Policy, Geospatial, and Market Factors in Solar Energy: a Gestalt Approach

by

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ABSTRACT

Our dependence on fossil fuels is driving anthropogenic climate change. Solar energy is the most abundant and cleanest alternative to fossil fuels, but its practicability is influenced by a complex interplay of factors (policy, geospatial, and market) and scales (global, national, urban). This thesis provides a holistic evaluation of these factors and scales with the goal of improving our understanding of the mechanisms and challenges of transitioning to solar energy.

This analysis used geospatial, demographic, policy, legislative record, environmental, and industry data, plus a series of semi-structured, in-person interviews. Methods included geostatistical calculation, statistical linear regression and multivariate modeling, and qualitative inductive analysis. The results reveal valuable insights at each scale, but moreover a gestalt model across the factors and scales draws out a larger pattern at play of the transmutational weighting and increasing complexity of interplay as the level of analysis cascades down through the three geographic scales.

DEDICATION

To Nichole, Kobi, Juno, and the rest of my family and friends… you have given me unyielding love and support, and filled my life with joy beyond anything I could have asked for.

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I first want to thank my advisor and mentor, Rob Melnick. You had no good reason to take me on as a PhD student, and you certainly already had more than enough going on to keep you busy. Yet the time and attention you spent mentoring me along this process has been nothing less than phenomenal. I am forever indebted for all that you have done.

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scientist, or much of anything for that matter. Grandpa Moore, you taught me so many life lessons, like never turning your back to a friend or family member in need, and to always leave the campsite cleaner than how you found it; I miss you so much Grandpa and I wish you could have lived to see this. Aunt René, I could not have had a better godmother; I have never known another person with such innate and unflinching generosity to their friends and family. Randy, as I told you the day you married my mother I am forever grateful that you came into our family. Mom, it took decades for me to realize that your composure, humility, and empathy were not weaknesses but the hallmarks of true strength, thank you for your nearly inexhaustible patience while I learned and continue to learn those lessons. Nichole, I stand fearless and sometimes foolhardy in the face of any storm only because I know you are the unshakeable bedrock upon which we have built our lives all of these years. Finally, you were just a baby Kobi, and Juno you were still in your mother's womb, when my father, your grandfather, died. On his deathbed I made a promise to you that not only would I do the very best I could to be a good father to you, but also to be a virtuous human being in this world. I vowed to do everything within my ability to pass on to you a world that hopefully is better off than when I found it… just as my grandfather had taught me. I have struggled on both fronts of this undertaking. One day I hope you come to understand my motivation for this toil, and you can consider this partial fulfillment of my lifelong promise to you.

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1. INTRODUCTION

1. Abstract

The vast majority of the greenhouse gases that are driving anthropogenic climate change are produced when we burn fossil fuels. Yet these very fuels are still used to meet most of the energy needs of the human species. This dedication to fossil fuels persists despite the existential threats their combustion produces, and despite the existence of clean alternatives. The most promising of these alternatives bathes Earth every day, warms us, gives us light, powers the global ecosphere, and still has plenty left over to meet our other energy needs. This resource is solar energy, and it is the only renewable energy resource that has the scale potential to satisfy all human global energy needs now and into the foreseeable future.

This thesis attempts to identify how policy, geospatial, and market factors influence the adoption of solar energy. Rapid and ongoing advancements in solar technology is accounted for within the price-performance metrics of the market factors. These specific factors were chosen as they represent the foremost drivers in a global transition to an energy paradigm dominated by solar. The three factors are examined at three distinct geographic scales –global, national, and urban. A single factor at a single geographic scale fails to capture the complexity of this problem space and the encompassing form that any viable set of solar energy solutions will need to take. Thus the need arises for the gestalt approach and operationalized model taken here. This approach necessarily culminates in a whole that is greater than the sum of its parts, as examining ever narrower slices of the problem in isolation will not reveal the complete picture. Ultimately this thesis reveals that scale

matters, as does the synergies among these factors, in decisions about the future role of solar energy.

The global scale of analysis captures the world market in the aggregate where macro trends are more easily discerned from analysis. On the other end of the scale for this work, the "Special Administrative Region" of Hong Kong, China was chosen for the urban level of analysis specifically because it represents an extreme case in terms of unique obstacles in geography and sociocultural makeup that make renewable energy adoption challenging. In the national scale between these two bookends, the United States was chosen because the heterogeneity and intricacies in both the policy landscape and solar natural capital exemplifies the complexity of this topic. While many factors might influence a preference of solar energy over other forms of energy, a reading of the literature suggests that more can be understood through an analysis of both the natural and social data. This analysis used geospatial, demographic, policy, legislative record, environmental data, and industry data, plus the results from a series of semi-structured, in-person interviews. Methods included geostatistical calculation and correlation, statistical linear regression and multivariate modeling, and qualitative inductive analysis.

At the global level, this dissertation finds that all human electricity needs can be met exclusively with distributed solar energy. Moreover, all human energy needs –with U.S. consumption rates ascribed to all people on the planet– can be fully met with distributed solar on 99.85% of the land surface area of the Earth. There is a particularly pronounced opportunity to meet energy needs via distributed solar in impoverished areas that currently lack access to grid-based electricity. At the national level of analysis in the United States, solar potential and policy drivers effect solar energy adoption, but their interplay is a more prominent driver. A statistically significant interaction effect can be found between spatially specific solar energy potential and local policy that yields greater solar energy utilization; this is despite the fact that these two variables share almost no correlation with each other. Finally, at the urban level of analysis, the oft mutually reciprocal relationship of public perception and policy appears to be the paramount factor in solar energy adoption, despite otherwise seemingly favorable market conditions in Hong Kong.

Beyond these specific insights gained from examining these scales in isolation, more novel insights emerge when cascading through the geographic levels of analysis. When examining the global level, market factors are paramount, geospatial factors are of consequence, and policy factors are largely negligible. Yet as the examination moves down in scale consideration towards the urban level of analysis, an inversion occurs where policy factors begin to dominate, geospatial factors still play a notable but moderate role, and market factors become seemingly immaterial. This more comprehensive framework elucidates both the barriers to, and opportunities for, greater utilization of solar as a dominate source of energy for humanity. This is the most valuable contribution this work makes to sustainability scholarship; further, it provides a salient and tractable framework for addressing this vexing challenge. Overall the gestalt approach used here is essential in identifying and understanding the transmutational weighting and increasing complexity of interplay in the policy, geospatial, and market factors of solar energy as the level of analysis cascades down through the three geographic scales. Leveraging the major takeaways from these insights can help policymakers, energy managers, and stakeholders make more informed decisions to transform notional sustainability principles into actionable aptitude.

2. General Background

Modern scientific consensus estimates that around 4.54 billion years ago the band of dust particles in the disc orbiting our recently formed Sun began to accrete into the Earth (Barry & Taylor, 2015). Compressing the Earth's entire history into a single year can help conceptualize this vast amount of time and our planet's evolving relationship with our Sun. With Earth starting the moment after midnight on January 1st, single-celled life in the form of photosynthesizing bacteria start to appear at the beginning of April, Spring passes to Summer and Summer to Autumn until finally multi-cellular life starts forming around mid-October. A little over a month later in mid-November photosynthesizing plants evolve to survive on dry land and a few days later the first animals follow them into this new frontier on *terra firma*. By around the 12th of December dinosaurs start to roam the Earth and last just under 2 weeks going extinct by Christmas (December 25th). On December 31st, New Year's Eve day, just after 6pm in the evening the genus *homo* appears. About 45 minutes before the stroke of midnight on New Year's Eve *homo erectus* learns to directly harness a form of energy by controlling fire, then at 23 minutes until midnight *homo sapiens*, the species of modern humans, appear. With one minute to go before midnight human beings start forming the first cities in ancient Mesopotamia. Finally, the count down to the New Year begins; 3… 2 … the Industrial Revolution begins, 1… Heinrich Hertz observes the "photoelectric effect" demonstrating that photons of light can be converted into sparks of electricity. And just a fraction of a second before the stroke of midnight, Bell Labs creates the first working solar (photovoltaic) cell in Murray Hill, New Jersey, USA.

The above allegory is not only an attempt to express the enormity of scale in cosmic and geologic time, but also to illustrate the incredible acceleration of maturity in our relationship to the sun and our ability to capture, transform, and use its energy. The notion of accelerating advancement will be a recurring key theme throughout this discourse.

Humans have a long and evolving history of harnessing the sun's energy for our well-being. Technological practices such as "passive solar" heating –constructing dwellings with a large south-facing exposure (in the Northern Hemisphere) to capture as much radiant heat from the sun as possible to warm dwellings– has been a common practice for thousands of years (Jefferson, 2015). Beyond just radiant heating, the ability to convert electromagnetic waves of light into electrical energy was first detected by Heinrich Hertz in 1887 with his observation of the "photoelectric effect" (Young & Freedman, 2015). Nearly two decades later in 1905, as the first of four papers in his so-called "miracle year", Albert Einstein publishes a paper that more definitively describes and quantifies the photoelectric effect (Einstein, 1905). Einstein's description of the photoelectric effect is confirmed via experiment several years later, and in 1921 he is subsequently awarded the Nobel Prize in Physics for this work.

In a seemingly unrelated thread of early 20th century history, in 1937 U.S. President Franklin D. Roosevelt begins to codify what will become our modern-day concept of "natural capital" while addressing a small, informal audience in rural Montana. He remarks, "we have lost sight of the fact that the natural resources of our land – our permanent capital – are being converted into those nominal evidences of wealth at a faster rate than our real wealth is being replaced," (The Cincinnati Enquirer, 1937). Roosevelt was not referring to sunlight specifically, as it would be many decades later before the technology to actively harness usable electricity from sunlight advances to a state to make this even conceivable as an exploitable natural resource. However, the paradigm shift from regarding the environment as a mundane extraction pool for the machine of capitalism towards a “circular economy” –where abundant natural capital is fully valuated and responsibly harnessed– is still evolving and maturing (Solow, 1956; Daly & Farley, 2004; Jefferson, 2015).

Even decades after Einstein’s famous photoelectric paper, the ability to convert light into electricity remained merely a laboratory curiosity, tinkering in the realm of 1% conversion efficiency. But in 1954, a small team at Bell Laboratories was able to make huge leaps pushing the energy conversion efficiency (photons to electrons) to 5-8%. This is widely regarded as the “birth” of the modern solar photovoltaic (PV) panel and the subsequent industry that emerged and continues to rapidly develop today (Kazmerski, 2005).

The continued significant and accelerating advances in engineering efficiency and price performance of PV modules up to the present day will be discussed in great detail in later sections of this dissertation. For now, this is meant merely to highlight and operationalize the concept of sunlight as natural capital, and the mechanisms that lead to the efficient capture of this near limitless resource.

One can burn a lump of coal or barrel of oil and watch it produce heat energy. Similarly, one can gaze at the giant spinning blades of a windmill and see the once invisible kinetic energy of the wind be transformed into visible motion energy. In contrast, generating electricity from photovoltaic modules has no inherent moving parts. Lifeless black rectangles sit placidly tucked away atop roofs or often spread across desolate fields. A notable exception are solar panels that are mounted on motorized swivels so their faces can track the slow arc of the sun across the sky, but even those move so imperceptibly slow that they appear virtually motionless. Ironically while light is what makes the act of seeing possible, converting that light to energy is entirely imperceptible to the human eye. Understanding solar energy is necessarily a process of intellection. The notion of a wave of light propagating millions of miles through the vacuum of empty space and being converted at the subatomic level to free electrons via a quantum mechanical effect invokes dizzying levels of mental abstraction. Reifying solar natural capital is a major challenge to overcome if we want to move beyond our current pollution and greenhouse gas-intensive global fossil-fuel regime.

3. Research Question and Approach

Our current fossil-fuel energy paradigm is the main driver of anthropogenic climate change (Baes, Goeller, Olson, & Rotty, 1977; IPCC, 2011; Höök & Tang, 2013), while the massive potential value of a transition to solar energy remains largely unrealized (EIA, 2016). With regards to this challenge, the purpose of the research in this dissertation is to answer the question:

How do policy, geospatial, and market factors interact to leverage natural capital and drive a transition to solar energy at global, national, and urban geographic scales?

This dissertation examines the collective pool of interaction between policy, geospatial (in the form of geographically specific solar irradiance), and market factors at each of the three specified geographic scales. *Figure-1.01* shows the conceptual diagram of analysis irrespective of geographic scale.

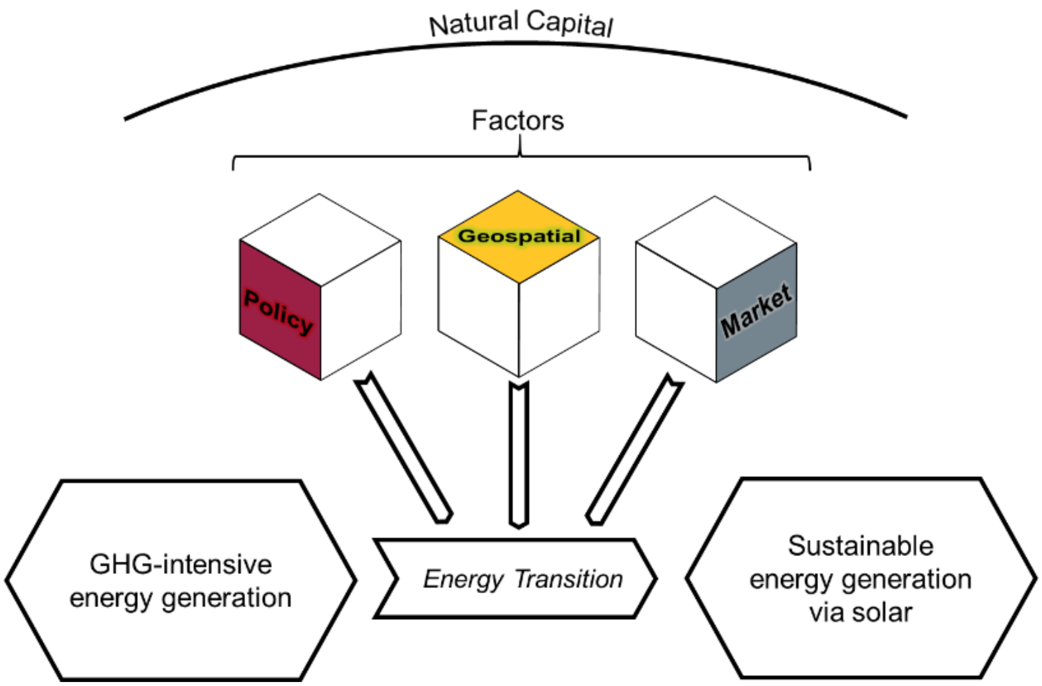


FIGURE-1.01: Factors in the Energy Transition to Solar

From the conceptual starting point of these three factors interacting to stimulate more solar energy uptake in an abstract sense, *figure-1.02* then details how these three interacting factors will be examined through the specific geographic scales of global, national, and urban.

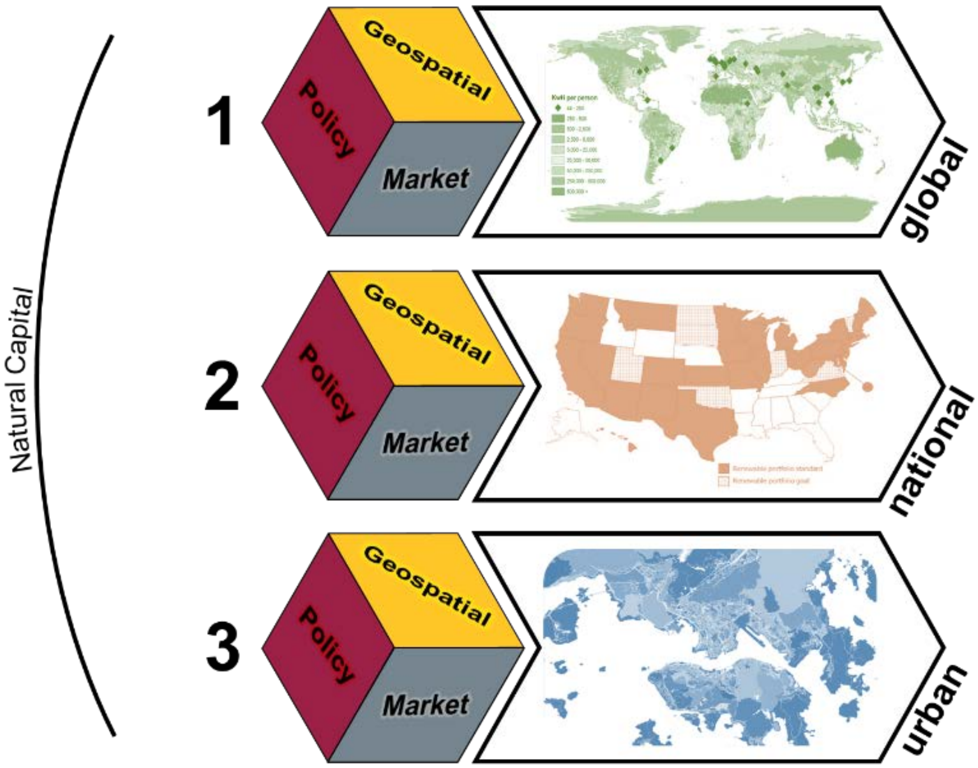


FIGURE-1.02: Factors Across Three Geographic Scales

Neither the relative importance nor interaction of these factors are uniform across these three geographic scales. The scale factor draws out stark contrasts that are both of scholarly interest and candidly highlight a crucial real-world incongruity that humanity will need to contend with to fully realize a clean energy future. The three geographic scales of analysis are more than just three convenient waypoints along a telescoping zoom-in on the problem. At the macro scale this dissertation finds market drivers to be clear, strong, and even predictable. Specific solar irradiance is also an important geospatially driven determinant, and policy is by far the weakest driver of the three factors. Counterintuitively, as we drill down in scale, market and policy factors swap places in their relative importance, and the overall picture of what drives or even correlates with solar energy adoption becomes less clear, and more complex. This emergent property of complexity could not have been ascertained with a simple single-factor examination at a single scale of analysis. A *gestalt*[1] approach is necessary; and furthermore, is the most significant contribution of this work.

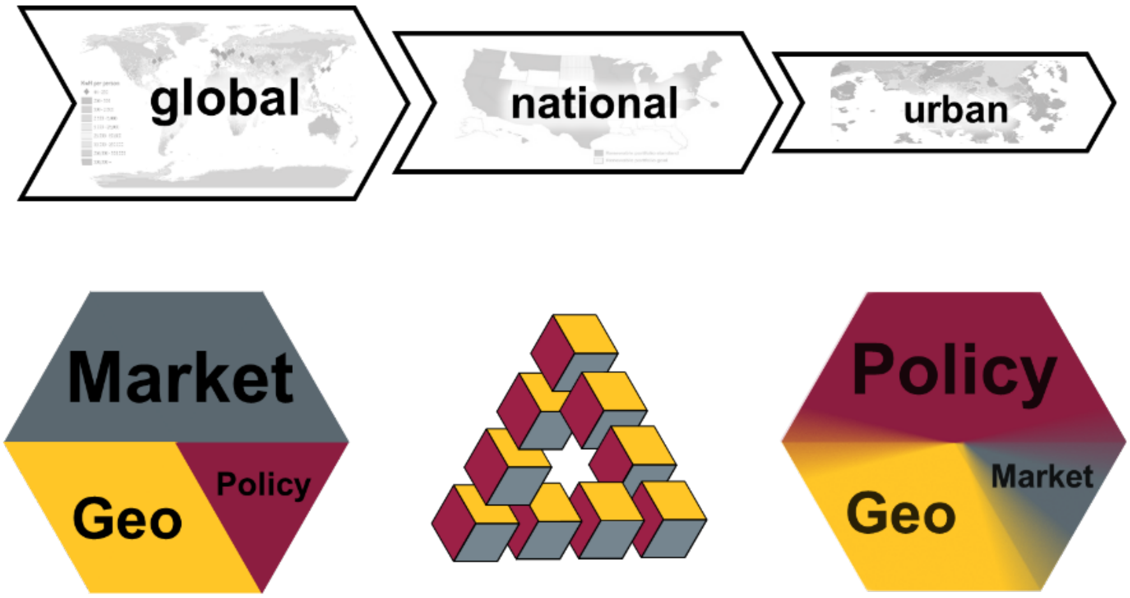


FIGURE-1.03: Change in Factors Through Three Geographic Scales

The holistic approach taken here stands in stark contrast to the Cartesian method that has served as the philosophical underpinning of modern scientific thought for several centuries. Specifically, in René Descartes's *Discourse de la Methode* (Discourse on the Method) –perhaps best known for the infamous "Je pense, donc je suis" (I think, therefore I am)– Part 2 of Descartes's 4 part "method" can be summarized as: question everything, break every problem down into smaller and smaller parts, solve the simplest parts first, and be thorough. Nearly four centuries after this method was proposed it still readily describes the current

[1] Gestalt is a word borrowed from the German language, meaning: a configuration, pattern, or organized field having specific properties that cannot be derived from the summation of its component parts; a unified whole.

blueprint for scientific theses and manuscripts across a near comprehensive swath of fields of study. While the ambitious and somewhat unconventional approach taken here will surely suffer from numerous critiques for shortcomings, examining any one of these components in isolation will fail to capture both the true complexity and interdependencies of scale and factors for this issue. (Descartes, 1637)

4. Dissertation Structure

This dissertation eschews the linear style of exposition where one well-scoped research question is marched through a series lockstep chapters of development. The linear method of highly specified analysis would have failed to capture the complexity that is the essence of this research effort. Instead the structure here consists of three discrete “papers” –chapters 2, 3, and 4 presented here as Study A, Study B, and Study C respectively– with the uniting thread of a theoretical construct for all three papers being offered in the introduction chapter (chapter 1) and the concluding chapter (chapter 5). At the time of this writing, Study B (chapter 3) is in press and scheduled for publication at the journal Renewable & Sustainable Energy Reviews (Herche, 2017); the headings and figure numbers of that piece have been altered for this work to achieve a consistent style.

One of the drawbacks to this approach is that a small amount of material overlaps across the three papers, but great efforts have been taken to keep this to a minimum. However, there are no overlaps in the original data, analysis, or approach among each paper. Furthermore, three different analytical methodologies of geospatial calculation and correlation, statistical linear regression and multivariate modeling, and qualitative inductive analysis were used as the primary tools of investigation for Study A, Study B, and Study C respectively. The more cogent reason for this approach is based on the content and concept of the dissertation. Any meaningful global energy transition to solar energy has to simultaneously operate on multiple geographic scales through numerous factors. This will be explored further in the theoretical background of the introduction.

5. Theoretical Framework

GENERAL CONCEPTUAL FRAMING

While this discourse draws heavily on multiple bodies of scientific literature it is firmly rooted and most appropriately housed in sustainability science. The distinction is not merely catalogical but meaningful in shaping the approach used here as, “sustainability science is a field defined by the problems it addresses rather than by the disciplines it employs,” (Clark W. C., 2007, p. 1737). Other epistemological lenses are insufficient or inappropriate. The precise tactics, rate, and urgency at which we should pursue abating anthropogenic global climate change is a question of a “trans-scientific” nature; scientific inquiry can perhaps offer some explication but cannot definitively guide our impetus to action (Weinberg, 1972). Rather, this is a question of our collective moral imperative to act (Kant, 1785).

