_b is Boltzmann's constant (in this equation, equal to "1.3806503 x 10^{-23} J/K" (Villalva, Gazoli, and Filho 2), rounded to 1.381 x 10^{-23} in my simulation), T is the temperature of the *p-n* junction, and q is the charge on an electron (in this equation, equal to "1.60217646 x 10^{-19} C" (Villalva, Gazoli, and Filho 2), rounded to 1.60217646 x 10^{-19} C, in my simulation).

I chose to model the SolarWorld Sunmodule SW 245 polycrystalline panel with a Version 2.5 Frame. The datasheet states that states that this model has 60 cells. It does not say whether they are connected in series; however, most panels *should* have *only* series connections (Nelson 4-5); so it does not seem too absurd to assume that N_s = 60. I also set a equal to 1 (in general, 1 < < 2) (Nelson 15).

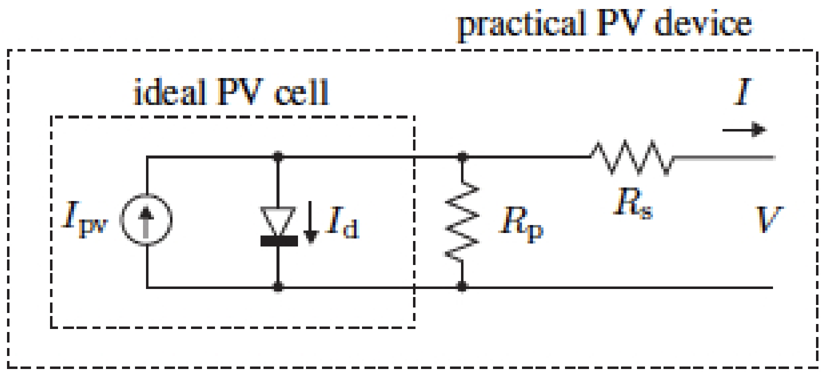


Fig A.1 The circuit diagram used to build my simulation, from Villalva, Gazoli, and Filho's treatment, from Fig. 1 of Villalva, Marcelo Gradella Villalva, Jonas Rafale Gazoli, and Ernesto Ruppert Filho, "Modelling and Curcuit-Based Simulation of Photovoltaic Arrays" (*10th Brazilian Power Electronics Conference (COBEP)* n.v. (2009): n.p; Web; 7 Jul 2013; 1).

In order to accurately model the effects of temperature on electrical power output and vice-versa, I decided to model the temperature dependence of resistance so that

$$R(T) = R_0\left[1 + \alpha\left(T - T_0\right)\right]$$

for "temperature coefficient of resistance" α, reference temperature T_0, and $R_0 = R(T_0)$ (Kuphaldt). I chose to let the temperature coefficient for the series resistance equal to $4.5 \times 10^{-3}\ K^{-1}$, the average of the coefficients given for metals ("Electrical resistance and conductance"), the parallel temperature coefficient equal to the same quantity, T_0 equal to the STC panel temperature, and R_0 for the parallel resistance equal to 500Ω. As Villalva, Gazoli, and Filho point out, the parallel resistance should be quite high in a good PV device (Villalva, Gazoli, and Filho 2); hence, my choice for a high parallel resistance. The value of R_0 for the series resistance was set equal to 0.28Ω after a benchmarking process described in Appendix C.

Now I will discuss the calculation involved in determining the other quantities used in the model. As stated above, these values can be obtained form datasheet values. These values are taken at a particular temperature and under exposure to a particular irradiance. Villalva et al term these “nominal” quantities (Villalva, Gazoli, and Filho 2-3); therefore, I will do the same. Starting with the photocurrent, we have that

$$I_{pv} = \left(I_{pv,n} + K_I \Delta_T\right)\frac{G}{G_n}$$

for nominal photocurrent $I_{pv,n}$ taken at “nominal temperature” T_n and under “nominal irradiance” G_n, non-nominal irradiance G, quantity $\Delta_T \equiv T - T_n$ and “short-circuit/temperature coefficient K_I” (Villalva, Gazoli, and Filho 2). From the datasheet, I derived a value of $K_I = 8.49A \times [0.081/100]K^{-1} \approx 0.00688AK^{-1}$ (SolarWorld 2).

Villalva et al assume that the photocurrent is approximately equal to the short-circuit current, since for good panels the parallel resistance should be very high and the series resistance should be really low (Villalva, Gazoli, and Filho 2). This is an assumption that I used as well.

The diode saturation current is equal to (Villalva, Gazoli, and Filho 2)

$$I_0 = I_{0,n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right]$$

for nominal diode saturation current (Villalva, Gazoli, and Filho 2)

$$I_{0,n} = \frac{I_{sc,n}}{\exp\left(\frac{V_{oc,n}}{aV_{t,n}}\right) - 1}$$

(where $I_{sc,n}$ is the nominal short-circuit current, $V_{oc,n}$ is the nominal open-circuit voltage, and $V_{t,n}$ is the nominal thermal voltage).

In order for the above saturation current equation to work, the bandgap must be treated as a constant. This is the treatment that I followed, using Villalava, Gazoli, and Filho's quoted value of "1.12 eV" (Villalva, Gazoli, and Filho 3). This is not necessarily a physically accurate assumption. The bandgap energy *does* change with temperature; the same paper offers the following equation for "the best value (…) for the model so that the open-circuit voltages of the model are matched with the open-circuit voltages of the real array in the range $T_n < T < T_{\max}$" (Villalva, Gazoli, Filho 3). This equation is given by (Villalva, Gazoli, Filho 3)

$$E_g = -\ln\left[\frac{\left(\frac{I_{sc,T\max}}{I_{0,n}}\right)\left(\frac{T_n}{T_{\max}}\right)^3}{\exp\left(\frac{qVoc,T\max}{aN_s k_B T_{\max}}\right) - 1}\right]\frac{ak_B T_n T_{\max}}{q(T_n - T_{\max})}$$

for (Villalva, Gazoli, and Filho 3)

$$I_{sc,T\max} = I_{sc,n} + K_I\left(T_{\max} - T_n\right),$$
$$V_{oc,T\max} = V_{oc,n} + K_V\left(T_{\max} - T_n\right)$$

where K_V is "the open-circuit voltage/temperature coefficient" (Villalva, Gazoli, and Filho 2). I had intended to treat this model in such a way that T_{max} was equal to the cell temperature. A problem comes up, though, if the cell temperature is ever equal to the nominal temperature, as this would cause the denominator to equal zero. To avoid this risk. I therefore chose to treat the bandgap energy as a constant.

This circuit model also enabled me to determine the resistive heating for the PV panel. The amount of power dissipated (as thermal energy) by a current I passing through a resistor R is

$$P_{resistive} = I^2 R$$

For a case in which the parallel resistance is very high, and in which the current approximately flows through just the series resistor and not the parallel resistor, the current *I* flowing through the series resistor is equal to

$$I = \frac{P_{electrical,out}}{V}$$

and so the resistive heating effect is equal to

$$P_{resistive} = R_s \frac{P_{electrical,out}}{V}$$

In the case in which the current flows substantially through *both* the parallel *and* the series resistor, then this power has the form

$$P = I_s^2 R_s + I_p^2 R_p + I_o^2 \left[\mathrm{Exp}\left(\frac{V + R_s I}{mV_t} \right) - 1 \right]^2 Z_d$$
$$= I^2 R_s + I_p^2 R_p + I_o^2 \left[\mathrm{Exp}\left(\frac{V + R_s I}{mV_t} \right) - 1 \right]^2 Z_d$$

for current $I_s = I = \frac{P_{electrical,out}}{V}$ flowing through the series resistor and I_p flowing through the parallel resistor, and diode impedance Z_d. It turns out that (Gan slide 2)

$$Z_d = 25\Omega I_0^{-1} \left[\mathrm{Exp}\left(\frac{V + R_s I}{mV_t} \right) - 1 \right]^{-1}$$

We can also solve for I_p. We do this through Kirchoff's Current Law. We know that

$$I_s = I = I_{pv} - I_0 \left[\exp\left(\frac{V + R_s I}{V_t a} \right) - 1 \right] - I_p$$

If we set this equal to the initial *I-V* equation for this model we find that

$$I_p = \frac{V + R_s I}{R_p}$$

Therefore, the full resistive heating equation is

$$P = I^2 R_s + \frac{(V + R_s I)^2}{R_p} + 25\Omega I_0 \left[\mathrm{Exp}\left(\frac{V + R_s I}{mV_t} \right) - 1 \right]$$

Once I numerically solved the temperature differential equation in Mathematica, obtaining an interpolating function for the temperature as a function of time, I was able to plug this temperature in for T, and obtain the power output for a PV system, factoring in the effects of energy inputs on the panel's temperature.