A key advantage of the ability to adroitly move within the defined factors and across scales of analysis in examining this particular sustainability challenge is that it permits both the “universalist sustainability” and “procedural sustainability” frameworks to become useful and relevant frameworks. Form a universalist framing, energy is the key driver of anthropogenic climate change; thus achieving a complete energy transition to solar –and other renewables that do not emit greenhouse gases–

is an existential imperative. But this begs the question: How, specifically, do we accomplish this? Procedural sustainability can be invoked here for the arduous task of achieving energy sustainability through the pathways of its pursuit and the affected stakeholders. (Miller, 2013)

The massive collection of infrastructure involved in the global energy system is a complex socio-technical system. This system underpins all aspects of our contemporary world. Focusing merely on narrow slices of the technological components could not hope to capture the complexity, ubiquity, and intricacies of the challenge. However, this discourse will not ignore the technological factors that drive solar energy; these engineering advances have driven exponential price performance gains in solar energy since the 1970s and will be discussed in great detail in later chapters. Rather, this component, particularly its aggregate outputs and detailed trends, is weaved into the narrative within all three factors of this analysis. Moreover, this work generally takes the approach outlined by Pasqualetti (2011), "The more suitable and expedient approach would be to consider the challenges of development as predominantly social matters with technical components, rather than the other way around. To accept this view is to unlock the door to a renewable energy future." (p. 201)

From this trailhead another marker to help ground the theoretical framing is Allenby and Sarewitz's concept of "Level 1", "Level 2", and "Level 3" technologies (2011). To borrow their archetype, consider an airplane; an airplane is an extremely complex technological marvel consisting of tens of thousands of precision-tuned interlocking pieces. However, an airplane is still considered a "Level 1" technology as it is a discrete object. As such, since we understand a great deal about airplanes, we can optimize their performance to make them incredibly safe and reliable technologies. Moving up to "Level 2", consider the airline industry; this is a vastly more complicated socio-techno system consisting of corporations, laws and regulations, market forces, and a global network of terminals and interfaces. At "Level 2" complexity has been amplified immeasurably and increasingly becomes amorphous and potentially incomprehensible. While airplane accidents are (thankfully) rare, we usually can ascertain with great accuracy what causes an individual airplane (Level 1) to crash, but we are much harder pressed to comprehensively explicate flight delays, lost luggage, long security lines, or minute-to-minute fluctuations in ticket pricing. At the individual level, we feel powerless or lost in contrast to the complexity and extent of this Level 2 technology and assume any unsatisfactory aspects of the system must be predominantly inexorable. At "Level 3" we move up to the level of Earth systems described as, "complex, constantly changing and adapting systems in which human, built, and natural elements interact in ways that produce emergent behaviors which may be difficult to perceive, much less understand and manage," (p. 63).

Thus, in this discussion while solar PV modules are the Level 1 technology that is most graspable, the energy socio-technical system is the Level 2 technology that is the primary driver of anthropogenic climate change at Level 3. The distinction of classifying this problem as socio-technical rather than purely engineering is far from just semantics and has a deep body of literature on the subject of acknowledging and understanding socio-technical systems to tackle complex problems in society (Mumford, 1934; Ravetz, 1971; Mumford, 1971; Nelson, 1977).

One final waypoint as this work moves from merely describing the challenge to elucidating a potential solution path, is to recognize the transition to solar energy, and all its intimately entangled components, as a "wicked problem" as formally defined by Rittel and Webber (1973). More precisely, the (Level 3) problem of anthropogenic climate change is the wicked problem we are trying to solve because the vast majority of greenhouse gasses that cause climate change are emitted from the human use of energy in various forms (EPA, 2014). A global energy transition to solar energy serves as both the solution and therefore conceptual formulation of the problem.

Applying Rittel and Webber's 10 characteristics of a wicked problem we arrive at the following: We struggle with a definitive formulation of climate change (1) other than we know it is happening, the problem has no stopping rule or a definitive solution (2), only preferable levels of average global temperatures and causal proxy measures such as CO2. Our proposed solutions to the problem, like a global transition to solar energy, are not true or false but rather are good or bad (3), but there is no immediate test (4) and as there is only one planet Earth our attempts are all "one-shot operations" (5) with no control group or "Planet Earth B" (7). This work will make the case for solar energy as a solution but other viable and complimentary options also exist and this set is seemingly innumerable (6). The problem of anthropogenic climate change can, and often is, described as a symptom of other problems (8) such as the negative externalities of energy fuel choices, global development, or personal behavior and consumption patterns, and how we describe the potential solutions to these symptoms determines the nature of the resolution (9). Finally, "the planner has no right to be wrong" (10); the challenge of climate change represents a pressing existential threat to all of humanity.

"Wicked Problems"	**Climate change & a global energy transition**
1. There is no definitive formulation of a wicked problem.	We struggle with a definitive formulation of climate change other than we know it is happening
2. Wicked problems have no stopping rule.	The problem has no stopping rule or a definitive solution, only preferable levels of average global temperatures and causal proxy measures such as CO2.

3. Solutions to wicked problems are not true-or-false, but good or bad.	Our proposed solutions to the problem, like a global transition to solar energy, are not true or false but are good or bad.
4. There is no immediate and no ultimate test of a solution to a wicked problem.	There is no immediate test to the proposed solution of a global energy transition to solar energy only hypotheses and models.
5. Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial and error, every attempt counts significantly.	As there is only one planet Earth our attempts are all “one-shot operations”.
6. Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.	This work will make the case for solar energy as a solution but other viable and complimentary options also exist and this set is seemingly enumerable.
7. Every wicked problem is essentially unique.	There is no control group or “Planet Earth B”.
8. Every wicked problem can be considered to be a symptom of another problem.	The problem of anthropogenic climate change can, and often is, described as a symptom of other problems such as the negative externalities of energy fuel choices, global development, or personal behavior and consumption patterns.
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution.	How we describe the potential solutions to these symptoms determines the nature of the resolution.
10. The social planner has no right to be wrong (i.e., planners are liable for the consequences of the actions they generate).	The challenge of climate change represents a pressing existential threat to all of humanity.

TABLE 1.01: The Global Energy Transition as a Wicked Problem

OPERATIONALIZATION THROUGH CONSIDERATION OF SCALES

At the largest scales, when all markets and location-specific considerations are fully aggregated and generalized we see a seemingly unstoppable juggernaut of technological advancement in solar energy technology. In an unprecedented occurrence, on the 9th of January 2017, a sitting U.S. President published an article in a scientific journal. President Barrack Obama’s paper titled “The irreversible momentum of clean energy" lays out the challenge of anthropogenic climate change and the remarkable and relentless advancements of global market forces at play in renewable energy technologies (Obama, 2017).

Thus, Study A (Chapter 2) will examine this inexorable momentum at the global scale to detail the remarkable exponential pace of solar energy generation and related storage technologies in terms of global adoption rates and price-performance over the last several decades. Further, this study will survey how the potential for distributed solar energy is suitable across the entire planet with a particular emphasis on rural developing areas. Study A takes a deductive approach with hypotheses generated *a priori* and then tested largely with geostatistical –spatially specific properties and correlations– tools for examination of data.

Study B (Chapter 3) will drill down a tier to the national level and look at the electricity utility market in the United States. This level highlights the clash between the "irreversible momentum" of a global energy transition when it meets the massive inertia of a business model and embedded infrastructure that has changed very little in over a century going back to Samuel Insull and the model of the vertically integrated, "natural monopoly" utility company (McDonald, 1958; Posner, 1969). Furthermore, the homogenous national level policies, and the heterogeneous state level policies regarding renewable energy technologies, provide fertile ground for investigation. Like the previous study, this study is a deductive process with a set of *a priori* hypotheses which are then tested. Statistical regression and multivariate modeling are used to test these hypothesis and draw conclusions.

Lastly, Study C (Chapter 4) moves down to the urban scale of analysis, as the final stage where policy, market, and geospatial (natural capital) factors are played out and theory gives way to reality. The Special Administrative Region of Hong Kong was chosen for analysis at the city-level because of its unique set of factors-- high population density, extreme lack of useable[2] open space, and enduring attitudes towards its unique political history make it quite possibly one of the most challenging areas on earth for transitioning to a renewable energy paradigm. Because Hong Kong currently has almost no renewable energy generation (less than 1%), the approach for this study was investigative and highly inductive with no *a priori* assumptions. Instead, semi-structured interviews were conducted with sustainability professionals in Hong Kong. The result is a case study that attempts to understand and interpret the current state of awareness and attitudes towards solar energy use in Hong Kong.

6. Conclusion

At any scale of analysis below global, certain choices must be made in regards to the scoping of the investigation and subsequent analysis. Those choices carry the consequence of dereliction of other angles of inquiry that could have been chosen, this investigation is not exempt from that unavoidable sacrificial alter. At the national and urban levels of analysis a paradoxical conundrum emerges. If one were to take on multiple countries or urban areas, any sample size of countries or large cities that could yield statistical significance would also represent an appreciable portion of the entire world's population and gross domestic product (GDP). Consequently, scale relevance would then inadvertently slip back to a "global" scale of analysis by default. Thus, constraining choices must be made. The

[2] About three quarters of Hong Kong's 1,108 km^2 of surface area is protected from commercial development under the longstanding "Country Park Ordinance" legal framework (GovHK, 2016)

choices made in this work serve not to be comprehensively encompassing, but rather, illustrative.

Here the central theme of investigation is to understand how policy, geospatial, and market factors morph in their relative importance and interaction as they cascade through more granular geographic levels of analysis. As the respective studies will illustrate, the relative level, as well as the interaction dynamics, of the policy, geospatial, and market factors vary significantly at each scale. Geospatial factors, captured here as spatially specific solar irradiance, are exogenous and are of import at all scale levels of analysis, but vary considerably in specific interaction and operationalization at each scale. At the global scale, market factors seem to be of primary importance.

The United States was chosen for the “national” level because the heterogeneity of the state by state policy measures, and widely varying amounts of solar irradiance potential across and within states, made it a prime choice for analysis of these factors. As Chapter 3 will illustrate in greater detail, the U.S. case demonstrates a particularly revealing example of how the interaction of these three factors increase in complexity from the global level.

While at the urban scale the choice of investigative focus becomes necessarily even more exclusionary. As Chapter 4 will explain the Special Administrative Region (SAR) of Hong Kong, China was chosen not under a pretense that it is generically representative of all cities in the world, but rather because it is demonstrative of an extreme case in the factors of investigation here. Policy seems to be the main driver –or more specifically here, inhibitor– of adoption of solar energy technologies.

Chapter 2

2. STUDY A - THE GLOBAL SCALE: GLOBAL POTENTIAL FOR DISTRIBUTED SOLAR : GEOSPATIAL AND ECONOMIC CONSIDERATIONS

1. Abstract

Given the massive amount of natural capital that strikes the Earth every day in the form of sunlight, and the accelerating developments in price-performance of both solar photovoltaics and distributed energy storage technologies, solar energy has been experiencing rapid growth across the world, and is poised for an even more substantial role in the global energy market.

This paper assesses (1) the ability of solar energy to meet the world's energy needs in geospatially explicit terms and to act as a major tool to combat global greenhouse gas emissions that cause anthropogenic climate change, and (2) how solar energy resources might be leveraged in rural and underdeveloped areas that currently lack access to electricity. The overarching objective here is to ascertain the ability of solar energy to singlehandedly meet the world's energy needs and act as a major tool to combat global greenhouse gas emissions and, thus, anthropogenic climate change.

Geostatistical calculations were used on the spatial distribution of solar energy potential (irradiance) in relation to the specific population density distribution of the world to explicitly identify all discrete areas of the earth's land surface area where solar energy can meet the energy needs of the specific population. Based on the spatial limitation of available datasets this analysis was calculated on a one degree of latitude and longitude cell basis. Findings suggest that the global

population is geospatially distributed in such a manner that fully distributed solar energy is manifestly sufficient for this task; specifically, for 99.85%[3] of the earth's land surface area all human energy needs could be met exclusively with the available solar irradiation in that specific area. Further linear regression was used to reveal a latent opportunity for areas of high rural and poor populations to utilize the fortuitously abundant solar potential (irradiation). Additional economic and demographic data are considered such as gross domestic product, poverty, electrification rates, and macroeconomic market trends in solar energy and related technologies.

The decision to examine the global potential for solar in both the developed and developing world is one of philosophical and ethical significance. On one hand access to electricity for people who have none should be paramount, the highly correlated advancements in health, education, and livelihood that accompany electrification are significant. However, a transition to a clean energy global economy in the developed world is necessary for the cessation of the greenhouse gas emissions that are responsible for anthropogenic climate change and pose an existential threat to all humanity. Solving this particular conundrum of competing interests is fertile grounds for future work; regardless, a thoughtful discussion regarding a comprehensive energy transition across all socioeconomic categories is apropos.

[3] Of the 64,800 1° by 1° cells of latitude and longitude (180 * 360), approximately 18,792 cells (29%) are over land surface areas; thus 28 out of 18,792 = 0.15%, or inversely 99.85% of the Earth's land surface is outside of the 28 cells identified.

2. Introduction and Background

GLOBAL ENERGY TRANSITIONS

When energy is looked at comprehensively across all forms, the greenhouse gases emitted from the sum of all activities involved in the sourcing, production, transportation, sale, and consumption of energy dwarfs emissions from all other forms of human activity. Even excluding food and water for this discourse, which are inexorable and intimately related to energy in a so-called energy-water-food nexus (Bazilian, et al., 2011), the scale of the energy enterprise *writ large* is so perplexingly vast that we typically focus on components of the energy industry such as electricity, transport fuels, or heating fuels. However, taken in whole at the largest spatial scales, this work will propose some specific potential vectors of action relevant to the discussion of energy regime change.

In this dialog a transition to clean energy is given to mean when the global economy is able to produce all the goods, services, and energy requirements it needs while generating net-zero or net-negative emissions of greenhouse gases. This type of energy transition has no precedent in human history, but the driving pressure that may nonetheless spur its enactment is countervailing threat of what Scheffer (2009) describes as a "critical transition". This so-called critical transition is tantamount to a tipping point that rapidly descends into planetary ecosystem collapse making the earth uninhabitable for our current notion of modern human life.

Given the magnitude and near omnipresence of the global energy regime, some scholars argue that rapid progressive transitions are circumspect because of their absence in the historical record. Perhaps they are instead better understood as undulating and largely overlapping slow waves or eras of technology convergence that unfold over decades and centuries (Marchetti & Nakicenovic, 1979; Smil, 1994; Smil, 2014; Starr, Searl, & Alpert, 1992). Looking at primary energy sources as a percentage of market share in the Unites States over the last two centuries (*figure-2.01*), we see the overlapping, slowly swelling and subsiding wave pattern of energy consumption (Nakicenovic, 1998). The original graph plot of this analysis by Marchetti and Nakicenovic (1979) (*figure-2.02*) –where the y axis is scaled to *log[F/(1-F)]* with F equaling the fraction of market share– renders the wave-like pattern over time even more distinct.

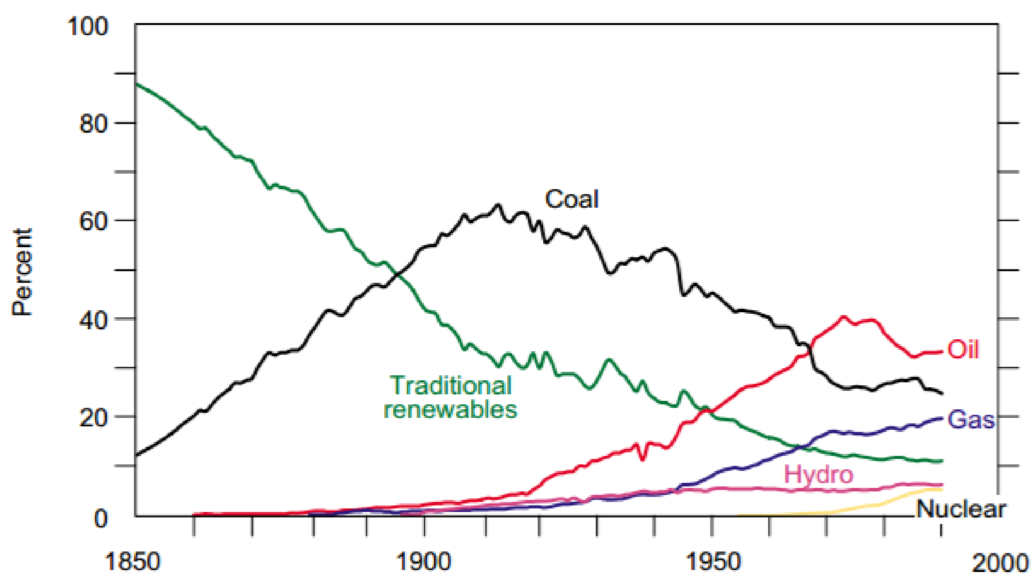


FIGURE-2.01: Primary Energy Sources as a Percent of Market Share (Nakicenovic, 1998)

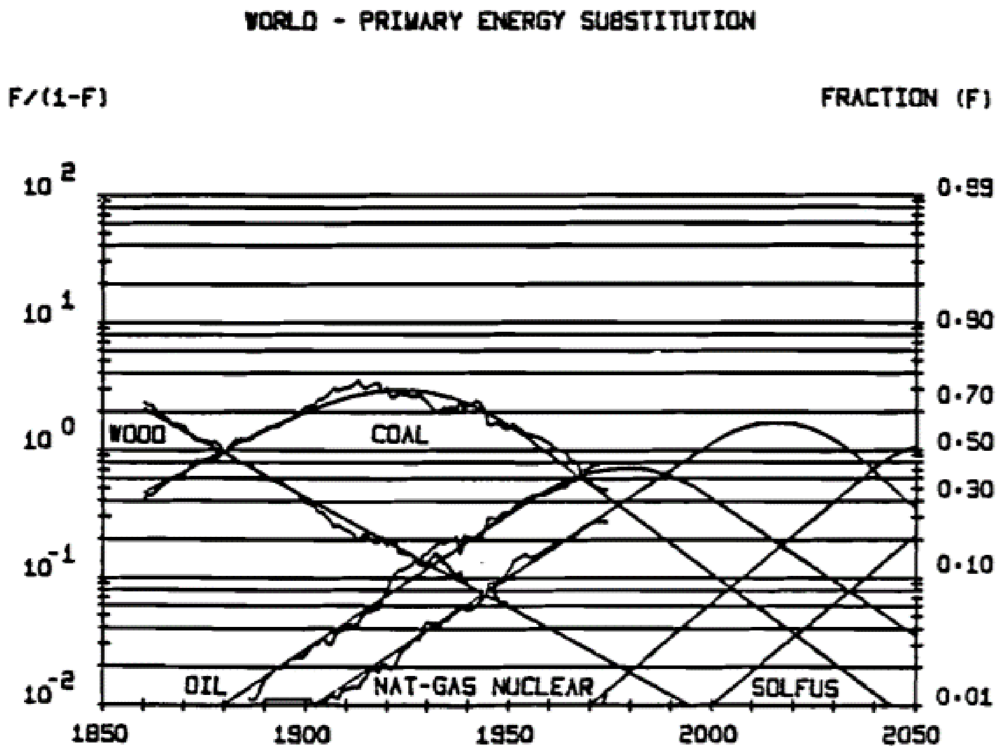


FIGURE-2.02: Log Plot Energy as a Percent of Market Share (Marchetti & Nakicenovic, 1979)

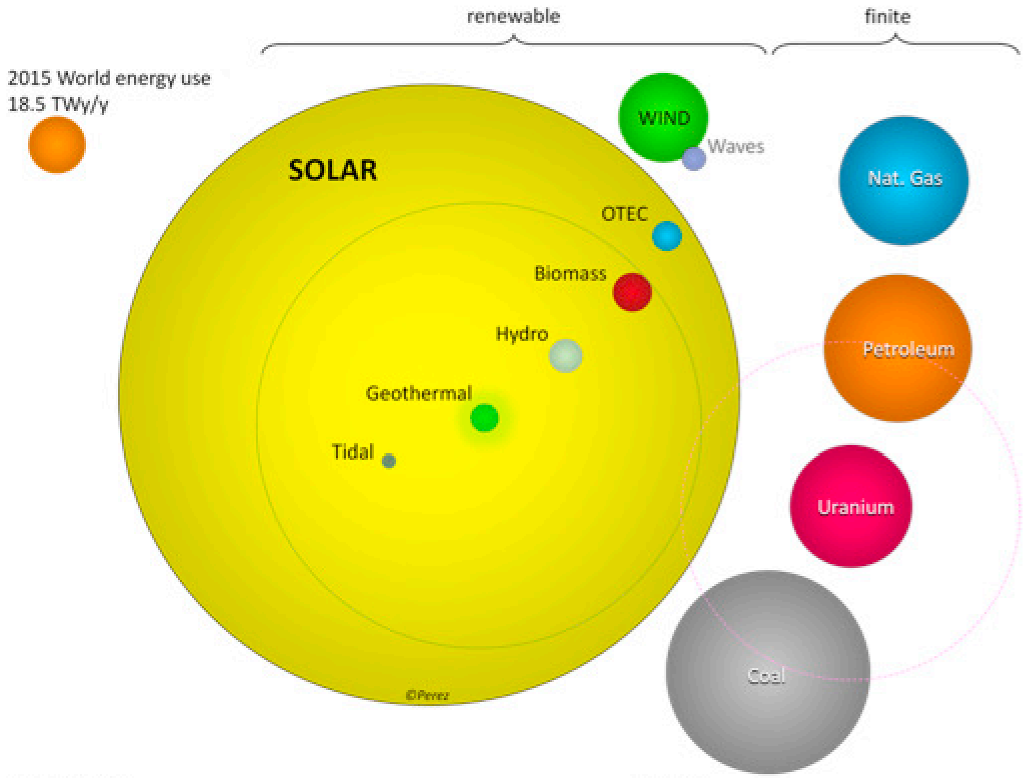
At these scales the framing of Thomas Kuhn's "The Structure of Scientific Revolutions", specifically the nature of paradigm shifts, becomes a useful lens for analysis (1962). If the next global energy transition is at or near the level of a full scale paradigm, shift then it may indeed not only be impossible to plan and potentially mitigate path dependencies, but it may be very difficult to envision the other side of the transition. Other public thought leaders on this topic predict a break from historical precedence and fully anticipate a far more rapid energy transition into renewable energy, with solar energy being the prime driver (Fuller, 1938; Kurzweil, 1999; Seba, 2014).

TECHNOLOGY, MARKETS, AND SCALE

It is important to closely consider the exponential growth in technological developments and market proliferation of solar PV modules, and the enormity of the scale of global solar potential. As a brief demonstration of the discrepancies in scale, consider coal compared to solar energy. When burned anthracite coal can generate approximately 24 MJ (~6.66 kilowatt-hours) per kg of coal while the principles of Carnot efficiency put a working limit on conversion efficiency at approximately 64% (Brown, Protano, & Ulgiatib, 2011). If we harvested all known and estimated coal reserves on the planet it would provide the equivalent of roughly 7,276 petawatt-hours of energy (Perez, et al., 2016). By comparison, enough energy from the sun strikes the earth in an hour –roughly 120 petawatt-hours[4]– to satisfy humanity's global consumption of all forms of energy, for an entire year. Less than three days' worth of sunlight hitting earth, if fully harvested, would eclipse the energy output of all coal reserves on the planet. Add in a few more days and this would render all known reserves of all fossil fuels superfluous. As a final point on scale, just a few weeks' worth of the sun that strikes the Earth exceeds the cumulative energy use of our species since the dawn of humanity (DOE, 2005).

In comparison to all other known forms of energy generation, the scale of solar is overwhelming. Note the graphic below (see *figure-2.03*) by Perez et. al. (2016) that compares a single year of solar energy potential (and other renewables) to the respective projected cumulative fossil fuels reserves on the planet. A single year of solar power dwarfs all other forms of renewable energy and the entire lifespan of all known fossil-fuels… combined!