Appendix B: Calibration of the Resistances

Villalva, Gazoli, and Filho also describe a technique by which the series and parallel resistances can be benchmarked. This is an "iterative process" in which resistance values are varied until "the peak of the mathematical *P-V* curve coincide[s] with the experimental peak power at the (V_{mp}, I_{mp}) point" (Villalva, Gazoli, and Filho 4). I chose to implement essentially this method, by solving for the output power (via a solution for $I(V)$ found in Mathematica for the *I-V* equation), I varied the value of R_0 for the series resistance, until I obtained a value that seemed to approximately pair the datasheet's voltage for maximum power at STC (30.8 V) with its current at maximum power (7.96 A), *and* that maximized $P_{electrcal,out}(V)$ at approximately 245 W, the datasheet value (SolarWorld 2).

I was able to show that a series value of R_0 equal to 0.28Ω produced a power output with a maximum of 245.28 W and a corresponding voltage of 7.96248 V. The maximum power current is for this series R_0 is therefore equal to approximately 30.804 A. These values are in good agreement with the datasheet values. Therefore, I chose to let the series R_0 equal 0.28Ω in my simulation.

I should briefly detour to discuss the solution that Mathematica provided for the output current. This solution takes the form

$$I(V,T) = \frac{1}{R_s\left(R_s + R_p\right)}\left(\begin{array}{l} -30.8R_s + R_sR_p\left(I_{pv} + I_0\right) \\ -\left(R_s + R_p\right)aV_t\text{ProductLog}\left[0, \dfrac{\mathrm{I}_0 R_s R_p \,\text{Exp}\left[\frac{R_p\left(30.8 + R_s\left(I_{pv} + I_0\right)\right)}{aV_t\left(R_s + R_p\right)}\right]}{aV_t\left(R_s + R_p\right)}\right] \end{array}\right)$$

where the ProductLog function is the Lambert *W* function (Weisstein). This function was plottable, and as stated above it could be numerically manipulated.

Yet I did not use this function to determine the maximum power point. What was my reason for this choice?

It turns out that this solution applied under certain conditions on the quantities involved in the *I*-*V* equation. These conditions held in the regime of STC, where I was calibrating the series resistance. But that did not mean that they would hold in other environments that panels in Hawai'i would be exposed to.

Mathematica did offer alternative solutions to alternative conditions, yet I deemed that it would be too complicated to decide which conditions held at any given time of day and year. Instead, there is a simplified approximation for the maximum power as a function of temperature, that also can be made to yield an approximation of the fill factor. A discussion of this model takes place in the following Appendix.

Appendix C: Power Output and Sanity Checking

However, these equations alone do not give us a complete model of the PV panel's power output.

As stated in Chapter 3, the maximum power out of the panel (which is what an inverter puts out, allowing for inverter efficiency and input cutoffs) is

$$P_{electrical,out,\max} = FF \bullet I_{sc} \bullet V_{oc}$$

where *FF* is the fill factor.

It is possible to obtain a linear approximation for the maximum power by simply multiplying the incident irradiance GHI_{panel} by a temperature-dependent equation for "electrical efficiency" (Tiwari and Dubey 104). So in some sense, it is unnecessary to calculate *FF* or V_{oc}. (Given the approximation used in the circuit model that equates the photocurrent with the short-circuit current, I_{sc} would still be necessary).

Yet calculating and plotting *FF* with respect to the numerical solution for the panel's temperature, alongside V_{oc}, I_{sc}, and I_0 can provide a quick and vital sanity check of the code's functioning. As temperature increases, the former two quantities should decrease (thermal excitation of electrons drops V_{oc}, which in turn drags down *FF*), and the latter two quantities should increase (thermal excitation makes more electrons available to join I_{sc} and I_0) (Nelson 173). If the quantities in question do *not* behave in this manner, then there would seem to be an indication of a problem somewhere in the code. Plots of these four quantities can therefore serve as the proverbial canary in the coal mine, and alert the simulation's user to potential errors that could jeopardize the code's results.