[4] 120,000,000,000,000 kilowatt-hours



RENEWABLE				FINITE	
Solar	23,000 TWy/y	Biomass	2-6 TWy/y	Nat. Gas	220 TWy
Wind	75-130 TWy/y	Hydro	3-4 TWy/y	Petroleum	335 Twy
Waves	0.2-2 TWy/y	Geotrm	0.2-3++ TWy/y	Uranium	185++ TWy
OTEC	3-11 TWy/y	Tidal	0.3 TWy/y	Coal	830 TWy

FIGURE-2.03: Energy Resources of the Planet (Perez, et al., 2016)

Solar energy generation is a direct capture and use of “natural capital” that is fully distributed, though not evenly, across the Earth’s surface (Roosevelt, 1937[5]) (Schumacher, 1973; Russo M. V., 2003; Matson, Clark, & Andersson, 2016). A key but perhaps non-obvious insight is to recognize that solar PV panels do not “generate” electricity in the same sense that wood, coal, oil, or similar fuels do. Instead, they are a technology designed to capture and convert existing sunlight into

[5] The notion of “natural capital” goes back at least to 1937 when while addressing a small informal audience in Montana U.S. President Franklin D. Roosevelt remarked, "we have lost sight of the fact that the natural resources of our land – our permanent capital – are being converted into those nominal evidences of wealth at a faster rate than our real wealth is being replaced."

useable energy.

Unlike any other form of energy generation today, solar has near universal and unlimited scalability; from the tiny solar strip that powers a pocket calculator, to the giant field arrays that can generate up to and over one thousand gigawatt-hours per year, and any level between (Wesoff, 2015).

Despite such amazing potential, solar constitutes less than 1% of global electricity consumption (EIA, 2016). From here this discourse will make the case that solar is poised for a massive growth in capability to become the major source for energy worldwide. A series of indicators and recent trends help to show the evidence for a very near-term revolution in solar energy. While currently small, electricity is the fastest growing end-use form of energy in the world, renewables in general are the fastest growing form of electricity generation, and solar is the fastest growing form of energy generation (EIA, 2016). However, systemic skepticism for the global growth of renewables seems to persist despite repeated results to the contrary. The graph below (see *figure-2.04*) shows how the International Energy Agency's annual World Energy Outlook report has repeatedly underestimated the growth trend of renewable energy (being driven largely by new solar and wind) and failed to recognize its exponential growth trend (Metayer, Breyer, & Fell, 2015). Metayer, Breyer, and Fell note that the IEA used the same methodology and consistently under-predicted despite years of evidence that their approach may be flawed.

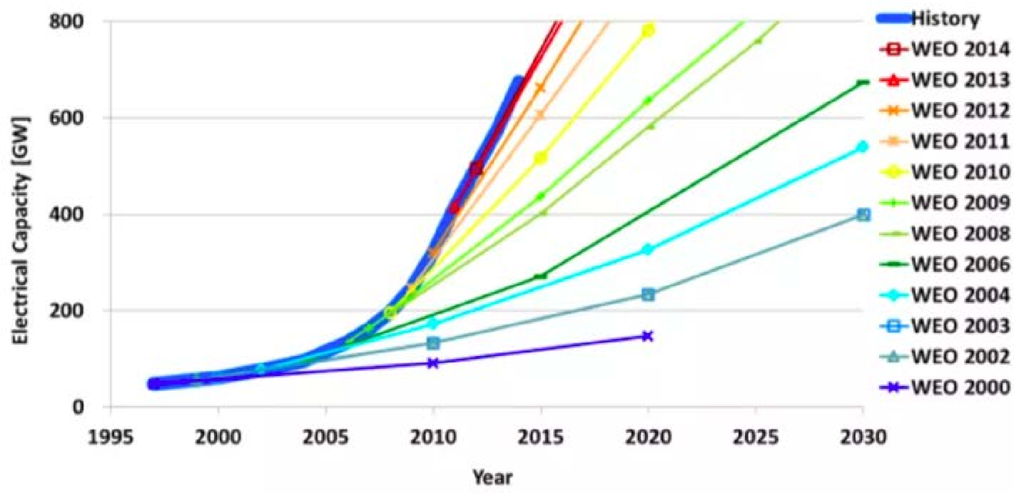


FIGURE-2.04: IEA Projections versus Actual Growth of Solar (Metayer, Breyer, & Fell, 2015)

Specific to solar PV, an examination of the real market trends is quite a striking picture. First on the supply side (see *figure-2.05*) we see the so-called effect of “Swanson’s law” of price performance of solar PV. Similar to the perhaps more famous “Moore’s law” for computers (Moore, 1965), this phenomenon was first observed by SunPower Corporation founder Richard Swanson, who noted, "module prices reduce 20% for every doubling of cumulative volume," (Swanson, 2006, p. 444). At the time of this writing, this has led to solar PV setting a global record for the cheapest wholesale energy of any form on the planet. In an open bid Power Purchase Agreement (PPA) in Abu Dhabi, the bid for solar PV energy generation was offered at 2.42¢ (USD) per kWh by the company JinkoSolar (Dipaola, 2016). This is the inclusive price of equipment, installation, maintenance, and (presumably) a profit margin for JinkoSolar. The top 5 lowest bids were all solar generation, and all under 3¢ (USD) per kWh.

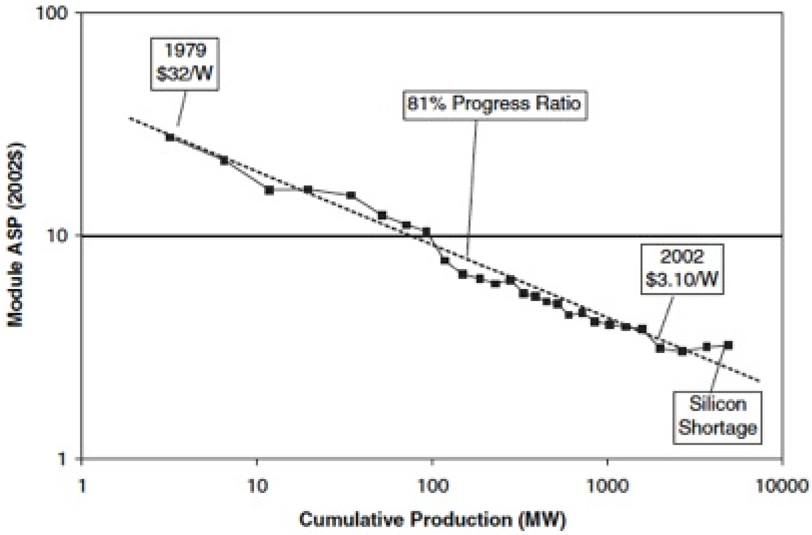


FIGURE-2.05: Historical Plot of PV Module Prices (Moore, 1965)

Two important things to note are that this is an exponential development trend and that it has been remarkably consistent for decades. Further, there is empirical evidence to suggest that both “Swanson’s law” for solar PV and “Moore’s law” for computation are actually just specific cases of a phenomenon called “Wright’s law” (Wright, 1936). In a recent publication titled “How predictable is technological progress?” Farmer and Lafond (2016) did statistical “backcasting” analysis for 53 technologies in order to ascertain and characterized their growth trends in price performance. Consistent with Swanson, they found a 10% annual growth rate in the price performance of solar PV[6] (see *figure-2.06*).

[6] This is consistent with Swanson’s 20% prediction as Swanson’s was describing the price performance based on a doubling of shipped capacity whereas Farmer and Lafond are describing annual growth; historically solar doubles in shipped capacity approximately every 2 years.

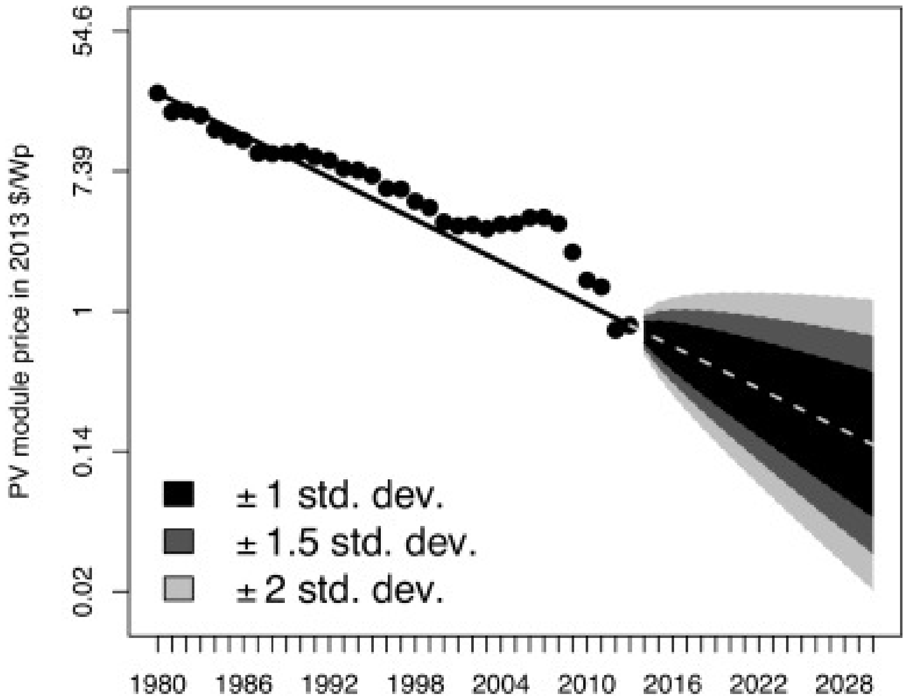


FIGURE-2.06: Actual and Predicted PV Module Price (Farmer & Lafond, 2016)

While the descriptions of these growth trends are quite remarkable, to explain the driving force of these trends there is the “experience curve” body of literature (Alberth, 2008) and the more generalized “law of accelerating returns” (from author and futurist Ray Kurzweil (1999) that has reached a fair degree of mainstream notoriety

One major piece missing from this investigation thus far is the issue of the daily intermittency and seasonal variability of solar. More specifically, there is a significant challenge in the daily timing of load and demand management for regional electricity grids with high solar penetration. This was first recognized in the United Stated by the California Independent System Operator (CAISO). CAISO coined the now somewhat infamous term “the duck curve” based on the shape of the graph of the daily actual and predicted net generation curves that loosely resemble the shape of a duck (see *figure-2.07*). The graph depicts the potential for net overgeneration where load is high when driven by peak sun during the midday, but demand is relatively low. This load and demand reverses later in the evening as the sun sets and people are returning to their homes thus increasing net grid demand. While this is empirical data and prediction based on the California market, given the similarities of daily work-life patterns across the globe, it is reasonable to presume any market with high penetration of solar generation might experience similar challenges.

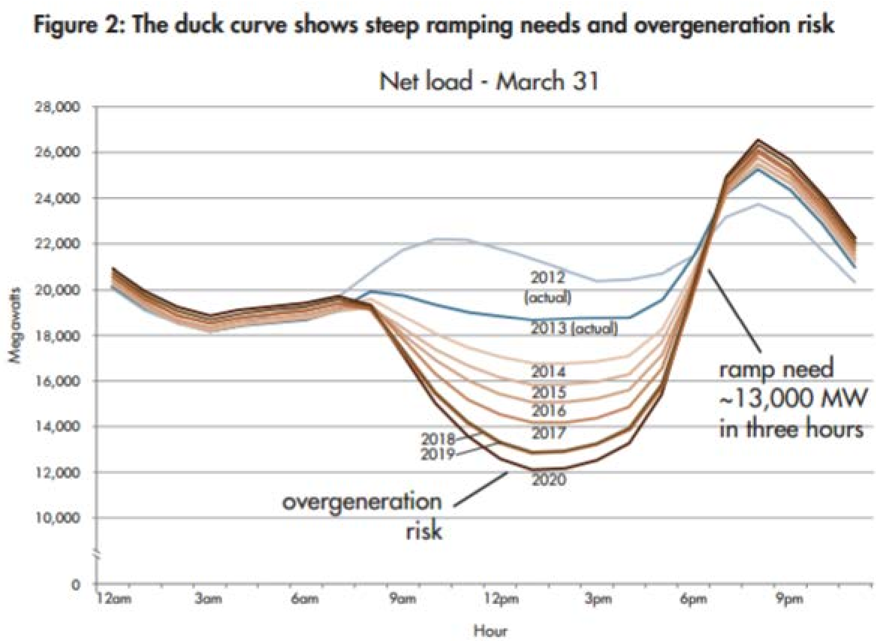


FIGURE-2.07: Actual and Predicted Generation (California Independent System Operator, 2016)

Solutions have been proposed for how to deal with this so-called duck curve through demand shaping via variable pricing –charging consumers more for electricity when supply is low– but perhaps it is useful to look at energy storage. Lithium-ion battery technology has thus far demonstrated remarkable trends in price performance (Denholm, O'Connell, Brinkman, & Jorgenson, 2015). A meta-analysis of price estimates and reporting of lithium-ion battery storage technology found that, much like the cost of solar PV, lithium-ion battery storage has been rapidly decreasing in price at an annual exponential growth rate of 14% (see *figure-2.08*). Thus with a compounding rate of roughly every 5.3 years, the same amount of storage performance will halve in price[7].

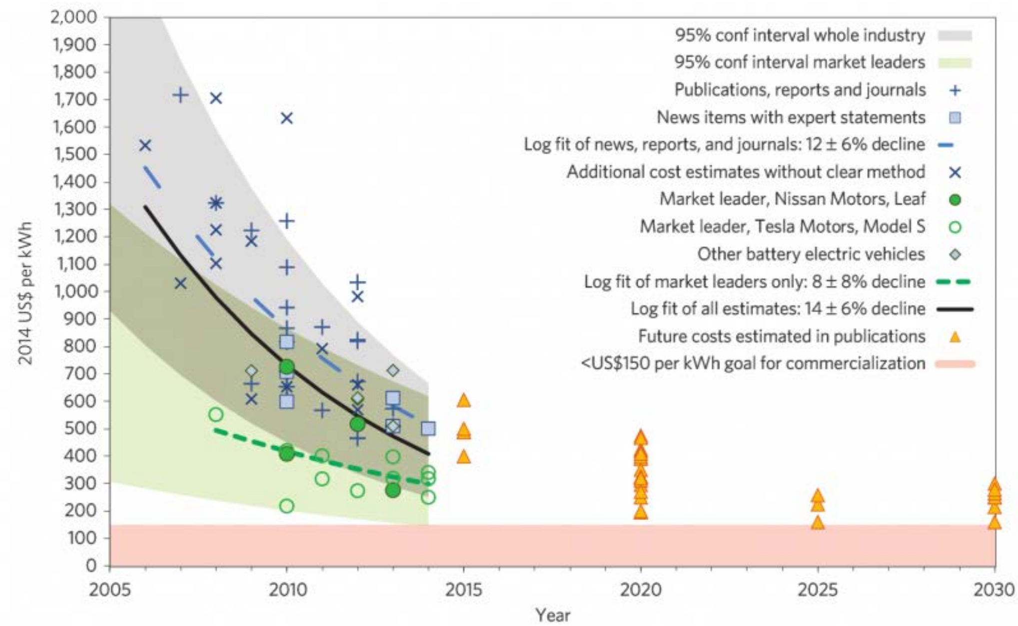


FIGURE-2.08: Lithium-Ion Battery Storage Price-Performance Curve technology (Denholm, O'Connell, Brinkman, & Jorgenson, 2015)

Much like solar PV, lithium-ion storage shares the advantage of being extremely scalable and sourced from materials (lithium) that are exceptionally abundant in the Earth's crust (USGS, 2015). Thus far lithium-ion storage technology has been used in a range of applications from mobile phone batteries to San Diego Gas & Electric's unveiling of 120 megawatt-hour lithium-ion storage plant that can

[7] Doubling time = log(2)/log(1+r), where r = rate of return

meet the electricity needs of 20,000 customers for up to 4 hours (Energy Matters, 2017).

POLICY AT THE GLOBAL LEVEL

At the global level, the most significant policy development related to anthropogenic climate change was the so-called “Paris Agreement”. At 7:16pm on the 12th of December, 2015 at the 21st Conference of the Parties (COP21) held in Paris, France, the world celebrated as 196 nations agreed to reduce emissions to levels sufficient to limit global warming to less than 2° Celsius (3.6° Fahrenheit) over pre-industrial levels. This agreement under the United Nations Framework Convention on Climate Change (UNFCC) was hailed as both, “historic, durable and ambitious”, as well as, “the world’s greatest diplomatic success” (Harvey, 2015; Domonoske, 2015; UNFCC, 2017). The vast majority of the 196 signatories signed just a few months after the Conference, on Earth Day, the 22nd of April, 2016. At present, 146 countries have ratified this agreement. The agreement is not a legally binding policy, and countries can walk away from this agreement at any time with no legally enforceable repercussions. Terms like “sanctions” and “punishment” were specifically barred from the agreement language in favor of phrases like “peer pressure” and “cooperation” (Lane, 2016; Bodanksy, 2016; Euractiv, 2015). U.S. President Donald Trump campaigned on a promise to “cancel” or “renegotiate” the American participation in the historic deal (Chemnick, 2016). This is not without historic precedent as former U.S. President George H.W. Bush pulled out of the Kyoto Protocol treaty, signed but not ratified by the previous U.S. President Bill Clinton, citing concerns that it would hinder the U.S. economy (Kahn, 2003).

While international endeavors towards voluntary efforts and agreements across nations are worthy of pursuit, they also highlight the fact that the mechanisms for actual implementation mechanisms to curb greenhouse gas (GHG) emissions happen at the nation-state and below. Thus "global policy" is a bit of a misnomer, and even previous discourses on "global solar energy policy" is merely a composite list of what individual countries are doing (Solangib, Islamb, Saidura, Rahimb, & Fayazb, 2011).

GEOGRAPHY MATTERS: TWO CONTRASTING SCENARIOS FOR A RENEWABLE PARADIGM

A geographic lens can be useful for understanding a global energy transition towards solar energy because it helps us understand energy challenges within their specific locational context and to highlight broader spatial patterns and their implications (Pasqualetti M. J., 2011; Bridge, Bouzarovski, Bradshaw, & Eyre, 2013; Pasqualetti & Brown, 2014). Across the global electricity sector two emerging yet completely divergent schools of thought are forming. In one camp, the idea of converging towards an energy regime of loosely coupled modularization and total decentralization of energy with total, or near total, distributed solar with household or building level battery storage to offset the intermittency issue with solar (Gagnon, Margolis, Melius, Phillips, & Elmore, 2016; Seba, 2014; RMI, 2015). At the other extreme from the "personal electric utility" is the notion of offsetting renewable intermittency with so-called "smart grid" technologies to manage demand and load balancing across large, complex networks (Pasqualetti & Sovacool, 2012, p. 172). Further still is the potential development of a "super grid" (see *figure-2.09*) that would load balance the diurnal and weather differentials across continental scales (DOE, 2008; Ohbayashi, 2016). The idea for a "super grid" is far from new. Author and inventor Buckminster Fuller proposed the idea of a "Global Electric Network" as far back as 1938 (see *figure-2.10*) for the expressed intent of planetary load balancing (Fuller, 1940).

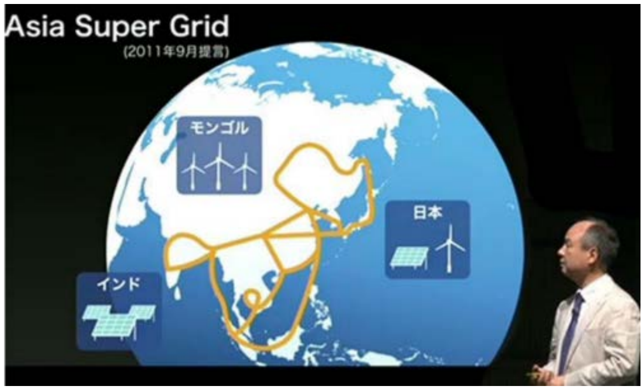
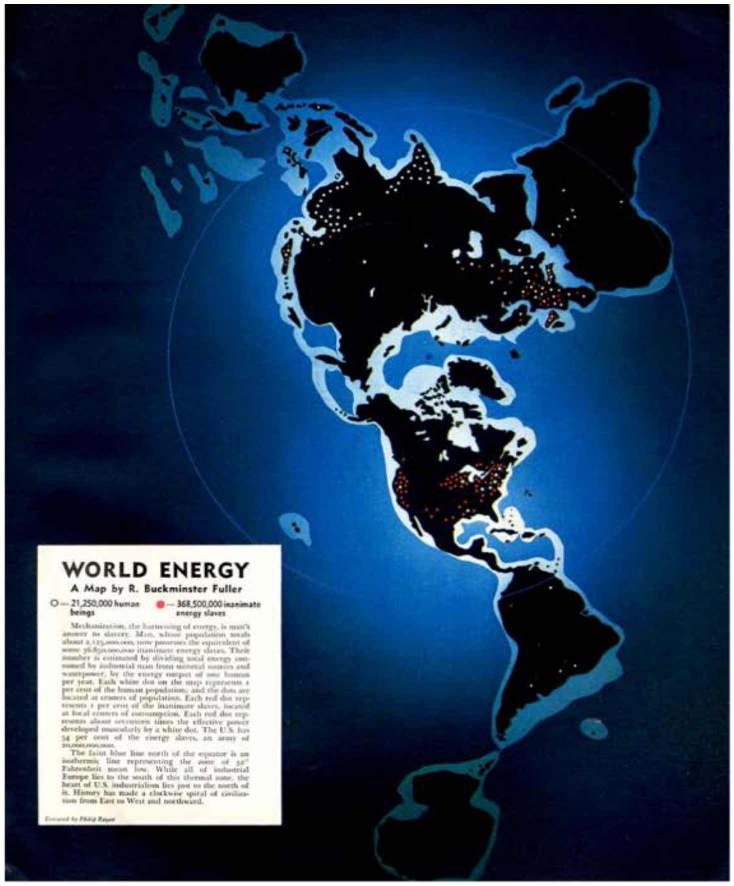


FIGURE-2.09: The Proposed “Asia Super Grid” (Ohbayashi, 2016)



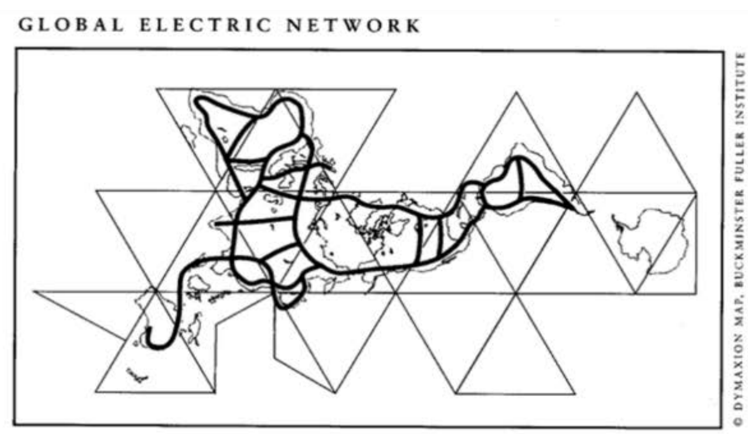


FIGURE-2.10: Buckminster Fuller's "Global Electric Network" Concept (Fuller, 1940)

This discourse will investigate the potential for a fully distributed, global solar energy paradigm. This decision is largely motivated by the more fundamental, yet often overlooked, idea of noting the relative costs of electricity generation versus the costs of? transmission and distribution.

In the United States utility market generation accounts for 58% of the retail price while transmission and distribution make up the other 11% and 31% respectively (Conti, et al., 2014).

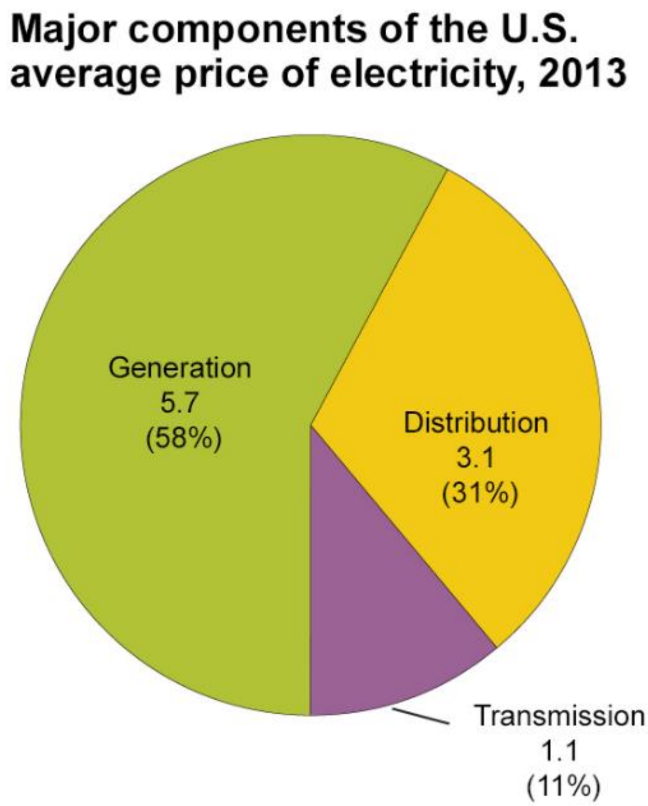


FIGURE-2.11: Major Components of Electricity Price (Conti, et al., 2014)

For absolute costs, in other developed countries, such as those in the European Union, just the cost to operate and maintain the grid infrastructure is approximately €0.06 (~$0.07 USD) per khW of delivered electricity (Seba, 2014). And this does not include the massive initial capital investments needed to initially build the grid infrastructure (NREL, 2016). But if the current falling cost trends hold, some have argued that at some point in nearly every region, and as soon as 2030 for regions with high solar natural capital, solar PV and lithium-ion storage will dominate all growth in the global energy market as their combined cost per kWh will be cheaper than the average price per kWh just to maintain the electricity grid infrastructure (Jacobson & Delucchi, 2010; Lund, 2011; Seba, 2014). The consequences of a rapid and fundamental energy transition at this magnitude is unprecedented in human history, and would represent a massive challenge to global stability and security.

The specific mechanism for this acute disruption, the so-called "utility death spiral", has been hypothesized in the academic literature but was at first dismissed as hyperbole by many in the electric utility industry (Graffy & Kihm, 2014; Costello & Hemphill, 2014). This notion is a scenario where continuous rapid advancements in price-performance of direct-to-consumer energy platforms like distributed solar and storage make it impossible for vertically integrated and conservative utility companies to keep up in the market place. Consumers start to flock to rooftop solar and storage motivated mostly by cost-savings. And since a non-trivial portion of the cost base for major utilities is that transmission, distribution, and generation assets often have financing structures spread out over multiple decades, a utility company has a similar cost structure but rapidly declining revenues forcing it to increase consumer rates to maintain production and grid infrastructure. The rise in consumer rates only makes the personal solar and storage option more enticing, thus further advancing the “death spiral” (see *figure-2.11)* (Herche, 2017). Many researchers in this field have posited that this trend is already happening in Germany and other European utility markets as utilities are squeezed between reduced revenues from both distributed renewables and reduced overall consumption since the 2009 European financial crisis (Lacey, 2014; Costello & Jamison, 2015).

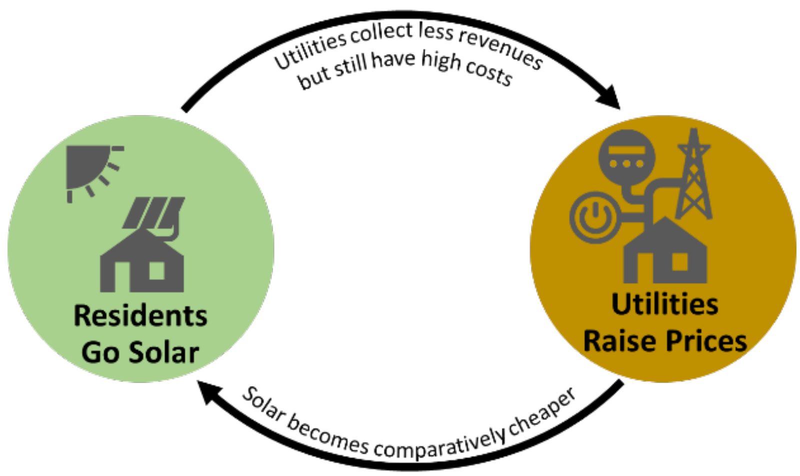


FIGURE-2.12: The So-called “Utility Death Spiral”

Outside of the developed world, there are still more than 1 billion people who currently have no electric grid infrastructure (IEA, 2015). This calls into question the validity, and feasibility, of making the enormous capital investments needed to construct a grid based electricity system. These are oft overlooked, but important preliminary considerations to take into account before seeking to form relevant hypothesis about potential future scenarios dominated by solar energy.

3. Hypotheses

Given the massive potential of solar energy previously illustrated by the works of Perez et al (2016) and others, a relevant question emerges about whether or not the potential of this energy resource is sufficiently distributed –via the natural process of the sun's light striking the earth– to meet the needs of all people based on where they currently live. While the market pricing trends seem to indicate that a distributed solar future scenario is at least plausible, the question remains of whether or not solar irradiation is sufficiently distributed, with given technological capabilities, to satisfy the spatially specific needs of the global population through distributed solar generation. This is a question both of intellectual interest, but also of value in ascertaining the economic viability of maintaining an electrical transmission and distribution infrastructure.

> *Hypothesis 1 (H1): The abundant solar energy natural capital that is geospatially distributed across the earth can provide enough energy via distributed solar PV generation to meet all human needs given our current population density and global distribution*

Similarly, the question of the economic viability of a transmission and distribution grid becomes even more pointed when we consider developing communities and areas of the world that currently lack an existing grid infrastructure. The capital expenditure costs, combined with the projected lifetime costs of operations and maintenance, might make a fully distributed strategy much more enticing. However, this would also create an unprecedented set of challenges in terms of market logistics and self-management of energy generation and consumption at the individual level. A relevant question is whether or not these communities possess the solar natural capital necessary to pursue this approach.

Hypothesis 2 (H2): Solar natural capital is geographically distributed in a manner sufficient to meet the energy needs of rural and poorer communities.

Many of the developing countries south of the so-called "Brandt Line" –originally proposed in 1980 meant to demark the wealthier countries of the "North" from the poorer countries of the "South"– are in equatorial regions known for high levels of sunlight (Brandt Commission, 1980).

4. Analysis and Results

GLOBAL DISTRIBUTED SOLAR POTENTIAL

H1 expects the capacity of global solar potential measured against the geospatial population distribution profile of the world is sufficient to provide all forms of energy for society across the globe. Analysis for this work strongly supports this hypothesis with results indicating that 99.85% of the land surface area of the earth, and a thus a vast majority of the human population, can readily be supplied sufficient energy via distributed solar PV to meet all of their energy consumption needs. The resulting map below generated for this analysis (see *figure-2.12*) is a result of the most conservative and strenuous estimates feasible for all variables that are described in detail below.

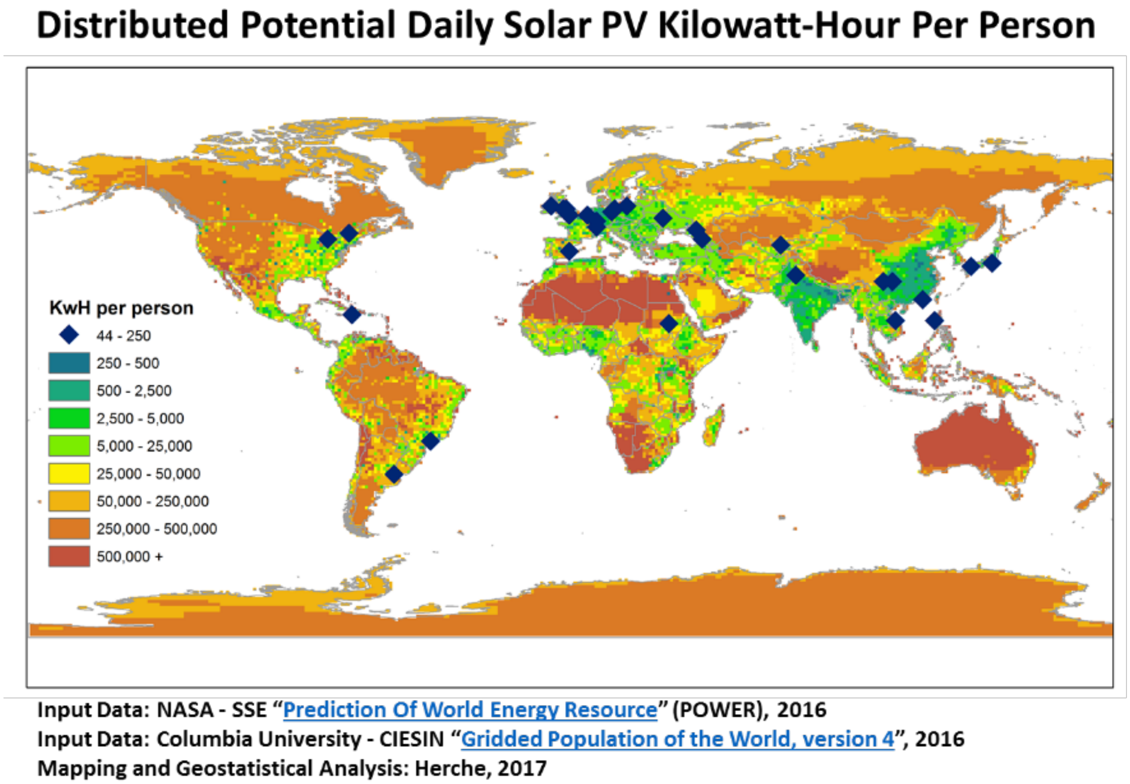


FIGURE-2.13: Location-Specific Potential Distributed Solar per Person

The spatial resolution of analysis was at the 1 degree cell level for global estimates of population density[8] as well as for Global solar irradiance on a horizontal surface[9]. This is thus indicative of potential generation with constitute flat, stationary PV panels. Panels angled towards the sun or even equipped to track the sun's progress across the sky are readily available, but this analysis will skew towards an extreme least-favorable set of assumptions for all pertinent variables.

Table 2-01 denotes the calculation used on each pixel value. In the numerator are the potential for solar energy generation for that given geographic

[8] http://sedac.ciesin.columbia.edu/data/set/gpw-v4-admin-unit-center-points-population-estimates
[9] https://eosweb.larc.nasa.gov/sse/documents/SSE6Methodology.pdf

location given the latitude (and corresponding solar insolation angle), annual averages of daily weather patterns, and related factors. In the denominator are not only the population density of that particular point on the land but also an accounting of all energy consumption would need to be accommodated –electricity, heating and cooling, transport (assuming 100% electric vehicle use globally), and all other activities. Further it is assumed for these calculations that all human beings on Earth will no longer consume energy at the current global average of ~60 kWh per day (~205k BTU) but at the extravagant US rates of ~250 kWh per day (~853k BTU) (EIA, 2017). Finally, while advancements in solar PV conversion efficiency regularly make headlines for reaching levels as high as 22.5%, for the calculations an extremely conservative figure of 10% conversion efficiency was used which is well below most conventional standards to represent the current least-case viable market option[10].

$$\text{Pixel value} = \frac{\text{Spatially specific average annual solar irradiation potential (kWh)} * 0.10 \text{ solar conversion efficiency}}{\text{Spatially specific population density} * 250 \text{ kWh per person per day total energy consumption}}$$

TABLE-2.01: Formula for Location-Specific Potential Distributed Solar

Despite these overly stringent parameters the results are quite remarkable. The vast majority of the planet's population receive enough solar natural capital by one to two orders of magnitude to meet 100% of all their energy needs. This demonstrates that it is possible to satisfy all current and projected future energy needs with a fully distributed generation approach, and without a major distribution

[10] http://www.pv-magazine.com/news/details/beitrag/panasonic-announces-225-module-level-efficiency-solar-panel_100021400/#axzz4PIYxG7cE

or transmission network[11]. Further, this could be delivered via PV modules that only cover a small fraction of the land surface area at any given location. There are 28 points (1° by 1° cells) on the planet denoted with a blue diamond on the map that fall at or below the 250 kWh per person per day threshold of solar potential. These 28 cells are from the approximately 18,792 cells of land surface on earth, or approximately 0.15% of the Earth's land surface. Typically these are areas that have the combination of urban areas with extremely high population densities and less than superlative conditions for solar.

However, even in the case of all 28 outliers they still have enough solar potential to accommodate all of their electricity needs. Further, even with a modest length of transmission or distribution network from the any of the abundant areas near those locations 100% of energy needs across all sectors could easily be met for all people on the planet. Though not the focus of this chapter, this points to the particular challenge for some dense urban areas to meet energy demands with distributed solar.

These results are significant in two major ways. First, they demonstrate not just the vast cumulative potential of solar, but its geographically specific capacity to serve most all human energy needs where they are needed. Second, in most cases these results show this can be done with a complete absence of a large energy transmission system. Totaling just the transmission networks of the U.S., China, and Europe yields more than 33 million km of power lines (Siemens, 2014).

DISTRIBUTED SOLAR POTENTIAL IN RURAL AND DEVELOPING AREAS

Energy development challenges in rural and developing communities are also

[11] This assumes transmission of no greater than 79km, based on half the distance of the diagonal of the largest possible 1° by 1° cell on Earth ((111.66km * √2)/2).

well plumbed in previous literature. Consumption of energy is often regarded as nearly synonymous with human and societal development. In the last 200 years not only has total global energy consumption increased at an exponential rate, but energy consumption per capita also exhibits a sharp growth trend despite an eight-fold increase in world population over the same time period (Roser, 2016). Electricity consumption specifically has long been used as a marker for development with the notion of measuring nighttime illumination via satellite imagery as an apt proxy for national gross domestic product (GDP) dating back to the late 1970s (Croft, 1978) and brought into regular practice in the late 1990s (Elvidge, et al., 1997; Henderson, Storeygard, & Weil, 2012).

Even with a cursory look there is a noticeable geospatial relationship between Gallup, Sachs, and Mellinger's "GDP Intensity" map (1999) and NASA's "Earth Lights" composite (2000) (see *figure-2.13*). Beyond just a visual correlation numerous scholars have teased out a causal relationship with electricity consumption prompting economic growth, with some cases of a bi-directional positive feedback loop, in both OECD and non-OECD countries (Chontanawat, Hunt, & Pierse, 2006; Yoo & Kwak, 2010). Yet approximately 1.2 billion people in the world do not currently have access to electricity; 95% of those without access are in Sub-Saharan Africa and developing regions of Asia, and 80% live in rural areas (IEA, 2015).

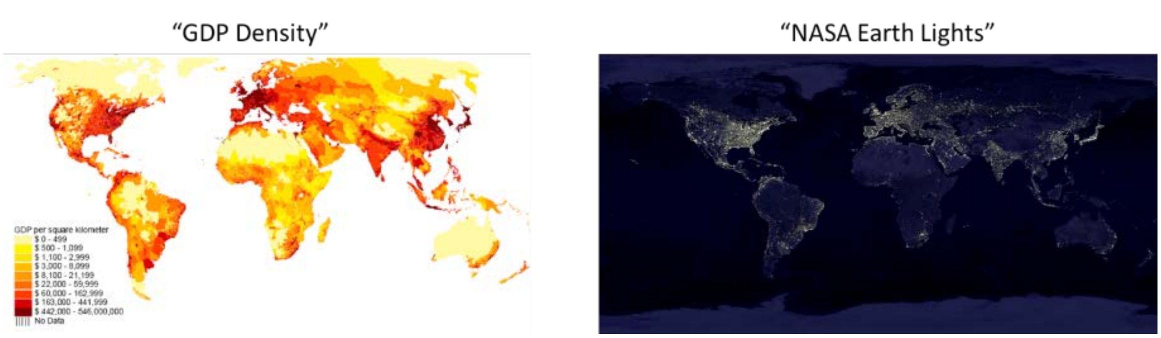


FIGURE-2.14: GDP Density and NASA Earth Lights

Solar energy generation, particularly distributed generation (DG), could be an untapped opportunity in these areas. Taking a look at the overall geographic distribution of solar potential calculated from the average annual solar irradiance (*figure-2.14*) and comparing it to the geographic density of electricity inaccessibility (*figure-2.15*) reveals the opportunity for emerging populations in areas such as South America, Africa, and portions of Asia. to leverage solar energy to generate electricity (Pachauri, et al., 2013).

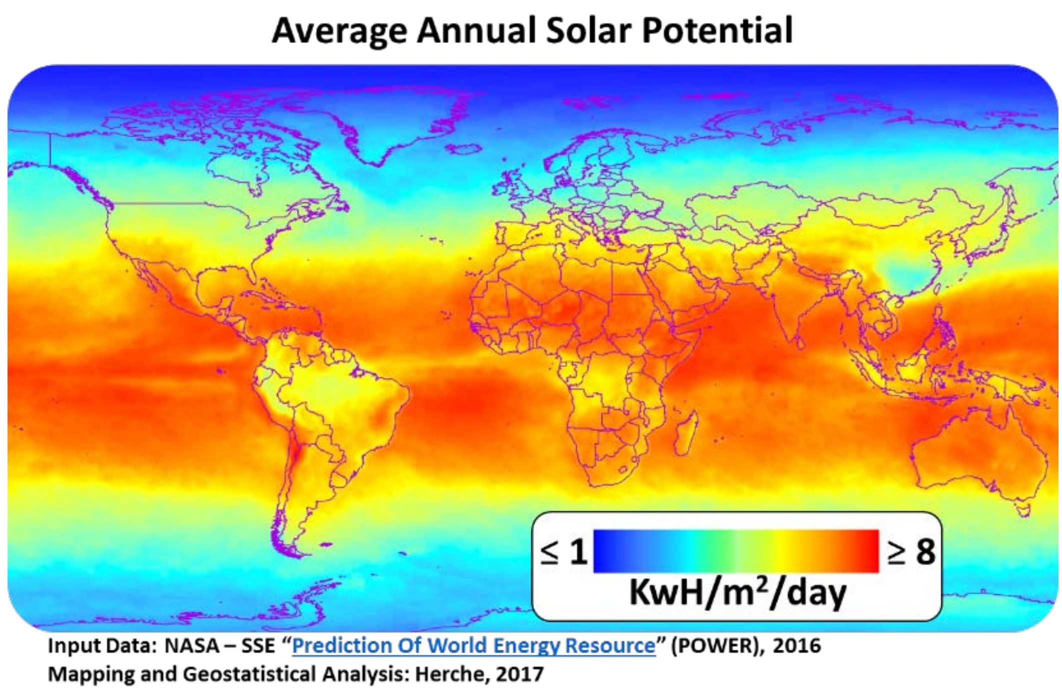
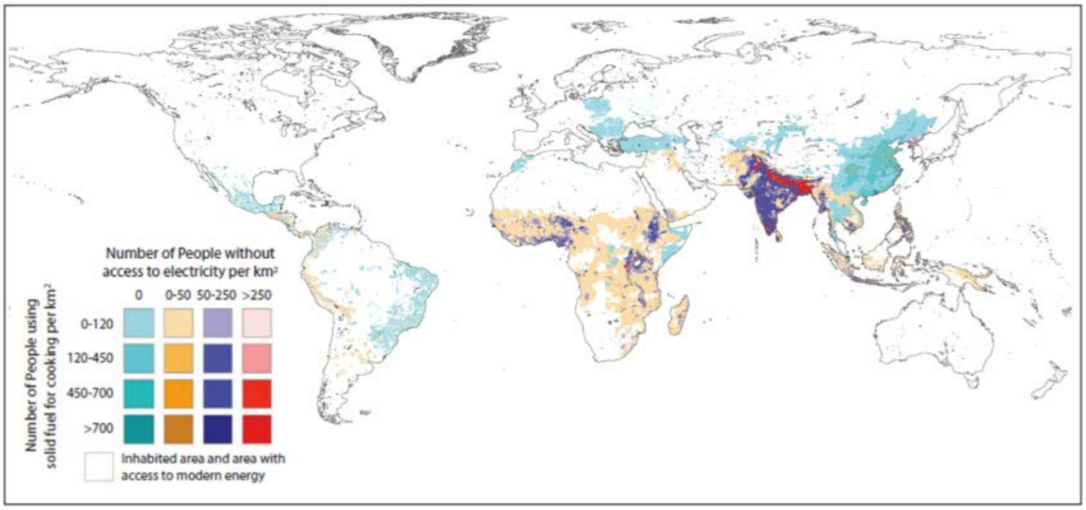


FIGURE-2.15: Average Annual Solar Potential



Pachauri et al (1999)

FIGURE-2.16: Electricity Inaccessibility Density

H2 predicted a non-casual correlation between poor and rural areas and the geographic opportunity for solar potential. This proposed relationship is not meant to be explanatory but prescriptive in that a particularly unique opportunity may exist that has been heretofore largely untapped. This hypothesis is principally supported. State level analysis comparing mean annual solar irradiance in terms of potential kilowatt-hours generated per square meter per day[12], with both GDP per capita[13] and the percent of population living in rural areas[14] (see *table-2.01*), shows a strong positive correlation between the percent of rural population and solar potential (0.4538) as well as a strong negative correlation between GDP and solar potential (-0.5510). Both correlations show strong statistical significance. These correlations of course are not causative but a profound twist of fortune that these developing

[12] Mean Solar Irradiance data were gathered from the U.S. National Renewable Energy Laboratory database download website (NREL, 2008)

[13] Gross Domestic Product per Capita data came from CIA World Factbook (CIA, 2017).

[14] Percentages of rural population per country were taken from The World Bank – International Development Association online data (The World Bank, 2017)

regions can greatly benefit from. Further, DG solar makes for an extremely attractive option for these rural areas that have little or no electricity grid infrastructure.

	MEAN Solar Irradiance (KwH/M^2/day)	*GDP/capita (2015)*	*% Rural population (2015)*
MEAN Solar Irradiance	-		
GDP/capita (2015)	**-0.5510***	-	
% Rural population (2015)	**0.4538***	-0.6761*	-
		* P < 0.0001	(Analysis: Herche, 2017)

TABLE-2.02: Solar Irradiance, GDP per Capita, and Rural Correlation

Using the figures of solar potential per square meter, as opposed to total capacity of the country, and GDP per capita, as opposed to total GDP, was a deliberate choice in order to ascertain the feasibility for distributed solar energy in its potential benefit to individuals and communities.

5. Discussion

Returning to the importance of spatial and temporal considerations in energy transitions, it becomes imperative to scrutinize these multiple levels of analysis not just in isolation but in combination (Pasqualetti & Sovacool, 2012; Calvert, 2015). This becomes particularly illustrative in an examination of energy infrastructure and its potential future directions. As an example, in the transportation sector hydrogen fuel cell technology for vehicles has advanced enough that it could be a clean[15] replacement for petroleum powered transport; however, this would require essentially paralleling the existing oil infrastructure –production, refineries, pipelines for transport, consumer distribution networks, etc– that globally represents trillions of dollars of investment over more than a century of previous development (Frenette & Forthoffer, 2009). In other words the Level 1 technology of the fuel cell and vehicle may be technically viable, but the addressing the more challenging Level 2 socio-techno infrastructure is nowhere in sight (Allenby & Sarewitz, 2011).