One should also not underestimate the pedagogical value in including plots of *FF*, V_{oc}, I_{sc}, and I_0 either. Creating these graphs can serve as a quick yet powerful demonstration of the physics that makes PV energy work.

I will now thus discuss the determination of V_{oc} and *FF*, based on simple linear models.

C.1. The MER Model for Efficiency and Open-Circuit Voltage

Sandia National Laboratories has developed a tool called "the MER model," which provides approximations of relevant electrical values (Skoplaki, Boudouvis, and Palyvos 1393-1395). This model "linearizes" the additive temperature effects on I_{sc}, and the deleterious effects on V_{oc} and electrical efficiency η_{pn}, as (Skoplaki, Boudouvis, and Palyvos 1393-1395)

$$I_{sc} = \frac{GHI_{panel}}{GHI_{panel,ref}} \left[I_{sc,ref} + K_I \left(T_{pn} - T_{ref} \right) \right]$$

$$V_{oc} = V_{oc,ref} \left[1 + \frac{K_V}{V_{oc,ref}} \left(T_{pn} - T_{ref} \right) \right] \left[1 + \delta(T) \ln \left(\frac{GHI_{panel}}{GHI_{panel,ref}} \right) \right],$$

$$\eta_{pn} = \eta_{ref} \left[1 - \beta_{ref} \left(T_{pn} - T_{ref} \right) + \gamma \log_{10} GHI \right]$$

where (Skoplaki, Boudouvis, and Palyvos 1393-1395)

$GHI_{panel,ref}$ is some reference irradiance,
$I_{sc,ref} = I_{sc}$ at $GHI_{panel} = GHI_{panel,ref}$, $T_{pn} = T_{ref}$,
$V_{oc,ref} = V_{oc}$ at $GHI_{panel} = GHI_{panel,ref}$, $T_{pn} = T_{ref}$,
K_V = open circuit voltage/temperature coefficient (as in Appendix B),
$\eta_{ref} = \frac{P_{electric,out}}{GHI_{panel}}$ for output electrical power $P_{electric,out}$ $(T_{pn} = T_{ref})$
$\beta_{ref} = \frac{1}{T_0 - T_{ref}}$ (T_0 = 546.15 K in "crystalline silicon" (Skoplaki and Palyvos 615)),
GHI_{panel} = total irradiance incident on panel,
$\gamma = 0.12$ (again "for crystalline silicon modules" (Skoplaki and Palyvos 615))

The first of these equations is familiar from the circuit model. The latter two require a bit more explanation.

With respect to V_{oc}, K_V, as with K_I, can be gleaned from the datasheet. Its value is 37.5 V x [(-0.37)/100] K^{-1} = -0.13875 (SolarWorld 2). I should also note that I used a simplified version of the second equation, given by

$$V_{oc} = V_{oc,ref} + K_V\left(T_{pn} - T_{ref}\right)$$

which I rationalize by pointing out that Villalva, Gazoli, and Filho propose replacing the diode saturation current equation given in Appendix A with (Villalva, Gazoli, and Filho 3)

$$I_0 = \frac{I_{sc,n} + K_I\left(T - T_n\right)}{\exp\left[\frac{V_{oc,n} + K_V\left(T - T_n\right)}{mV_t}\right] - 1}$$

for the more correct bandgap equation. The effect of this is to essentially linearize the voltage in “the Shockley diode equation” (Villalva, Gazoli, Filho et al 1),

$$I_d = I_{0,cell}\left[\exp\left[\frac{qV}{mk_BT}\right]-1\right] \text{ (one PV cell, no resistances)}$$

$$= I_{0,cell}\left[\exp\left[\frac{V+R_sI}{mV_t}\right]-1\right] \text{ (one or more PV cells with many resistances)}$$

$$\rightarrow I_{0,cell}\left[\exp\left[\frac{V_{oc}}{mV_t}\right]-1\right] \approx I_{0,cell}\left[\exp\left[\frac{V_{oc,n}+K_V\left(T-T_n\right)}{mV_t}\right]-1\right]$$

since V_{oc} is defined as the voltage resulting from no current (Masters 461). This served to simplify the model that I assembled. However, this simplification may be contributing to the physically inaccurate magnitudes for the simulation's output for panel temperature. One future goal may therefore be to work with the full open-circuit voltage equation.