Walking through this framing is necessary to articulate the enormity and complexity of the energy system existing somewhere in the realm of a Level 2 technology with reach and implications even into the Level 3 tier interacting in a nontrivial way with our entire Earth system. From this perspective the social and technological "lock-in" of our current energy paradigm becomes more discernable. Gregory Unruh first coined the phrase of "carbon lock-in" to explain the challenges of our current energy regime (2000); where, "industrial economies have been locked into fossil fuel-based energy systems through a process of technological and institutional co-evolution driven by path-dependent increasing returns to scale," (p. 817)

In Unruh's follow up piece, "Escaping carbon lock-in" (2002), he argues that our elopement into salvation will come from exogenous technological forces or by a sudden global epiphany and reinvigoration of resolve among policymakers on par with a transformed Ebenezer Scrooge on Christmas morning[16]. This longing for a *Deus Ex Machina* intervention of sorts is even commonplace among contemporary

[15] Hydrogen fuel cell have no GHG emissions form the vehicle but producing the hydrogen still takes energy inputs from other sources and could therefore have associated GHG emissions and other negative externalities.
[16] The fictitious character from Charles Dickens' 1843 novella, *A Christmas Carol*.

global thought leaders such as the many public speeches by Bill Gates where he is contributing billions of dollars in the hopes of finding energy “breakthroughs” (BusinessGreen, 2016) and “miracles” (The Atlantic, 2015). This is not meant to slight Unruh or Gates in any way. Instead, it is, simply meant to illustrate a pattern of our natural inclination of response –even among clearly brilliant thinkers– when faced with the dizzying scale and complexity of these problems.

Describing our energy challenges as (formally) “wicked” and some proposed solutions as “miracles” raises an interesting point on language. Much of the common parlance for how solar energy is discussed only probably muddies the conversation more than it clarifies. As Michael Webber quipped in a 2013 lecture for the Texas Enterprise Speaker Series, "we take power plants that are far away and call them ‘centralized’, and we take solar panels that are on our roof and call them ‘distributed’ even though they’re centrally located on our roof.” He added, “The ‘centralized’ versus ‘distributed’ is not a geographic comment it’s an authoritarian comment, it’s about who has authority over the energy, the power plants have centralized authority, solar panels have distributed authority,” (Webber, 2013).

The labels of “utility-scale” and “distributed generation” might need to be rethought as this terminology will become increasingly dubious. We might well see the further rise of “utility-scale distributed generation” where utility companies own and maintain massively distributed energy generation and storage tied into a smaller scale community “micro-grid” or no grid at all. A global energy transition does not necessarily need to mean the end of the electric utility company. While advances in finance innovation for solar has long been developing the fact remains that many people will not be able to afford the initial capital investments to purchase solar PV generation and battery storage. Utility companies might still very well serve a vital role given their vast institutional capabilities and access to capital, but the one-sizefits-all model of the vertically integrated utility whose main purpose is to build and manage colossal generation assets and a vast grid infrastructure might need to be reconsidered.

This reconceptualization is especially poignant in the discussion of large populations of people all over the world who currently have no grid infrastructure or large generation assets. Some developing countries are now presented with the socio-technological opportunity to “leapfrog” the predominant grid-driven paradigm.

While the case was previously stated that development is mainly being driven by social processes with technology merely being an element (Pasqualetti M. J., 2011), this so-called “leapfrog” is not without recent, modern precedent. In the telecommunication technology on the African continent many regions largely forwent the capitally intensive telecommunications infrastructure for “land line” telephones and jumped directly to mobile communication. Mobile penetration in many African countries is comparable to the developed world which is quite a remarkable feat given the huge disparities in wealth between OECD countries and many African nations (Pew, 2015). Further, African nations have and continue to be global leaders in the use of some telecommunication technologies such as mobile banking; by 2011 of the 20 countries that had a mobile banking penetration rate of 10% or more 15 of those countries were in Africa (The Economist, 2012). This was not because of technological superiority, as often the mobile handsets used for mobile banking in poorer African nations were far behind that of the developed nations; by 2014 “smart phone” penetration in Africa sat at a median average of 15% compared to 64% in the United States (Pew, 2015).

Many have begun to speculate whether developing communities and nations can make a similar “leapfrog” jump to solve the developing and rural electrification challenge (Simons, 2012; The Economist, 2015). While the challenges of development in impoverished populations is much discussed, compared to OECD countries there are several advantages that often go unnoticed. Communities who currently lack access to electricity by definition are unhindered by the entrenched business interests of powerful electric utility companies who often hold government sanctioned natural monopolies and deep political ties. Additionally, hand wringing around the intermittency challenges of solar (and other renewable) energy will likely be far less of a concern for those that currently have no electricity and comparatively far more tempered expectations for near-perfect reliability. Further, those with no access to electricity likely will not espouse NIMBY ("Not In My BackYard") and similar attitudes commonly found in developed nations (Devine-Wright, 2011; Carlisle, 2016).

6. Conclusion

The past market trends are empirical observations and are no guarantee of future performance. Further, energy transitions are fraught with complexity that are difficult or impossible to accurately predict. However, no other form of energy can come close to the enormous scale of potential and promise as that of solar energy to combat anthropogenic climate change.

Support for H1 indicates that a future energy paradigm dominated by solar is not feasible, but holds many advantages over other forms of energy generation. Further, support for H2 demonstrates the particularly pronounced opportunity for developing areas of the world to avoid locking in to pollution-intensive energy archetypes and instead opting for the particularly abundant resource of solar natural capital. This can satisfy both the macroscopic, universalist sustainability prescripts, but also thee procedural mechanism to use existing technologies to achieve collectively desired outcomes (Miller, 2013).

As climate change is a clearly a global challenge for humanity, the need for global energy governance is well noted but lack of robust international policy levers remain a challenge (Florini & Sovacool, 2009). The lack of enforceable climate change policy at the global level is a glaring lapse in effective stimuli. A policy recommendation from this work is to incorporate GHG emissions as an actionable trade dispute mechanisms within the WTO. Whether or not a country exports its energy or finished goods and services it is exporting the negative externalities of its carbon emissions in the form of global dumping of GHG emissions that proliferate throughout the earth's atmosphere and affect the entire world (Owen, 2006). While numerous other global GHG monitoring and trading schemes have been discussed over the last decade or so, the WTO provides a robust framework and dispute resolution mechanisms to leverage, and already enjoys wide participation by a vast majority of the world's nations.

Specific to the energy technologies that can be used to help limit emissions such as solar PV, which is the focus of this discourse, those are subject to the more binding agreements in global trade under the World Trade Organization (WTO). In a recent example in September of 2016, India lost its WTO appeal in the dispute brought by the U.S. claiming that India's practice of requiring solar developments in India to use Indian-made modules had resulted in a 90% drop of U.S. solar module exports to India (WTO, 2016; Miles, 2016). However, while many scholars agree that the mechanisms of the WTO help promote the general effectiveness of global trade markets, which solar and other renewable technologies markets can generally benefit from, they operate at the periphery to the core issue of using renewable energy technologies to combat anthropogenic climate change (Jackson, 2000; Keisuke, 2004; Rose, 2004; Green, 2005).

The idea of a comprehensive transition to solar energy, or “leapfrog” for the developing world, is hard to imagine when the thread of the existing energy paradigm is so deeply woven into the psyche and fabric of every aspect of our lives. But this discourse has detailed both the existing precepts that make this necessary and the combination of factors that may indeed make it possible. And as futurist Ray Kurzweil has often famously quipped, “a kid in Africa with a cell phone has access to more intelligence than the President of the United States did 15 years ago,” (Burke, 2012, p. 3). This may seem deeply counterintuitive or even preposterous, but a vast convergence of ingredients demonstrated here that there is both geographic opportunity and economic motive to achieve such a transition. And while currently still small in overall market-share, long-standing exponential trends point to significant disruption and transformation of this paradigm.

Ultimately this investigation sought to answer a cross-cutting slice of William C. Clark’s challenge of integrating complex interactions of human and natural systems into more holistic conceptual models. The policy recommendations here seek to lead to more sustainable trajectories by leveraging existing global trade policy levers. The goal here is to demonstrate that as sustainability science “transcends the concerns of its foundational disciplines,” (p. 1737), this provides the necessary and unique lens to arrive at these conclusions. For global sustainability challenges of such immense scope and scale, the integrative approach of sustainability science draws out unique conclusions that likely would not have been possible under a more narrowly focused, single discipline approach.

(Clark W. C., 2007)

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Chapter 3

3. STUDY B - THE NATIONAL SCALE: SOLAR ENERGY STRATEGIES IN THE U.S. UTILITY MARKET : NATURAL CAPITAL AND RENEWABLE PORTFOILIO STANDARDS[17]

1. Abstract

Given the exponential cost decline trend of solar energy generation technologies, and the targeted tax incentives and loan guarantees for renewable energy in the American Recovery and Reinvestment Act of 2009 and other policy measures, solar energy generation has been enjoying rapid growth in the United States. This paper examines the incorporation of solar renewable energy into generation portfolios, and the effects of natural capital – specifically the geospatially calculated potential solar energy generation as measured by potential average annual kilowatt-hours per square meter per day – and respective state mandated "renewable portfolio standard" targets on utility-scale solar energy generation. Findings suggest that a state's natural solar energy potential is a predictor of solar energy generation development, and further this relationship is significantly moderated by state-specific renewable energy portfolio standard targets.

[17] Other than some edits made for this dissertation, the bulk of this chapter appears in the journal Renewable and Sustainable Energy Reviews (Herche, 2017)

2. Introduction and Background

INTRODUCTION

Consumer demand for a greater emphasis on renewable energy generation is very high in the U.S..A 2013 Gallup poll of Americans showed support for “more emphasis” on solar and wind energy at 76% and 71% respectively (Gallup, 2013). The poll further indicated that support for solar power was high regardless of geographic region with “East”, “Midwest”, “South”, and “West” indicating support at 79%, 75%, 74%, and 78%, respectively. A follow up Gallup poll in 2016 showed increasing levels of support from the 2013 poll among both self-identified Democrats and Republicans; further, 73% of Americans now believe the U.S. should prioritize renewable energy over oil and gas (Gallup, 2016). Meanwhile, prices for solar generation technologies continue to rapidly decrease. The average consumer cost per kilowatt-hour for unsubsidized solar photovoltaic systems have become cost-competitive with fossil fuels; further, the average wholesale cost per kilowatt-hour of utility scale solar PV is less than any form of fossil-fuel based generation (Lazard, 2016). But this strictly economic comparison ignores the externalized costs of fossil fuels in terms of environmental degradation and public health. Thus, when factoring in fossil fuel’s negative externalities, renewable technologies become even more attractive (Clark C. W., 1991). Despite large consumer appetite for renewables and falling prices, the most current estimates show renewables making up just 13% of US electricity production with solar (utility scale and distributed) being just under 1% (EIA, 2016).

Policy initiatives at the national and state level have directly targeted renewable energy production. At the federal, level Section 1603 of the American Recovery and Reinvestment Act of 2009 (ARRA) had investment tax credits (ITC) of

30% for qualifying commercial renewable installations. These took effect in 2009, were extended twice, and have run through 2016 (US Department of the Treasury, 2016).

At the individual state level, many states have created some version of a "Renewable Portfolio Standard" (RPS). An RPS mandates a specific target date and target percentage of energy that must be from renewable sources such as solar, wind, geothermal, and biomass. Electric utility companies must source their energy generation according to these minimum targets or face penalties imposed by state regulatory agencies. The RPS concept was first proposed and developed in the 1990s and implementation varies widely across states (Rader & Norgaard, 1996). *Figure-3.01* shows the 29 U.S. states have some form of statutory RPS, usually these are a targeted percent of renewable generation by a certain year with a graduated schedule of advancement to the target goal. An additional 8 states have non-binding, voluntary renewable goals (Durkay, 2016).

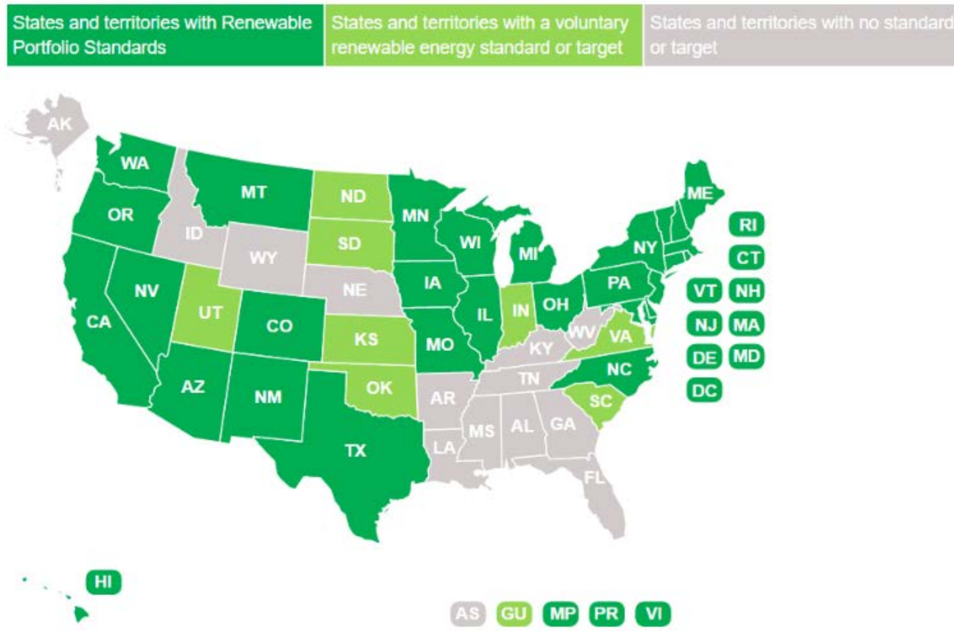

FIGURE-3.01: Renewable Portfolio Standards in the U.S. (Durkay, 2016)

States differ on their overall target goals as well as respective “carve outs” and “multipliers” for specific renewable technologies that legislatures may be trying to promote in their state[18]. It should also be noted that many states without an existing RPS still have sizeable renewable energy generation collections.

The RPS, ITC utilization rates, and the natural capital potential of solar irradiance within each state are all examined against solar energy generation for electricity. The results provide a contribution to the literature on identifying the relative strengths and interaction effects of key correlates of electrical generation from solar. Because this examination is across multiple sets of data with varying

[18] i.e.: Within an overall goal of “15% renewables by 2015” a particular portion may be mandated for residential rooftop solar, or a wind energy generation may be counted towards the goal as at “1.5 times” rate.

degrees of temporal currency, various annual ranges were utilized to have valid comparisons across datasets. In all cases the most current points or ranges of available data were used where appropriate.

BACKGROUND

Benefits from both economies of scale (Stigler, 1958) and technological innovation (Farmer & Lafond, 2016), have yielded consistent, exponential performance improvements in solar PV technology when examined on a global scale. The notion of “Swanson’s law” has emerged; similar to “Moore’s law” for computers (Moore, 1965), this phenomenon was named after SunPower Corporation founder Richard Swanson, who first noted, "module prices reduce 20% for every doubling of cumulative volume." (Swanson, 2006; The Economist, 2012). *Figure-3.02* illustrates Swanson’s Law with the non-linear (inflation adjusted) dollars per watt from 1977 to 2013. Thus considering a broader framing that also considers policy, geospatial explicitness, and market factors might yield more heterogeneous, and therefore more interesting, insights. Numerous bodies of literature have identified the need to incorporate these types of sociocultural and sociotechnical dynamics into the energy discussion (Shwom, 2009; York & Lenox, 2013; Pasqualetti M. J., 2011; Allenby & Sarewitz, 2011; Unruh, 2000; Chow, Kopp, & Portney, 2003; del Ríoa & Burguillob, 2007).

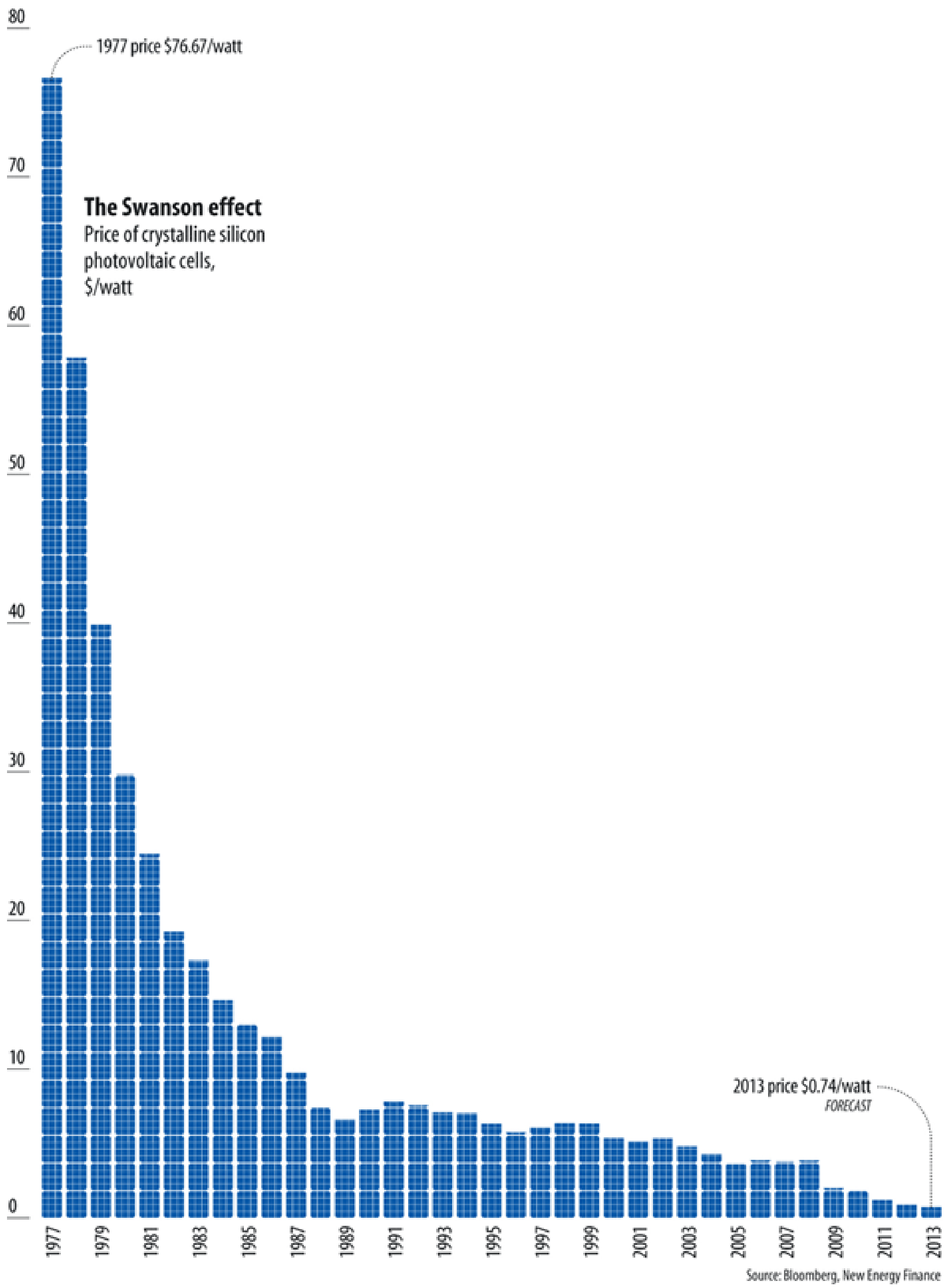

FIGURE-3.02: An Illustration of “Swanson’s Law” (The Economist, 2012)

For this analysis only the RPS goal for the state, if applicable, will be used as a general proxy indicator of the state's political appetite for renewable energy within their electricity generation portfolio mix (Stokes & Warshaw, 2017). Prior research on RPS policies have found that initial adoption of RPS by a state varies depending on the political makeup of the state legislature, the size of the existing renewable energy industry within the state, the state's reliance on natural gas, and the regulatory state of the electric utility market (Lyon & Yin, 2010). Further, not recognizing the heterogeneity of implemented RPS programs across various U.S. states has been insufficient for analysis that explains variation among specific properties and provisions of the state's RPS and the resulting growth of renewables in that state (Yin & Powers, 2010).

This discussion extends the discourse on market effects of state and federal policies and incentives on a still emerging industry (Delmas, Russo, & Montes-Sancho, 2007; Russo M. , 2003). Further it extrapolates from well-established geographic theories of spatial autocorrelation (Tobler, 1970). Understanding these interaction effects has significant strategic implications for state and national policy makers, renewable energy advocates, entrepreneurs, and utility industry managers.

3. Hypotheses

The overall effect of RPS policies on the retail price of electricity is contested in both the political and academic arena. Generation is certainly the dominant factor in price; *figure-3.03* illustrates estimates by the U.S. Environmental Information Administration revealing 58% of retail electricity prices are determined by generation, with transmission and distribution making up the other major components of the cost (Conti, et al., 2014).

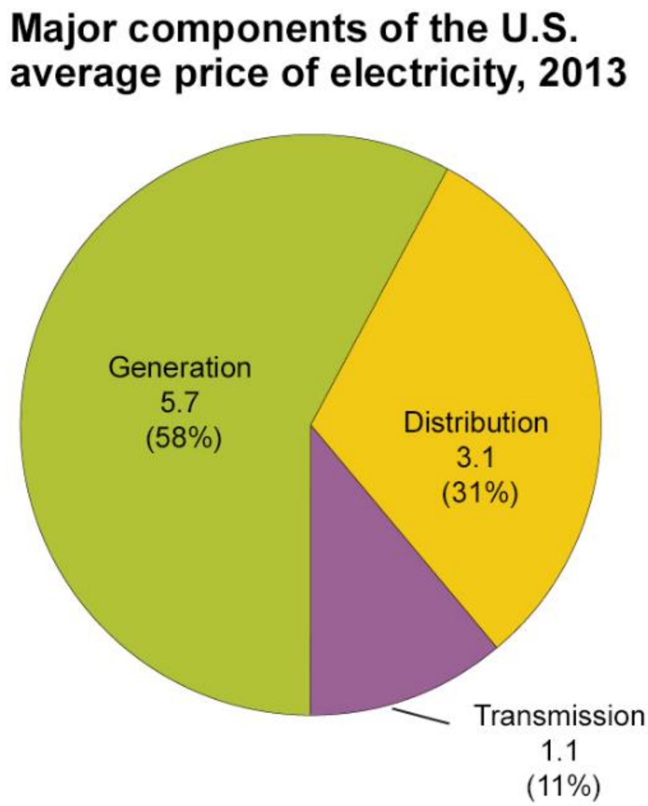

FIGURE-3.03: Major Components of Electricity Price (Conti, et al., 2014)

While critics often make unsubstantiated claims that renewable generation is more expensive than fossil fuels, if true this would logically indicate that the influence on markets of RPS laws would ultimately increase retail electricity prices. Yet previous research pursuits have been mixed arguing that RPS implementation could raise prices by increasing electricity generation costs or even lower prices because of reduced demand on non-renewables (EIA, 2007; Fischer & Newell, 2008; Fischer C. , 2010).

Those assumptions are tested here with empirical findings based on the state average change in retail energy price from 2005-2012 against the state's RPS percentage of renewables target for 2012. The years from 2005-2012 seem most critical as this is the general timeframe when most states began implementing initial, incremental targets to meet overall RPS goals the state had set. There were 26 states with enforceable RPS policies during this timeframe existing within both regulated and deregulated electric utility markets. The price data were aggregated by state across all electricity providers including federal, state, municipal, political subdivisions, cooperatives, retail providers, and investor-owned utilities. In 2012 non-hydroelectric renewables only accounted for 7% of total U.S. electric energy generation so the expected effects on prices should be small, yet given the high proportion of costs associated with generation these effects should be noticeable.