In order for the third equation to be useful, more calculations have to be performed; although these too are of a simple nature. Once again, I made use of the data obtained form measurements of the panel at standard test conditions $\left(25\ {}^{o}C = 298.15K,\ GHI_{panel} = 1000Wm^{-2}\right)$ (SolarWorld 2). Since my simulation treats panels that are hooked up to inverters, I assumed that the power out of the panel would be equal to the maximum power that the panel could produce. At STC, this was measured to be 245 Wp (SolarWorld 2). This makes $\eta_{ref} = 0.245$, and $\beta_{ref} \approx 0.004032$. Many times the log term is discarded as well (Skoplaki, Boudouvis, and Palyvos 1394); this is something I chose to do.

C.2 Further Use of η_{pn} and V_{oc}

Tiwari and Dubey (2010) assert that the maximum power $P_{electrical,out,max}$ produced by a PV panel is equal to (Tiwari and Dubey 99, 104)

$$P_{electrical,out,\max}\left(T_{pn}\right) = \eta_{pn}\left(T_{pn}\right) \bullet GHI_{panel}$$

Since we know the relationship between FF and $P_{electrical,out,max}$, we can use algebra to arrive at an expression for FF that includes temperature dependence:

$$FF\left(T_{pn}\right) = \frac{\eta_{pn}\left(T_{pn}\right) \bullet GHI_{panel}}{I_{sc}\left(T_{pn}\right) \bullet V_{oc}\left(T_{pn}\right)}$$

This equation captures the effect of I_{sc} and V_{oc} on fill factor, as well as the effect of cell temperature itself. The numerical solution for cell temperature can be plugged into the equations for the efficiency, the short-circuit current, and the open-circuit voltage, which can themselves be plotted alongside I_0 as a function of panel temperature, *and* be combined to check the temperature response of FF.

Appendix D: Possible Inverter Specifications For Future Use

I should note an example of *which* inverter specifications might be used in any future efforts geared toward making the simulation more realistic, with respect to connecting between a PV panel and loads that run on AC inputs.

One can obtain relevant values for the SunPower SPR-2800x, SPR-3300x, SPR-4000x, and SPR-5000x inverters. For the 5000x model, these are: CEC efficiency is “95.5%” at “240 V” and “95.0%” at “208 V” (SunPower 73), lower voltage bound “235 Vdc,” upper voltage bound “550 Vdc”, upper V_{oc} limit “600 Vdc,” upper I_{sc} limit “24

Adc,' upper regular current limit "22.0 Adc" at "240 V" and "20.0 Adc" at "208 V" (SunPower 74).

Appendix E: Relevant Equations for the Effect of Earth's Orbit on Irradiance

The aim of this section is to demonstrate the calculations required to determine the irradiance that would be incident on the Earth's surface, were it not for the effects of radiative transfer.

The quantity that we want to derive is the cosine of the solar zenith angle. From a non-heliocentric view of the universe, the zenith angle is the angle between the sun and the zenith, the highest point in the sky (Duffie and Beckman 7). The cosine of the solar zenith angle is equal to

$$\cos(sza) = \sin(lat) \bullet \sin(dec) + \cos(lat) \bullet \cos(dec) \bullet \cos(ha)$$

where *sza* is the solar zenith angle, *lat* is the latitude at which the cosine is measured or calculated, *dec* is "the declination of the sun (…) the angle between a plane perpendicular to a line between the earth and the sun and the earth's axis" (UO Solar Radiation Monitoring Laboratory), and *ha* is the hour angle, the number of hours until solar noon (when the sun is at its highest point in the sky) or after it at a particular time of day (Vignola, Michalsky, and Stoffel 14-16).

The declination is given by (Vignola, Michalsky, and Stoffel 11).

$$\begin{aligned} dec &= 0.006918 - 0.399912\cos\beta + 0.070257\sin\beta - 0.006758\cos(2\beta) \\ &+0.000907\sin(2\beta) - 0.002697\cos(3\beta) + 0.00148\sin(3\beta) \end{aligned}$$

where $\beta = \frac{2\pi d}{365}$ for the day number of the year *d* (Vignola, Michalsky, and Stoffel 11).

The hour angle (in degrees) is given by (Vignola, Michalsky, and Stoffel 17)

$$ha = 15 \bullet (st - 12)$$

where *st*, the solar time, is (Vignola, Michalsky, and Stoffel 17)

$$st = lst + EoT + \frac{long_{sm} - long_{ob}}{15}$$

In this equation, *lst* is the local standard time in hours and hour decimals, $long_{sm}$ is "the longitude of the standard meridian from which the clock time for the time zone [in which cos (*sza*) is determined] is measured," and $long_{ab}$ is "the longitude at the location of the observer" (Vignola, Michalsky, and Stoffel 17). *EoT*, the equation of time, is meant to compensate for the ellipticity, i.e. non-circularity, of Earth's orbit. It is equal to (Vignola, Michalsky, and Stoffel 13)

$$EoT - 0.000075 + 0.001868\cos\beta - 0.032077\sin\beta - 0.014615\cos(2\beta) - 0.040849\sin(2\beta)$$

(in units of radians).

We can *also* specify the directed irradiance's "[a]ngle of incidence," i.e. the angle between this irradiance and a "normal" line to the largest face of the panel (Duffie and Beckman 11). The cosine of this angle (θ) is given by (Duffie and Beckman 11)

$$\begin{aligned}\cos\theta = &\sin(dec)\sin(lat)\cos(tilt) - \sin(dec)\cos(lat)\sin(tilt)\cos(\psi)\\ &+\cos(dec)\cos(lat)\cos(tilt)\cos(ha) + \cos(dec)\sin(lat)\sin(tilt)\cos(\psi)\cos(ha)\\ &+\cos(dec)\sin(tilt)\sin(\psi)\sin(ha)\end{aligned}$$

where *tilt* denotes the angle of tilt between the panel and the ground, and ψ is "the surface azimuth angle" of the panel, which is defined to be 0 at due south (Duffie and Beckman 10).

For my model, I took *tilt* to be 20°, as per HECO's recommendations (Hawaii Energy Industries, "Site"). I took ψ to be 0, as it is widely recommended that solar panels “in the northern hemisphere” face due south (Duffie and Beckman 16). In this manner I sought to help optimize the effectiveness of the panels that I modeled.

Appendix F: Effects of Reflection by PV System

Martín and Ruiz (2001) propose a model for the effect of reflection on the DNI, the DHI, and “ground-reflected irradiance” (Martín and Ruiz, “Calculation” 32). The effects on each component are specified as coefficients that multiply each component (Martín and Ruiz, “Calculation” 31-32):

$$\text{For DNI: } \cos\theta[1 - F_B(tilt)]$$
$$\text{For DHI: } F_{sky->panel,front}[1 - F_D(tilt)]$$
$$\text{For ground-reflected irradiance: } F_{ground->panel,front}[1 - F_A(tilt)]$$

where (Martín and Ruiz, “Annual” 75-76; Martín and Ruiz, “Calculation” 31-32)

$$F_{sky->panel,front} = \frac{1+\cos(tilt)}{2} = \text{ view factor between front of panel and sky}$$

(if the panel's view of the sky is unobstructed),

$$F_{ground->panel,front} = \frac{1-\cos(tilt)}{2} = \text{ view factor between fround of panel and ground,}$$

$$F_B(\theta) = \frac{\exp(-\cos\theta/\alpha_r) - \exp(-1/\alpha_r)}{1-\exp(-1/\alpha_r)},$$

$$F_D(tilt) \cong \exp\left[-\frac{1}{\alpha_r}\left(\begin{array}{l} c_1\left(\sin(tilt) + \dfrac{\pi - tilt - \sin(tilt)}{1+\cos(tilt)}\right) + \\ c_2\left(\sin(tilt) + \dfrac{\pi - tilt - \sin(tilt)}{1+\cos(tilt)}\right)^2 \end{array}\right)\right],$$

$$F_A(tilt) \cong \exp\left[-\frac{1}{\alpha_r}\left(\begin{array}{l} c_1\left(\sin(tilt) + \dfrac{tilt - \sin(tilt)}{1-\cos(tilt)}\right) + \\ c_2\left(\sin(tilt) + \dfrac{tilt - \sin(tilt)}{1-\cos(tilt)}\right)^2 \end{array}\right)\right],$$

with constants given as and/or taken to be (Martín and Ruiz, “Annual” 75-76; Martín and Ruiz, “Calculation” 31-32)

$\alpha_r = 0.165$ (average of endpoints of 0.16 and 0.17 given)

$c_1 = \frac{4}{3\pi}$ (constant),

$c_2 = -0.0715$ (average of values for $\alpha_r = 0.16$ and $\alpha_r = 0.17$)

The coefficients are multiplied by their corresponding irradiance components, and the results added up, to give the total amount of irradiance incident on the PV panel.