Hypothesis 1: Utility companies in states with an RPS will increase prices to accommodate extra expenses associated with renewable energy generation.

Another fundamental indicator to be empirically verified is whether the increase in RPS targets are positively associated with net level energy generated from renewable sources on a state by state basis.

Hypothesis 2: The overall RPS percentage target within a given state will be positively associated with total solar energy generation within a given state.

Admittedly this particular supposition is susceptible to a latent confounding variable effect (Fisher, 1935). Further, it may be difficult to definitively determine whether RPS policies are causing an increase in renewable energy generation or rather that states that are already predisposed towards renewable energy technologies are also more likely to enact legislation to support renewables. Nevertheless even if more aggressive RPS targets are a proxy for general proclivities towards renewables it is still important to understand empirically if the desired intent is for an expansion of clean energy, as measured in renewable energy generation. If the null hypothesis is supported for H2, this would call into serious question the validity of RPS programs in their ultimate ability to result in generation of electricity from renewables. However, since this analysis only examines the solar energy generation in H2 it will likely not explain a large portion of the variance in that (proposed) relationship.

The notion that solar energy generation potential should be positively and strongly associated with energy generated from solar seems intuitive but also needs to be tested empirically. Previous concerns with confounding variables are apropos here as well. Perhaps residents of a perceived "sunny state" such as Florida or Arizona are more likely to see themselves as potential benefactors of solar investments thus leading to more solar energy generation. However, this relationship is still important to ascertain whether these states are actually capturing their natural capital[19] from this natural resource (Roosevelt, 1937; Schumacher, 1973; Daly H. E., 1997; Russo M. , 2003).

Hypothesis 3: Values of potential solar energy generation (measured by average annual potential kWh/m^2/day) within a given state will be positively associated with total solar energy generation within that state.

Indeed if the null hypothesis is supported or findings are insignificant for H3 this would call into question the relative importance of natural capital and geographic specificity in solar energy generation (Russo M. , 2003) and instead point to other factors such as policy and financing as the more important determinates (Yin & Powers, 2010).

A further test for better understanding this phenomenon can draw from complex adaptive systems literature. Perhaps a piece of the “emergence” that may occur between multiple factors effecting net solar energy generation can be revealed here, “wherein the whole of the system’s behaviour goes beyond the simple sum of the behaviours of its parts,” (Holland, 2002). While this discourse will not fully capture the totality of complexity within this system with only a few empirical measures, this could give good indication as to the complex nature of the phenomenon discussed here.

[19] The notion of “natural capital” goes back at least to 1937 when while addressing a small informal audience in Montana U.S. President Franklin D. Roosevelt remarked, "we have lost sight of the fact that the natural resources of our land – our permanent capital – are being converted into those nominal evidences of wealth at a faster rate than our real wealth is being replaced."

Hypothesis 4: The overall RPS percentage target within a given state will have a moderating interaction effect with potential solar energy generation (measured by average annual kWh/m^2/day) such that when RPS targets are high the positive relationship of solar energy potential to generation will be stronger.

4. Data, Methods, and Analysis

Examining natural solar energy potential, RPS policies, and their specific empirical relationship to the generation of energy from solar will serve to test these hypotheses. Additional data sources include the Energy Information Administration's copious data holdings on all electric utility companies within the U.S., the installed capacity of major solar power plants and the history of claimed federal income tax credit (ITC) awards for qualifying renewables.

While average annual solar energy potential is relatively constant from year to year, the rest of the data sources examined are on a year by year average annual basis and range from the years 2005 to 2014, though not all are current up to 2014. This helps bolster the longitudinal efficacy of analysis and results.

VARIABLES

The dependent variable for analysis here is net generation of power from utility-scale solar sources aggregated by year and state. Actual electricity generation was chosen as the dependent variable over measures such as installed capacity because it represents a more stringent hurdle of analysis and is more indicative of actual realized benefit of renewable energy generating technologies. This data is obtained from the Energy Information Administration, a division of the US Department of Energy, that collects and publishes data on petroleum, natural gas, coal, electric, nuclear, and renewable energy. A number of independent variables are examined and a hypothesized moderating interaction effect. These variables include potential solar energy generation measured by average annual kWh/m^2/day (EIA data), yearly RPS targets from the "Database of State Incentives for Renewable & Efficiency" (DSIRE) for each state[20], income tax credit (ITC) awards from section 1603 of the American Recovery and Reinvestment Act of 2009 as administered by the U.S. Department of the Treasury[21].

Of special note, the ITC awards data as an independent variable is presumed to be highly endogenous with the outcome variable of energy generation during the same time period. Companies that have installed utility-scale solar during the qualifying time period would be remiss to not claim the 30% tax credit. However, this analysis is not without merit, even with its presumed endogeneity, because it is not certain that construction of a solar plant will necessarily be consistent with successful operation and maintenance of the facility, and successful transmission of the energy produced to a utility provider willing to pay for that energy. This is consistent with the decision to use actual generation over installed capacity for the dependent variable. This can serve as a validity check for the successful execution of the intent of the ITC in adding more utilized renewable energy (specifically solar in this examination) to the utility grid. A null or insignificant finding would call into serious question the legitimately and cogency of this federal tax credit program.

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[20] DSIRE is a joint effort by The U.S. Department of Energy and the North Carolina Clean Energy Technology Center: http://www.dsireusa.org/

[21] 1603 Program: Payments for Specified Energy Property in Lieu of Tax Credits http://www.treasury.gov/initiatives/recovery/pages/1603.aspx

ANALYSIS

Before delving into the formal hypotheses a quick check is in order on the relationship of net solar energy generation regressed on operating, utility-scale solar capacity, as well as net solar energy generation regressed on the claimed tax credits, on a state by state basis.

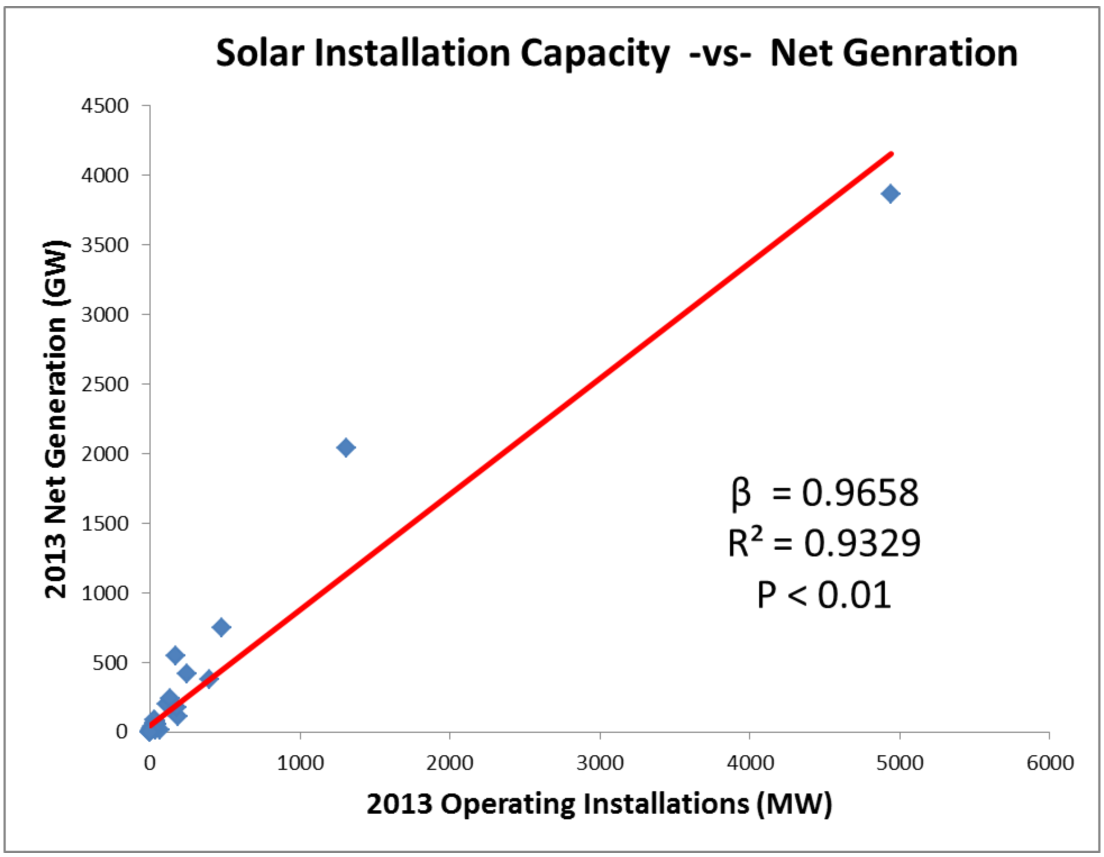


FIGURE-3.04: Solar Installation Capacity versus Net Generation

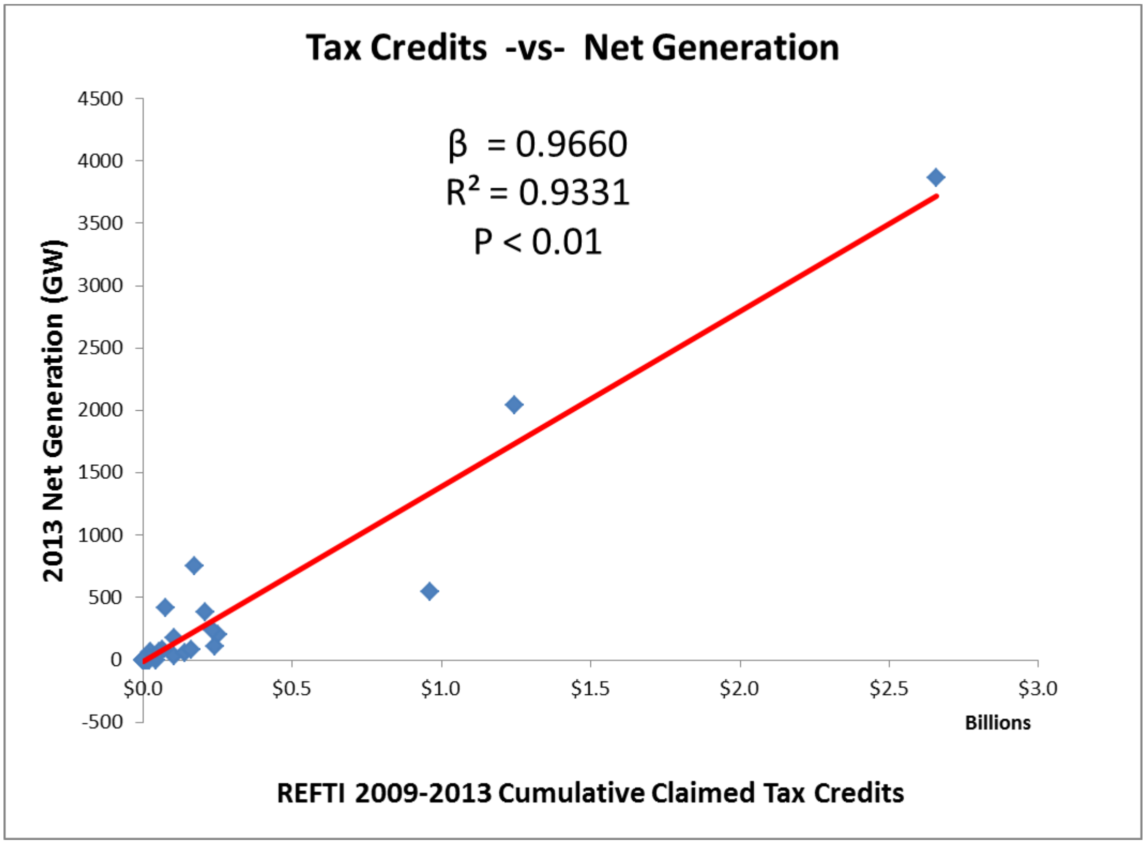


FIGURE-3.05: Tax Credits versus Net Generation

As suspected, shown in *figure-3.04* and *figure-3.05*, both of these potentially endogenous relationships are positive, statistically significant, and highly correlated. Both have standardized coefficients (beta) of 0.96 and explain 93% of the variance. However, with the very high correlation we can potentially infer that installed solar projects, which also happen to have largely taken advantage of the tax credit, seem to be adding additional solar-generated energy into the utility grid.

5. Results

H1 anticipated that increased RPS requirements would be positively correlated with increased costs of retail energy to the end customer. This relationship was not supported, see *figure-3.06*, as it failed to achieve statistical significance ($p = 0.7436$) and explained none of the variance in price. This lends credence to the position by Fischer (2010) that analysis of the effects of RPS on retail energy prices will take a more in-depth and nuanced model to derive useful explanatory power.

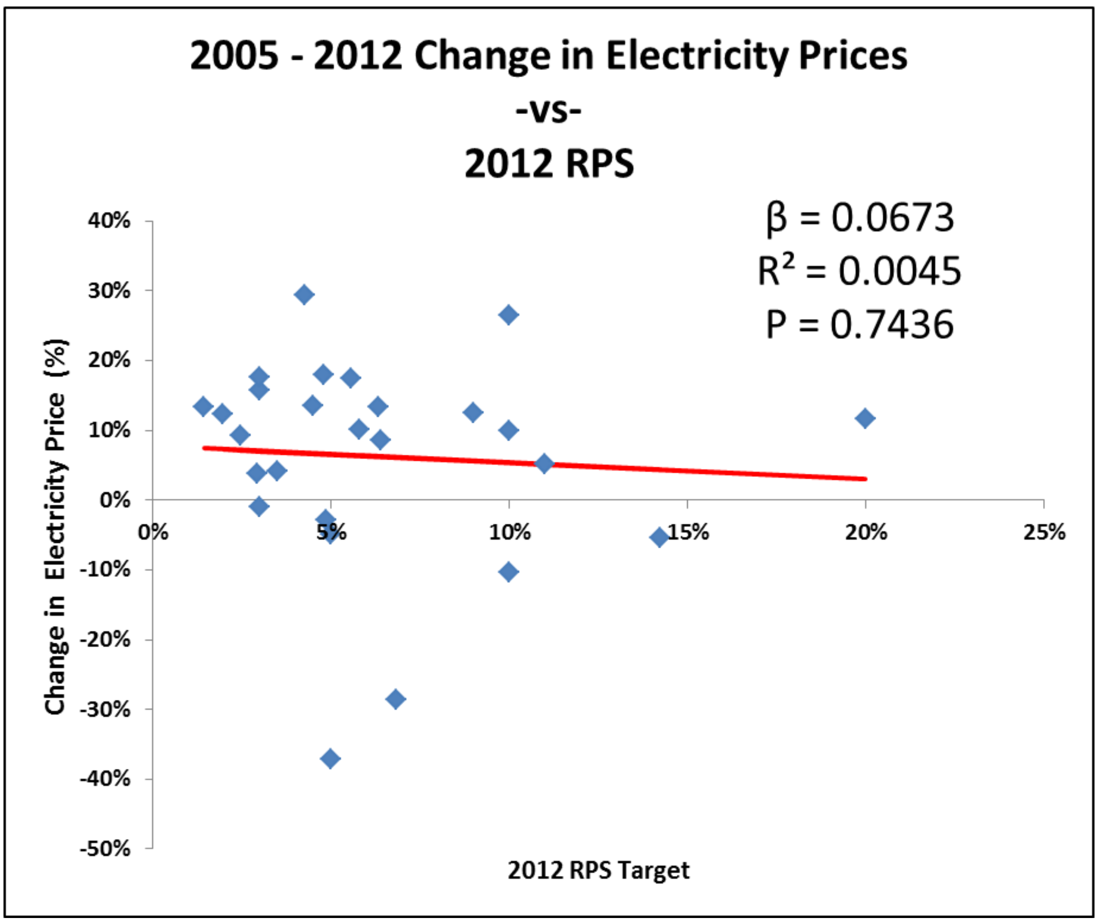


FIGURE-3.06: Change in Electricity Prices versus RPS

H2 proposed that the RPS percentage targets of a state will be positively associated with total solar energy generation. This hypothesis was supported, see *figure-3.07*, showing a moderate, significant, positive relationship (R^2=0.1848). Other than in the case of specific solar “carve outs” utility companies within a state can choose to meet the state RPS target with any renewable energy of their choosing. Thus this could help explain why only 18% of the variance is accounted for in this relationship.

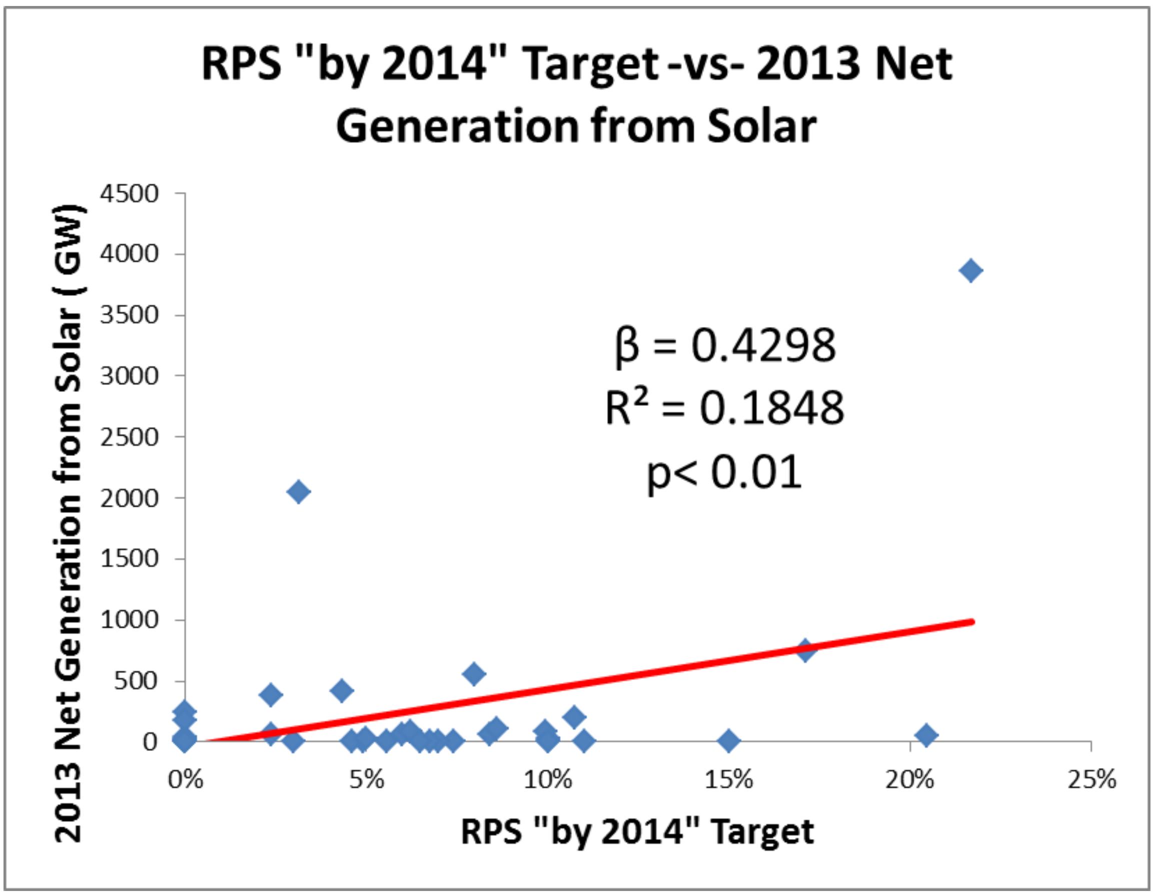


FIGURE-3.07: RPS Target versus Net Generation from Solar

H3 proposed that potential solar energy will be positively associated with total solar energy generation within a given state. This hypothesis was supported, see *figure-3.08*, showing a moderate, significant, positive relationship (R^2=0.2893). This result indicates that states with high, naturally occurring potential to generate solar energy are in fact doing so in many cases. Since these solar potential resources are heterogeneously distributed amongst states and stable over time this result closely parallels foundational strategic management theory of "resource-based view" for sustained competitive advantage (Barney, 1991), and extends it to the realm of natural capital.

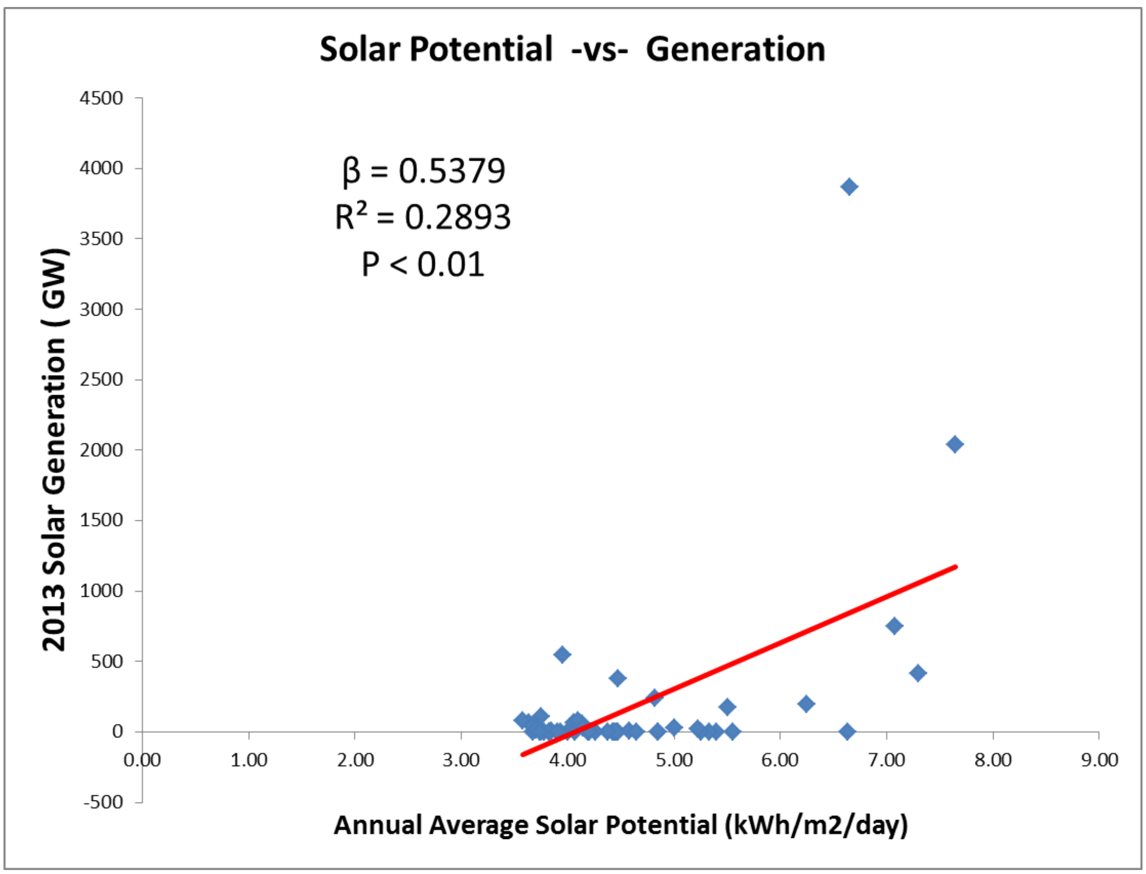


FIGURE-3.08: Solar Potential versus Generation

H4 suggested that the renewable portfolio standard target percentage would act as a moderator, amplifying the effect of solar natural capital on solar energy generation. This hypothesis was supported, see *table-3.01* and *table-3.02*, showing a significant, positive relationship (R^2=0.4610). Additionally this statistical model has a better fit, with more variance explained, than considering the effects of either RPS or solar natural capital independently on solar energy generation. This is the most novel and significant finding of this examination. Support of H4 reveals states that have higher potential for solar energy generation ultimately have higher energy generation from solar, and states that have higher renewable portfolio standards have higher energy generation from solar; but most critically, states that have both higher potential and higher RPS targets have the strongest positive effect on solar energy generation. While much of the sustainability management literature operates across the three broad perspectives of natural, social, and economic realms, fewer studies have looked at specific interactions from these three in regards to solar energy efficacy (Elkington & Trisoglio, 1996; Foran, Lenzen, Dey, & Bilek, 2005; Hubbard, 2009).