As a side note: The ground-reflected irradiance is approximated by multiplying the ground’s albedo and the GHI. This is a very crude approximation, because it does not take into account various effects of different surface types on the directionality of the reflected irradiance, e.g. Lambert’s Cosine Law (Fisher).

Appendix G: Effects of Longwave Radiation To/From PV System

Longwave radiation’s effects can be quantified by the equation

$$P_{longwave} = \varepsilon\sigma T^4$$

for object emissivity ε, Stefan-Boltzmann Constant σ, and emitter temperature T.

The PV system emits to its environment, at temperature T and emissivity ε_{pv}. The environment emits to the PV panel from two sources: the air and the ground, respectively at emissivities and temperatures ε_{air}, T_{air} and ε_{ground}, T_{ground}.

We assume, for ease, that the ground temperature is the same as the air temperature. (This temperature was measured “approximately 5 feet above ground level” for the data that I am using (National Renewable Energy Laboratory).) This is a very rough approximation, as the thermal properties of the ground can cause differences between ground temperature and air temperature (Herb et al). But it is good enough for our purposes.

We also assume, after the fashion of A.D. Jones and C.P. Underwood, that (Jones and Underwood 352)

$$\varepsilon_{sky} = \begin{cases} 0.95, & \text{no cloud cover} \\ 1, & \text{cloud cover is 100\%} \end{cases}$$

$$T_{sky} = \begin{cases} T_{air} - 20K, & \text{no cloud cover} \\ T_{air}, & \text{cloud cover is 100\%} \end{cases}$$

In order to describe the effects of intermediate cloud cover conditions, we assume that the sky emissivity and temperature can be linearized, with the endpoints being at no cloud cover and full cloud cover, and values on linearly-interpolating function describing the effects of intermediate cloud cover. There exist equations [e.g. in Daryl Myers's book *Solar Radiation*] that provide a way to back-estimate cloud cover from measured irradiance. However, the test data used to generate the results shown in this Thesis appeared to correspond to a cloudy enough day that a value of $\varepsilon_{sky} = 1$ was used.

We treat the front and back of the panel as having dissimilar emissivities: that of the front is given by $\varepsilon_{front} = 0.91$, and that of the back is given by $\varepsilon_{back} = 0.85$ (Armstrong and Hurley 1494). Additionally, we assume that the emissivity of the ground $\varepsilon_{ground} = 0.94$ (Armstrong and Hurley 1494).

I must also take into account the relevant view factors. Two have already been given in Appendix F; two more relate to the back of the panel, and are given by

$$F_{sky->panel,back} = \frac{1+\cos(\pi - tilt)}{2} \text{ (between the back of the panel and the sky)}$$

$$F_{ground->panel,back} = \frac{1-\cos(\pi - tilt)}{2} \text{ (between the back of the panel and the ground)}$$

The resulting balance of outgoing and incoming emitted power (with respect to the PV system) is thus equal to

$$P_{longwave,total} = \sigma \begin{bmatrix} \left(F_{sky->panel,front} + F_{sky->panel,back}\right)\varepsilon_{sky} T_{sky}^4 \\ +\left(F_{ground->panel,front} + F_{ground->panel,back}\right)\varepsilon_{ground} T_{ground}^4 \\ -T_{pn}^4\left(\varepsilon_{front} + \varepsilon_{back}\right) \end{bmatrix}$$