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.679[a]	.461	.426	.765277057314

a. Predictors: (Constant), RPS target * Solar Potential, Solar Potential, RPS target

TABLE-3.01: Model Summary

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	-.031	.109		-.283	.778
	RPS target	.213	.113	.213	1.888	.065
	Solar Potential	.512	.109	.512	4.718	.000
	RPS target * Solar Potential	.498	.134	.419	3.724	.001

a. Dependent Variable: Solar Generation

TABLE-3.02: Multivariate Model

A multiple regression slopes analysis, *see figure-3.09*, is necessary to confirm the moderator interaction in support of H4 (Aiken & West, 1991; Dawson, 2013). To address concerns for tautology or multicollinearity a correlation matrix, see *table-3.03*, for natural solar capital potential and RPS target demonstrate that the independent variable and moderator share almost no overlap (r= 0.01889). The issue of low correlation between solar potential and RPS is not trivial, it shows that just because a state has a potential to capture large amounts of natural capital from solar, this does not appear to affect the policy decision process on whether or not, and to what extent, a state should enact RPS targets.

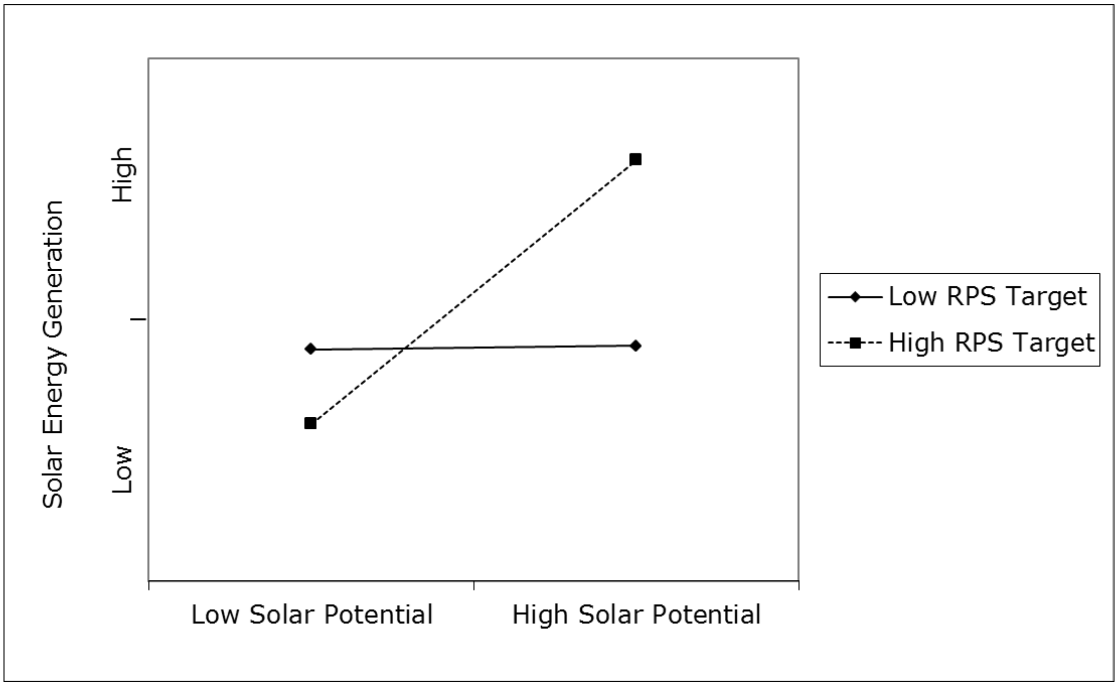


FIGURE-3.09: Multiple Regression Slopes Analysis

	1	*2*	*3*
1. RPS Target (%)	--		
2. Solar Potential (kWh/m²/day)	0.01889	--	
3. Solar Generation (GW/year)	0.20059	0.53789	--

TABLE-3.03: Correlation Matrix

5. Conclusion

Solar continues to emerge as a viable player in the energy generation portfolio of the United States; prediction models forecast its growth to continue for several decades (Fthenakis, Mason, & Zweibel, 2009; Mekhilef, Saidur, & Safari, 2011; Comello & Reichelstein, 2016). One of the difficulties for managers in the utility industry, federal and state policymakers, and other stakeholder groups, is accounting for the myriad of complex interactions that can affect the development of this technology and market.

Solar energy potential measures a facet of natural capital available to a state, it is a geostatistical measure of a naturally occurring phenomenon. RPS target values are a reflection of civic and political will, driven largely by concerns for global sustainability. Energy generation from solar is an aggregate measure of electrical and mechanical engineering advancements as well as corporate strategy to muster the large amounts of capital necessary to build utility-scale solar projects. The significant interaction between these seemingly disparate streams of scientific inquiry highlights the complex and adaptive nature of these phenomena. The advent and rise of renewable energy technologies is somewhat of a shakeup to an otherwise stoic industry; this makes for fertile ground for policy, management, and sustainability research on these topics.

The contribution of this chapter is in extending the resource-based view to include considerations for natural capital, and in showing how highly variegated sources for measured variables still have a strong interaction effect on one another in this field of research. While the concept of natural capital solidifies through its operationalization in diverse bodies of scholarship such as management (Russo M. , 2003), biology (Robinson, et al., 2013), and urban planning (Zank, Bagstad, Voigt, & Villa, 2016); its philosophical home remains firmly in sustainability science (Matson, Clark, & Andersson, 2016; Daly H. E., 1997; Borek, 2013). This is not an exclusionary claim to the concept. Rather, the use-inspired and pragmatic approach through sustainability science facilitates this interdisciplinary approach that can leverage across various scientific disciplines towards a more comprehensive understanding of complex challenges (Clark W. C., 2007). This can lead to the discovery of non-intuitive conclusions like the ones presented in this chapter.

Chapter 4

4. STUDY C - THE URBAN SCALE: SOCIAL ACCEPTANCE AND APPETITE FOR SOLAR IN HONG KONG

1. Abstract

The Hong Kong Special Administrative Region (SAR) of China has extreme and unique challenges in transitioning its energy generation into one that substantially increases the renewables in its portfolio and eliminates all greenhouse gas emissions associated with energy consumption. The city is famous for its extreme population density and verticality, almost all of its open land areas are permanently protected from development, and it has exhibited reluctance to importing more energy from the mainland China grid.

This investigation into the potential of solar energy in Hong Kong uses a qualitative and inductive approach. The goal here is hypothesis building, not testing. A series of semi-structured interviews was conducted with key stakeholder groups in Hong Kong. The results of this stakeholder engagement indicate that Hong Kong would require an engaged, sincere, and difficult public dialog to foster any serious movement towards a significant amount of solar energy growth in Hong Kong.

2. Introduction and Background

HONG KONG AS AN EXTREME CASE STUDY

This dissertation chapter serves as a bookend piece to the larger construct of the central thesis model for solar energy adoption. To illustrate the overarching concepts at the lowest, urban level of analysis, any chosen urban area will be susceptible to criticism. The specific, and obvious, concern here is generalizability of results. With any given urban area in the world, valid arguments can be made that the chosen city is inescapably and inexhaustibly unique and thus not suitable for generalizability of greater trends or insights.

To avoid this philosophical trap, here the opposite approach is taken. Hong Kong was chosen not because it represents the mean or median, but because it represents *an extreme case*. Hong Kong has abundant solar natural capital resource potential, ample levels of private and public wealth, and ready access to solar energy technology markets, and yet it currently has almost no installed solar energy capacity. The selection of an extreme case to tease out a larger operational construct and potential adaptation strategy is informed by principles of universal design (Preiser & Smith, 2011) and design science (Fuller, 1957; Simon, 1969; Van Aken, 2005). As a contemporary illustration, in the early 2000s the manufacturing company OXO sought to create a “universal” potato peeler. Their ensuing design featured a comfortable grip handle that was useable by both the able-bodied with a strong grip, and an arthritic elderly woman who struggled painfully when trying to use a typical potato peeler. By covering these two extreme ends of the spectrum they were able to satisfy nearly all potential customers through an array of abilities. (Denny & Sundedrland, 2014)

Similarly, with the entire global energy system on one end of the spectrum, and an extreme urban area on the other, the intent here is to cover the array between by proxy. Hong Kong exhibits extreme characteristics in all three of the primary factors of consideration –policy, geospatial, and market factors– to make it uniquely suited for this discourse.

THE GEOGRAPHIC CONSTRAINTS OF HONG KONG

Hong Kong is one of most densely populated places on earth with an overall population of 7.2 million and mean average density[22] of 6,690 people per square kilometer (2,582/sq mile). It's most dense district is Kwun Tong, which holds an astonishing 57,250 people per square kilometer (22,096/sq mile) (GovHK, 2014). Hong Kong is comprised of 1,108 square kilometers of land. However, nearly three quarters of Hong Kong's 1,108 square kilometers is legally designated as "countryside" and, as such, is protected from development under the "Country Parks Ordinance" (GovHK, 2016). Given these geographic and administrative constraints, Hong Kong has developed into what is widely touted as the "world's most vertical city" with more skyscraper buildings and more residents living or working above the 14th floor than any other city in the world (Curry & Hanstedt, 2014).

CULTURE DYNAMICS IN HONG KONG

Like many of the cities and nations in East and Southeast Asia, Hong Kong still exhibits a considerable Confucian cultural influence that stresses a deference of agency in the pursuit of societal accord (Chen M. , 2004). This seems to be further

[22] This is the average density if all Hong Kong residence were able to spread out over all land areas. Because nearly 70% of all land in Hong Kong is protected from all commercial development under the "Country Parks" ordinance, the actual living density is at least 3 times higher.

extended by an emphasis on central, formal control, deemphasized individualism, and group-centered decision making (Harrison, KcKinnon, Panchapakesan, & Leung, 1994).

Hoefstede's Cultural Dimension Theory may offer additional clues to help explain some of the general disposition found amongst residents of Hong Kong. Hong Kong is noted as scoring low on individualism, but skewed towards masculinity on the masculine/feminine scale. This results in a group dynamic that is driving by competition and not necessarily as preoccupied with the caring for others and quality of life. Paradoxically, Hong Kong residents are listed as long-term view oriented, yet exhibit low uncertainty avoidance. This would indicate a predilection to long-term planning, but a willingness to embrace ambiguity and risk. And most relevant to this discourse in terms of the resident's attitudes around a transition to renewable energy, Hong Kong scores low on indulgence which tends to correlate with a tendency towards cynicism and pessimism. (Hofstede, 1983; Hofstede, 1993; Hofstede, 2001; Hofstede, 2017)

ENERGY POLICY IN HONG KONG

As with many forms of "common law" in the world, the *modis operandi* of the judicial system in Hong Kong is *stare decisis*, or deference to a previous legal decision on the same topic (Douglas, 1949). Whether in the form of "horizontal *stare decisis*", a court citing its own previous ruling, or "vertical *stare decisis*", deference to a higher court ruling on the same topic, this results in law typically moving towards an increasingly steady state (Wesley-Smith, 1994). This is seemingly also reflected within policy frameworks as the lament for "policy inertia" in a wide array of areas such as industrial, environmental, and educational realms seems to be a global phenomenon. And Hong Kong is certainly no exception (Grant

& Wilks, 1983; Unruh, 2000; Taplin, 2013; Morris & Scott, 2010).

ENERGY IN HONG KONG

The majority (55%) of end-use energy in Hong Kong is electricity. This consumption is required to power a vast, state-of-the-art electric rail system, residential and commercial cooling, and many other services (GovHK, 2016). Hong Kong has been at full electricity access market penetration for many decades, well ahead of many of its Southeast Asian neighbors (The World Bank, 2017). The electricity market is serviced by two independent providers governed by the Government of Hong Kong Special Administrative Region "Scheme of Control Agreement" (SCA). The two corporate signatories to the SCA are the Hong Kong Electric Company, Limited (HKE), and CLP Power Hong Kong Limited (CLP). While both companies are full-service, vertically integrated utilities similar to the long-standing Samuel Insull utility model of the U.S. –handling generation, transmission and distribution, and all retail customer servicing– rather than a "natural monopoly", they enjoy the even stronger entrenchment of the sole-sourced SCA guarantee from the Hong Kong government (McDonald, 1958; Posner, 1969). The service territories are delineated by natural geographic boundaries (see *figure-4.01*: CLP service area in light green and HKE service area in grey) (CLP, 2001).

The SCA allows for itemized straight-line depreciation for all major assets that are built related to electricity generation in Hong Kong[23]. With a few small adjustments put in for performance target measures, the SCA dictates that Hong Kong utility companies can set customer tariffs (the retail price paid by customers) to recover a net return rate (corporate profit) at 9.99% of average annual net fixed

[23] The SCA itemization is highly detailed and includes fixed terms for various types of generation plants, buildings, cables, automotive vehicles, and even personal computers.

assets. Given this incentive structure and the straight-line asset depreciation structure, and provisions in the SCA to potentially mitigate any stranded assets on the part of the utility, building singular, large generation plants is fiduciarily advantageous as it locks in multi-decade profit streams. (GovHK, 2017)

FIGURE-4.01: CLP and HKE Service Areas (CLP, 2001)

A point of pride for both CLP and HKE is their extremely high reliability, making Hong Kong one of the most reliable electricity services in the world (HK-EMSD, 2003). Maintaining "the five nines" as many in the utility industry refer to it – an annual reliability rating of 99.999%– is paramount, with CLP boasting an average of only 1.5 minutes of unscheduled power outage per year, and HKE maintaining 99.999% reliability since 1997 (CLP, 2017; HKE, 2017). For comparison the average annual minutes of unscheduled power outage per year in Germany –the most reliable grid in Europe– is about 15 minutes, and 93 minutes per year on average in the

United States (Fairley, 2014). Under Hong Kong law in the SCA, utility companies are incentivized to maintain at or greater than 99.992% efficiency and they face a financial penalty if their annual average reliability dips below 99.985%.

In terms of electricity generation fuel sources, Hong Kong utilizes 53% coal, 23% nuclear, 22% natural gas, and 2% "other" (see *figure-4.02)* (Hong Kong Environment Bureau, 2014). Despite the ability of renewable energy technologies such as wind and solar to generate electricity with virtually no greenhouse gas (GHG) emissions[24], Hong Kong has not elected to bring its generation mix to even 1% renewable energy (IPCC, 2011). Some countries in Asia have managed to work more renewables into their electricity energy generation mix because larger scale solar and wind arrays are located in less populated areas with the energy transmitted into the more dense urban areas. Given Hong Kong's geographic constraints, a more objective comparison might be the country of Singapore, and it too has less than 1% renewable energy (EMA Singapore, 2016).

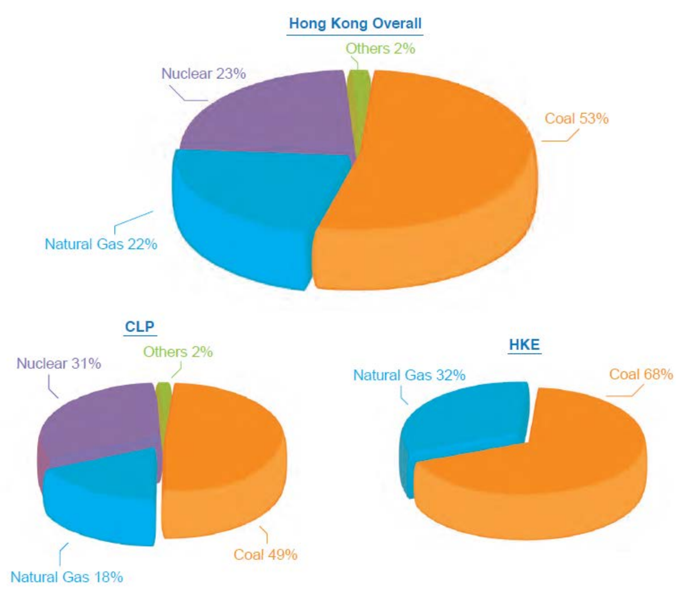


FIGURE-4.02: Hong Kong Fuel Mix (Hong Kong Environment Bureau, 2014)

[24] A small amount of GHG emissions may be generated in the production process of manufacturing the technologies

A PUBLIC CONSULTATION FOR THE ENERGY FUEL MIX OF HONG KONG

In 2014, the Hong Kong Environment Bureau conducted a public consultation concerning the desired future fuel mix for Hong Kong's electricity generation. A 52 page document was made available to all residents and businesses in Hong Kong. It outlined in great detail the electricity market in Hong Kong compared to other markets in Asia, electricity policy defined in the SCA, information on GHG emissions and other environmental concerns related to electricity generation, and provided a detailed description of the existing fuel generation mix. At the end of the document were two options for a desired future fuel mix that respondents could choose, and instructions for how to post, email, or fax a response (see figure-4.03). Option 1 was to purchase 30% of Hong Kong's future electricity needs from the Mainland China southern power grid, increase natural gas generation from 22% to 40%, and reduce coal generation from 55% to 10%. Option 2 was to increase natural gas generation from 22% to 60%, and decrease coal generation from 55% to 20%. Nuclear generation that is imported from Daya Bay Nuclear Power Station in mainland China would drop slightly from 23% to 20% in both scenarios. (Hong Kong Environment Bureau, 2014)

Fuel Mix Options

FUEL MIX		IMPORT		NATURAL GAS	COAL (& RE)
		NUCLEAR (DBNPS)	GRID PURCHASE		
Existing (2012)		23%	-	22%	55%**
OPTION 1*	Importing more electricity through purchase from the Mainland power grid	20%	30%	40%	10%
		Total : 50%			
OPTION 2*	Using more natural gas for local generation	20%	-	60%	20%

* The above fuel mix ratios aim at providing a basis for planning the necessary infrastructure for electricity supply. Flexibility should apply to actual deployment of each fuel type, having regard to the circumstances happening on the ground.

** Inclusive of a small percentage of oil

FIGURE-4.03: Hong Kong Fuel Mix Public Consultation (Hong Kong Environment Bureau, 2014)

After the consultation, the Hong Kong Environmental Bureau published detailed results on the responses. Out of a population of 7.2 million Hong Kong residents, 84,839 individuals responded, as did 1,289 groups or organizations. The vast majority of both individual and organization respondents voted for "Option 2" which would forgo buying power from the Mainland grid and would significantly ramp-up natural gas generation and ramp-down coal. The number one concern cited against Option 1 was an "over dependency on the Mainland". For Option 1, the main reasons cited for favoring it were listed in popular rank order as "reliability", "environmental performance", "safety", and "affordability". No renewable option was made available to the public, nor did either scenario have any specified targets for renewable generation. (Hong Kong Environment Bureau, 2015)

POTENTIAL FOR RENEWABLE ENERGY IN HONG KONG

Numerous scientific analyses have been conducted to assess Hong Kong's potential in terms of wind and solar energy. Shu, Li, and Chan (2015) estimated that outlying island and offshore wind within the SAR's legal boundaries could provide 25.1% of Hong Kong's electricity consumption needs. Wong et al (2015) conducted a thorough geostatistical analysis of all rooftops and open areas in Hong Kong suitable for solar photovoltaics (PV) and determined that if fully utilized, it could provide approximately 12.3% of Hong Kong's electricity needs.

However, neither of the previously mentioned generation percentages can be found in a straight-forward manner in either of those respective investigations on wind and solar potential. When getting to the point on the total capacity for wind energy, Shu, Li, and Chan switch to the passive voice starting the sentence with "it was suggested" and then, despite listing all previous units in GW (gigawatts), they switch to kWh (kilowatt-hours) and list the figure "112.81×10^8 kWh", thus making the only use of scientific notation found in the entire paper. Similarly Wong et al switch between using TJ (Terajoules) when listing energy consumption for Hong Kong, but then switch to TWh (terawatt-hours) when listing potential generation from solar, and break the generation potential out into three categories without ever listing the total amount or what that means in terms of total potential generation as a percentage of Hong Kong's energy mix. These are exemplar cases demonstrating the critical need for the "lay summaries" that Kuehne and Olden called for at the Proceedings in the National Academy of Sciences (2015).

3. Methods and Analysis

METHODS

This discourse represents an in-depth case study that attempts to discern outlooks and attitudes towards solar energy use for Hong Kong. The approach of the study is inductive with an attempt at theory-building rather than testing *a priori* hypotheses. This type of investigation is fraught with potential pitfalls in maintaining neutrality and fairness of representation. Rather than exhaustively rehashing a debate on the merits of ethnocentric and other forms of investigation with major social and cultural components, a pragmatic approach is taken with this investigation employing a constructivist grounded theory methodology. (Strauss & Corbin, 1997; Luker, 2008; Charmaz & Belgrave, 2012)

It is difficult to defend against criticisms that an outsider conducting research cannot truly capture the essence of an issue with such complex social and cultural dimensions. But perhaps a counter argument might come from 11th century poet Su Tungpo (aka Su Shi 苏轼) in his famed verse from *To know Mount Lu's True Face* (庐山真面目), "One cannot know the true face of Mount Lu simply because one is inside it" (1084).

For this research fifteen original interviews were conducted with Hong Kong residents from February to March 2017[25]. The interviews were in-depth, semi-structured engagements that lasted between 27 to 94 minutes. Two thirds of interviewees were native Hong Kong residents, with the rest composed of expatriates who have been working and permanently residing in Hong Kong for many years. All interviewees spoke English at a native or near-native level and all interviews were conducted in English with an interview guide that included the list of interview

[25] IRB approval is printed in Appendix A of this thesis

questions sent to interviewees in advance. All interviews were recorded and analyzed but will not be published. Because of the small size of the Hong Kong energy and sustainability community only basic occupation descriptors are listed (see *table-4.*01) to preserve the anonymity of participants. These data are supplemented with primary open source data.

Interviewee Occupation Type	Percent of Total
Academia	27%
Advocacy Group	7%
Energy Professional	20%
Sustainability Professional (non-energy)	46%

TABLE-4.01: Interviewee Occupation Type

A series of guiding questions for the semi-structured interview included questions on general feelings towards climate change, interviewees' perceptions of renewable energy and specifically solar energy potential for Hong Kong, and how they would rank affordability, reliability, and environmental concerns in terms of Hong Kong's electricity. The concentration of interviewees from the category of sustainability professionals outside of the energy sector was intentional. While energy professionals will likely be deeply entrenched into the complexities and minutiae of electricity generation, it was reasoned that sustainability professionals outside of the energy industry would represent the avant-garde or forefront of the public conversation and level of awareness around renewable energy issues pertinent to Hong Kong. Thus, for example, if this category of professionals seemed largely unaware of latest research and scientific discourse on the potential of solar energy for Hong Kong, then it seems reasonable that the general public would be no further advanced in their concern or level of information for these topics. Much in the spirit of the earlier reference to OXO potato peeler designed for the extremes, the selection of this group was an intentional research design choice.

ANALYSIS

The interviewees all readily acknowledged anthropogenic climate change as both a serious and pressing issue for Hong Kong and for the world. Most interviewees further elaborated on issues about record levels of summer heat and showed concern for both near-term issues like air pollution, and long-term problems such as sea level rise. A few even mentioned fundamental threats such as species extinction caused by climate change.