Appendix H: Approach and Form of the Temperature Differential Equation

Our treatment is based on that offered in Jones and Underwood (2001). We take as our starting point the equation

$$q = mc\Delta T$$

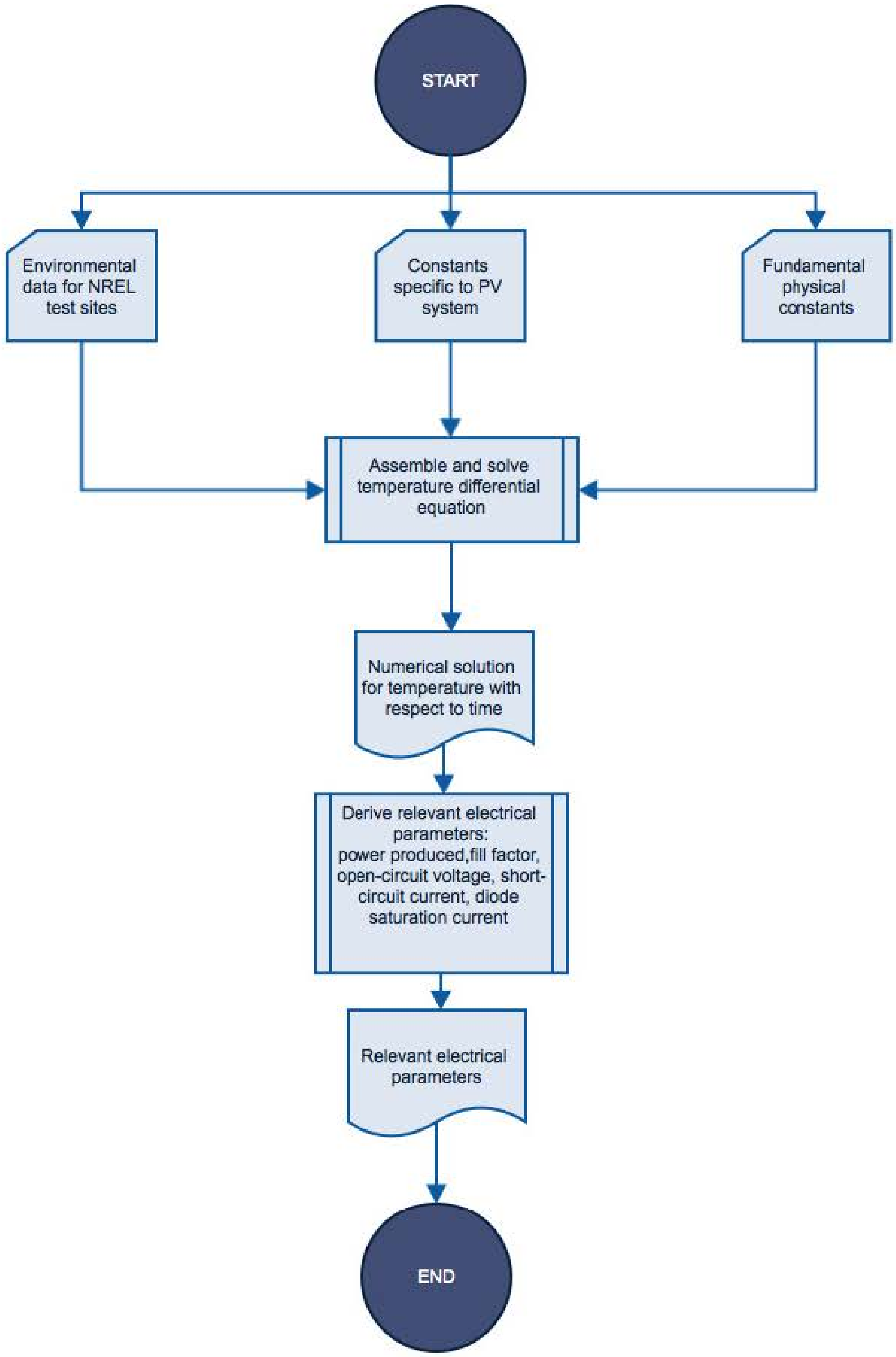
where ΔT is the change from some initial temperature of the PV panel to some final temperature.

If we divide both sides of the equation by Δt, where t is time, and take the limit as $\Delta t \to 0$, we see that

$$\frac{dq}{dt} = mc\frac{dT}{dt}$$

This gives us a differential equation for temperature with respect to time. If we can solve this differential equation for $T(t)$. We note that the PV panel power P depends on T; therefore, once we know $T(t)$, we can model how P depends on T. The final form of the equation is the sum of all the contributions determined in the above Appendices.

Appendix I: Detailed Flowchart of Final Simulation



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