When asked if they were aware of Hong Kong's current electricity fuel generation mix, 67% of respondents were unaware of the specific ratios. However, most interviewees noted that the fuel mix involved coal, natural gas, and nuclear. One interviewee commented,

> *Definitely coal, gas, and nuclear; mostly coal I think. I think there is some wind too, but I'm not sure how much.*

When asked about the relative importance of reliability, affordability, and environmental concerns in regards to energy, a large majority ranked reliability as the first priority. None ranked it lower than second. One interviewee remarked,

> *Here in Hong Kong our economy is built on our global reputation for secure banking. If our energy was thought to be unreliable, then what would that say about our finance sector? People wouldn't have confidence to put their money here. This is why reliability will always be the number one concern, without it there is no Hong Kong.*

When asked for their rough estimation on what the total potential capacity for solar might be in Hong Kong most responded that they had no idea and did not want to venture a guess. For those that did propose a number, given as a percentage of Hong Kong's total fuel mix with the interviewee answers ranged from "1%" to "30%".

Most critically to this discussion, when asked what they reckon an aspirational 2050 target for a renewable energy contribution to the fuel mix could or should be, 87% of the interviewees failed to give any direct answer[26]. Two interviewees, both energy professionals, responded by referencing and quoting the results of the 2014 fuel mix consultation. Some talked in vague terms about the next 5 to 10 years. And all but one failed to give even a rudimentary approximation of an aspirational vision for what they wanted the fuel mix to be.

CONCEPTIONS OF PLACE AND SPACE

Throughout the course of the interviews a dominant subtext was apparent on the role of perception on place and space. Many interviewees seemed to inherently conceptualize solar energy as being something that is not suitable for dense urban areas. There is a large and ongoing body of literature around the social acceptance of renewable energy technologies and installations. This dialogue often revolves around public perceptions on the visual effects of large installations on landscapes and how much of a role NIMBY ("Not In My BackYard") attitudes might play versus attachments to place. (Thayer & Freeman, 1987; Van der Horst, 2007; Akella, Saini, & Sharma, 2008; Sovacool, 2009; Devine-Wright, 2011) (Pasqualetti M. J., 2011; Carlisle, 2016)

[26] One interview said they believed it would be 100% renewable by 2050

Hong Kong seems an exceptional case in that public perceptions are not driven by whether or not renewable energy technologies should be employed, most believe they should, but residents question their affordability and viability in Hong Kong. The majority of the interviewees expressed various degrees of nebulous doubt around whether solar energy is viable in Hong Kong. As one interviewee explained,

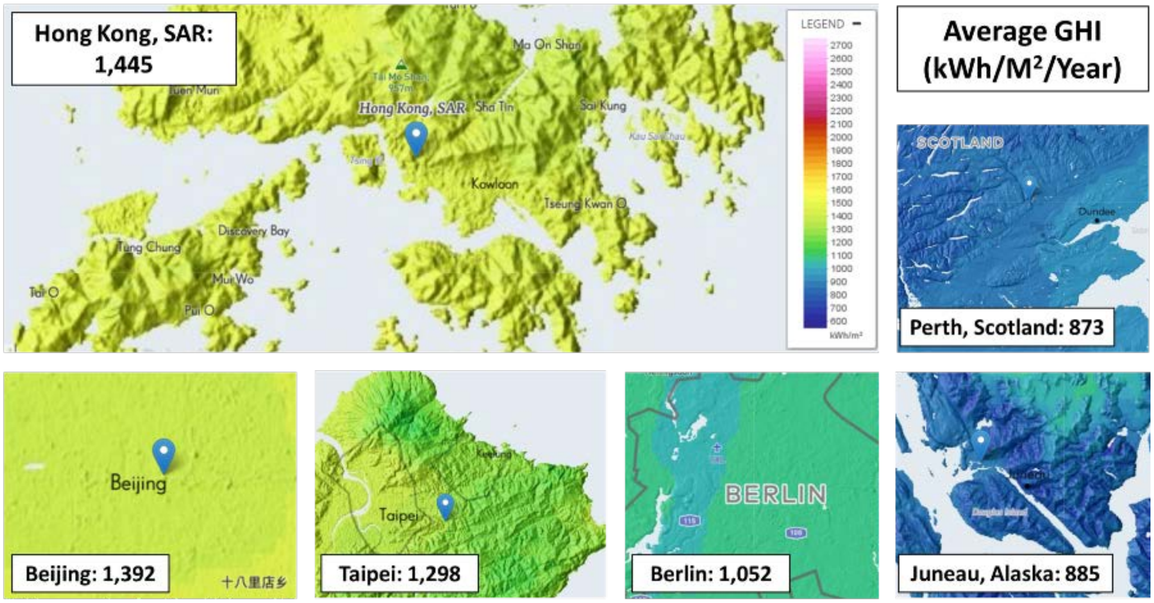
> *You know in Hong Kong there are so many high rise buildings with limited rooftop and it's very cloudy, I don't think it's realistic for solar.*

Among those interviewees that made any mention of "studies" in regards to their estimate for solar energy potential for Hong Kong, a follow up question was asked about their awareness of the government funded studies on this topic by Wong et al, of The Hong Kong Polytechnic University, that calculated a 12.3% figure for solar potential in Hong Kong. This detailed geostatistical analysis was funded under the Hong Kong "Public Policy Research Funding Scheme" which has a stated intent to, "provide advice on policy matters to the Chief Executive (CE)[27], the Chief Secretary for Administration (CS) and the Financial Secretary (FS)." The Wong et al research also has a corresponding user-friendly public web site (Solar Energy HK, 2017), and has been publically referenced and touted at conferences and speaking engagements by advocacy groups such as the World Wildlife Foundation's Hong Kong chapter (Edwards, 2017). Only three interviewees indicated any familiarity with this or similar studies and all expressed some level of doubt about the validity of the estimate. As one interviewee put bluntly, "I think it's an overestimate," but gave no further explanation.

In terms of comparative solar potential *figure-4.04* shows how the average annual Global Horizontal Irradiance (GHI) measured in potential kWh/m2 compares to the cities of Beijing, Taipei, Berlin, Perth (Scotland), and Juneau (Alaska). All of

[27] The "Chief Executive" of Hong Kong is the head of the government of Hong Kong

these comparison cities have active solar PV markets (Waldholz, 2017; BBC, 2016; SCMP, 2014; Kenning, 2016).



Input Data: World Bank Group – Global Solar Atlas, 2017
Mapping: Wes Herche, 2017

FIGURE-4.04: Hong Kong Solar Potential Compared to other Cities

PRICE SENSITIVITY, RELIABILITY, AND SOCIAL VALUE

Price seems to dominate the narrative around energy in Hong Kong. In public forums on the topic of energy and renewable energy in Hong Kong, price tends to play an overly prominent role in the discussion (Loh, Close, Lai, Shannong, & Valentine, 2014; Chen, et al., 2017). Despite regularly topping the lists of "World's most expensive cities" to live in, Hong Kong has surprisingly affordable electricity (Sheng, 2017). With the average Hong Kong household consuming roughly 380 kWh per month, a lone income earner in the household would spend about 1.15% of their annual income to provide electricity for the entire home[28] (GovHK, 2017; The World

[28] Calculation of cost of average electricity consumption ($3,774 HKD) as a percentage of average annual GDP per capita ($328,602 HKD)

Bank, 2017; CLP, 2017; HKE, 2017). By comparison, similar calculations for major U.S. cities show those Americans spending at least three times more of their annual income on electricity bills (Drehobl & Ross, 2016).

As Bozeman and Sarewitz posited on the notion of policy and economic myopia, "*reliance on economic reasoning tends to shift the discourse about science policy away from political questions of 'why?' and 'to what end?' to economic questions of 'how much?',"* (2005, p. 119). Even the Hong Kong Environmental Protection Department, the unit of government explicitly charged with protecting the environment, in the last bullet of its "Vision Statement" it lists "minimising environmental impacts" list out of 5 objectives:

Our vision is of a Hong Kong in which the community enjoys a reliable and safe energy supply at reasonable prices, while improving energy efficiency, promoting energy conservation and minimising the environmental impacts from the production and use of energy. (GovHK, 2017)

Affordability of energy was a critical concern for everyone who was interviewed for this research, but was readily eclipsed by the preoccupation with reliability. This is consistent with work by Holley & Lecavalier that specifically looked at the so-called "energy trilemma" –balancing priorities in affordability, reliability, and environmental concerns– among stakeholders in Hong Kong's power sector (2017). Though unprompted in this regard, some of the interviewees gave thoughtful explanations to explain their ranking of reliability as the prime concern. One of the energy professionals interviewed cited some striking safety concerns,

> *We have sixty-two thousands lifts in Hong Kong. Sixty-two thousand. And every day we have more than 5 million passengers using our electrical*

transport system, mostly under the ground. So reliability is extremely important from our point of view.

Interestingly, another interviewee cited Hong Kong's preoccupation with reliability as a massive obstruction to Hong Kong making progress on environmental concerns. The interviewee noted that many other major cities in the world also have safety risks related to electricity for elevators and underground transport but are able to manage with energy reliability that is not up to Hong Kong's exceedingly high standards. This interviewee further noted that there are ways to differentiate reliability of critical infrastructure without routinely over-generating electricity in order to ensure the achievement of reliability targets. All but one interviewee readily conflated intermittency with unreliability. Thus solar energy was seen as inherently unreliable. In fact, seasonal and diurnal patterns of solar capacity are quite well known for all points on earth, and performance degradation from inhibiting weather can be predicted with increasing precision (Wettengel, 2016). But strong biases seem to be fundamentally rooted, even among this set of interviewees who are largely progressive on sustainability issues. Further, it escaped all that coal and gas experience largely unpredictable outages, and incur substantial commodity price volatility. The outages are buttressed by routine overproduction, and the price volatility is largely shielded from the consumer in that their tariffs stay relatively consistent.

Like with the more recent example of the Wong et al research publications, this select set of sustainability focused Hong Kong residents seem largely unaware of the large body of research regarding the capabilities of renewable energy sources (Hui, 1997; CDM, 2002; Lu, Yang, & Burnett, 2002; Lee & Mok, 2010; Ma, Yang, Lu, & Peng, 2014). This raises concerns about the impact of publicly funded scientific research in its ability to influence the public conversation, even within the seemingly welcoming audience of sustainability professionals. If the most rudimentary highlights from these research endeavors are failing to resonate even with the vanguard population for these issues, then there's a "public-value failure" in the marketplace of ideas and scientific research as a public good (Bozeman, Public-Value Failure: When Efficient Markets May Not Do, 2002). Further, it fails to elevate the dialogue beyond academic disputes over calculations and a fixation with economic concerns that are often misconstrued. At a local half-day conference focused on the potential for a renewable energy future in Hong Kong, conference host and speaker Daphne Mah made the astute remark, "We need to move beyond just a technical and financial discussion on renewables and also start talking about it as a social issue." (Mah, Presentation given at "Renewable Energy: How Can it Thrive in Hong Kong" conference, 2017)

4. Discussion and Policy Recommendations

CONSTRUCTING A RENEWABLE ENERGY VISION

Of great concern here is the apparent lack of an engaged public dialogue and an aspirational vision for what Hong Kong residents could strive for in their energy sources as it relates to their environment. As a comparative example, Hong Kong employs a 10,500 person strong workforce to keep the streets clean and collect waste (GovHK, 2017). A detailed "rate of return", cost comparison, or "payback period" calculation down to the fraction of a penny is not the drive behind this effort, the people of Hong Kong have simply decided that as a society they value the public benefit of clean streets. But this framing seems to be largely nonexistent in the public conversation on Hong Kong's energy future. There is the obvious difference that street waste is both visible and immediately disruptive to daily life, while pollutants from energy generation remain largely hidden from view and their effects build slowly over long time periods. But there is a further distinction of societal norms and expectations. A few centuries ago or even a few decades ago in some places, waste disposal was not a "given". Perhaps one day the new norm will be to fully capture all of the pollutants associated with energy generation or to not emit them to being with.

Specific policy recommendations are to create public stakeholder engagement programs that promote two-way dialogue. As an archetype of the preferred approach for this engagement contemporary examples include the ongoing interdisciplinary work led by Daphne Mah, professor of Geography at Hong Kong Baptist University, and the various scenario-based community workshops to engage in debate and deliberation on the value of solar in Hong Kong (Mah, 2017). Further, the temptation to take a "we just need to educate the public" approach must be avoided as it does not engage citizens in the dialogue, nor consider their needs, values, and priorities (Sarewitz, 2004) (Fowler & Allison, 2008). This recommended ongoing public engagement effort should be done as a lead up to a new energy fuel mix public consultation where significant, specific, and quantified amounts of renewable energy options are included in the options.

5. Conclusion

This inquiry seems to indicate that there is little public conversation on the topic of a renewable energy future for Hong Kong. Even among the communities of energy, sustainability, and related professionals this conversation seems blunted. What discourse is taking place appears to largely be framed in the context of increased costs and technical minutiae.

This lack of impetus or vision is reflected in the published papers that detail the proceedings of the Legislative Council of the Hong Kong SAR, commonly referred to as the "LegCo"[29] (Legco.gov.hk, 2016). A clear vision for a sustainable energy future for Hong Kong is similarly lacking. The LegCo instead offers vague platitudes about "renewable energy" without outlining specific targets or a detailed plan of action. Returning to the "energy trilemma" framework, it is telling that the primary factors pertaining to reliability/security and affordability are mandated by law in the SCA. But even notional environmental targets –in terms of limiting emissions or other negative externalities– are absent, let alone binding policies.

There are indeed challenges with doing significant amounts of solar deployment in Hong Kong. But building coal, gas, and nuclear plants are not trivial endeavors either, they are and will continue to be massive undertakings that we as a species have tackled because we first decided it was in our best interest. The construction of these plants was of such great interest that government authorities in most parts of the world chose to heavily incentivize their construction with a guarantee of lucrative rates of return like those offered under the Hong Kong SCA.

If and when the residents of Hong Kong start to better engage in an ongoing public conversation and make a sustainable energy future a priority, this will be the mechanism towards policy that enables market action. For now most of the interviewees for this research assumed that either the LegCo or Mainland China would take some sort of action on this issue without their spurring. Their choice of

[29] Pronounced as [lej-koh]

verbiage and general disposition indicated they lacked any sense of agency to address the challenge even if they agreed and identified with the intended outcomes.

In a point that captures the essence of many of the themes discussed here, one interviewee voiced skepticism for any amount of solar being viable in Hong Kong,

> *That may work in Australia or similar places where you have a lot of open space, but I just don't think it can work here and that's why you don't see a lot of consumers who want that here in Hong Kong.*

This statement is particularly noteworthy because it expresses both doubts about the validity of the technology in Hong Kong's geographic environment, but moreover completely unprompted the interviewee conceptualized this in an entirely economic framing by using the term of "consumers" instead of "resident", "citizen", or even "people".

Geospatial disposition for solar irradiance in Hong Kong presents tractable, but as yet unrealized opportunities. Further, as a part of greater China, Hong Kong enjoys unencumbered trade access to the world's largest producer of PV modules (GovHK, 2016; Munsell, 2015). Yet this ready access to ideal solar PV markets seems to have no bearing on Hong Kong. Interviewees, and other common indicators in Hong Kong, expressed an adequate general desire to achieve more positive sustainability outcomes in terms of energy. But at this urban level of analysis impetus is seemingly squelched by policy factors that reflect a lack of specific commitment to action. At these local minima of actionable governance, policy impetuses become essential to markets adopting the solar energy technologies that are needed to thwart anthropogenic climate change.

Ultimately what led to, and justifies, the qualitative and inductive approach used for this chapter stems from the uniquely “trans scientific” question that is posed here; specifically, no amount of market indicators or scientific data will answer *why* Hong Kong should act on this sustainability challenge (Weinberg, 1972). This chapter illustrates the nontrivial discord between universalist and procedural sustainability when it comes to operationalizing these concepts (Miller, 2013). It becomes clear that this is a question of the moral imperative (Kant, 1785); Hong Kong’s future will not be mechanistically determined by mathematical output devoid of human agency, but rather by the vision, aspirations, and choices of its residents.

Chapter 5

5. SUMMARY

1. Summary and Contributions of the Research and Findings

This three-part thesis examined the policy, geospatial, and market factors across three different geographic scales of consideration. Beyond just the three separate examinations, the overriding effort was to show how the relative importance and interaction of these factors morphs and changes as the level of analysis cascades down.

At the risk of overgeneralization, but in deference to concision, some overall patterns can be observed. At the global level market and geospatial factors, and their specific spatial interaction, seem to be the dominant drivers. This interaction between geographic endowment of solar natural capital and the market will likely be of prime importance given the correlation and opportunity that was demonstrated for solar potential in underdeveloped areas of the world. At the urban level the examination turned to Hong Kong precisely because it represented an extreme challenge. While geospatial constraints or markets seem the likely dominant factors, the policy and public inertia was the underlying critical element. Between these two bookends of geographic scale the national level analysis showed a complex interaction among all three factors.

This thesis makes several contributions to a growing body of research and discourse. It identifies spatially specific solar per capita potential for the entire world, and solar potential for rural and poor areas. It teases out an empirically observed interaction effect between social and physical science variables within a multivariate model that can explain a significant portion of variance in generated solar energy in the United States. And it uncovers and offers some explanation into the human factors in collective social aspirations and civic leadership that can lead to or hinder policy action related to renewable energy adoption. These are just a few small steps in the "ingenuity gap" between the problems our previous innovations created and the ones our most contemporary innovations are trying to solve through the lens of sustainability science (Westley, et al., 2011).

2. Suggested Further Research

Numerous topics touched upon in this research are ripe for further investigation. In the global level analysis in Chapter 2, 28 cells of 1° latitude by 1° longitude, almost all urban centers, were identified as not able to fully support all energy needs using only a reasonable amount of solar PV. One of those urban areas was the city of Hong Kong, and this of course was further investigated. But detailed case studies could be conducted on all 28 identified cells.

At the time of this writing the 30% investment tax credit in the United States, which correlated so strongly with the uptake of solar illustrated in Chapter 3, is scheduled to abate over the next three years. Studying the potential level of impact this has on the solar market will be both intellectually interesting and also extremely useful in evaluating the impact of policy decisions. Much like with the study presented here, the additional factor of ongoing state-level Renewable Portfolios Standards will likely add additional dimension of novelty.

While a qualitative and inductive approach was taken in this research in Chapter 4, there is room for additional research here that considers the geospatial and social viability of renewable energy imports from mainland China. This topic started to arise during the 2014 public consultation on energy fuel mix because the “grid purchase” option could have included some renewable generation from the Southern China Grid. But further analysis on the viability of dedicated renewables and gauging the public of Hong Kong’s interest on so-called “renewable energy credits” from imported energy would be interesting areas to explore.

3. Final Conclusion

Beyond diving into the technological minutiae of solar energy and its potential future place in the global energy regime, it is perhaps equally useful to think about the question of “why solar” on a conceptual and inspirational level. As has been discussed previously in this conversation, ultimately energy decisions are not (just) about the scientific and specific techno-economic aspects of the process of capturing energy in the universe and putting it to use for human endeavors. Rather, energy paradigms are about human and social decisions. Complexity must be embraced, not circumvented, from the onset. Finding ways to sustainably manage and deliver against the demand for all manner of energy-derived goods and services –the hallmark of modern life– is a critical test in harnessing sustainability science as a problem-solving endeavor (Clark W. C., 2007).

And of course the “elephant in the room” sub-context that has loomed in the peripheral shadows here is that our energy choices as a species are having an existential impact on our planet as the main driver of climate change. Other than some aspects of the agricultural and forestry sector more than three quarters of global greenhouse gas emissions can be attributed to human energy use (EPA, 2014).

The catastrophic "doom and gloom" depictions of climate change, and other planetary devastation brought on by GHG emissions from our current fossil-fuel energy regime, is scientifically accurate but not useful in providing a positive path forward. Instead an intentional research design choice is made here to focus on the *technology* of solar energy generation for its potential to build the more sustainable world we are trying to create. This is a more useful framing as it gives us not only a narrative of hope but of agency in our own destiny as a species (McNall & Basile, 2013; Sarewitz, 2011; Sarewitz, 2004).

However, the "negative externalities" of fossil fuel use are nontrivial. A report by the International Monetary Fund estimates that the true costs of fossil fuels, in the various hidden subsidies and negative externalities, are over $5 trillion per year globally and exacerbate the global disparity between wealthy and poor (Coady, Parry, Sears, & Shang, 2015). Solar energy is perhaps one approach that can satisfy the Brundtland Commission (1987) charge of an approach that "meets the needs of the present without compromising the ability of future generations to meet their own needs." Solar is able to do this on a scale that cannot be matched by any other form of energy be it fossil-fuel or renewable.

One thing that often gets overlooked in the typical platitudes about advocating for an "energy mix" and an "all of the above"[30] strategy is that unlike all other forms of energy, solar can in fact provide 100% of the world's energy needs… all while only capturing less than one one-thousandth of the global solar energy

[30] "All of the above" was first advocated by US President Barack Obama in a speech on March 15, 2012 - https://www.whitehouse.gov/blog/2014/05/29/new-report-all-above-energy-strategy-path-sustainable-economic-growth

potential. As has been shown in this discourse, solar is the only energy source currently known to humanity that can readily satisfy all of our energy needs.

But as of yet, a global transition to solar energy, which could potentially solve one of the largest existential crises to ever face humanity, remains elusive. The work presented hear intends to not only be descriptive of solar energy growth factors, and their deep connection to core sustainability principles, but to also lend valuable insight into the process-oriented transition to a more sustainable planet (Wittmayer & Schapke, 2014). Understanding the complexity of interaction is crucial for the continued development and iteration of sustainability transition strategies (Wiek, Withycombe, & Redman, 2011).

The most significant contribution presented here is gleaned from the gestalt of examining all three geographic levels and three geographic factors in a holistic construct. From this vantage point, the twisting transformation of the relative factor importance becomes clear as the focus cascades down in scale.   Further, it demonstrates the more universal precept that more myopically focused pieces of research, on a greater list of sub topics related to this stream of exploration, will never “add up” to a more comprehensive understanding of this challenge.

REFERENCES

Aiken, L. S., & West, S. G. (1991). *Multiple regression: Testing and interpreting interactions.* London: Sage.

Akella, A. K., Saini, R. P., & Sharma, M. P. (2008). Social, economical and environmental impacts of renewable energy systems. *Renewable Energy*.

Alberth, S. (2008). Forecasting technology costs via the experience curve — Myth or magic? *Technological Forecasting and Social Change*, 952–983.

Allenby, B. R., & Sarewitz, D. (2011). *The techno-human condition.* MIT Press.

Baes, C. F., Goeller, H. E., Olson, J. S., & Rotty, R. M. (1977). Carbon Dioxide and Climate: The Uncontrolled Experiment. *American Scientist*, 310-320.

Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of Management*, 99-120.

Barry, P., & Taylor, L. (2015). Age of the Earth. In J. Rink, & J. Thompson, *Encyclopedia of Scientific Dating Methods* (p. Ch 3). Springer.

Bazilian, M., Rogner, H., Howells , M., Hermann , S., Arent, D., Gielen, D., . . . Yumkella, K. K. (2011). Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, 7896–7906.

BBC. (2016, June 7). *Scotland's largest solar farm formally opened*. Retrieved from BBC News: http://www.bbc.com/news/uk-scotland-tayside-central-36468301

Bodanksy, D. (2016). The legal character of the Paris agreement. *Review of European, Comparative and International Environmental* , 142-150.

Borek, S. V. (2013). Natural Capital: Illuminating the True Value of Nature's Services through Community-Engaged, Site-Specific Creative Production and Exhibition. *Sustainability: The Journal of Record*, 282-288.

Bozeman, B. (2002). Public-Value Failure: When Efficient Markets May Not Do. *Public Administration Review*, 145-161.

Bozeman, B., & Sarewitz, D. (2005). Public values and public failure in US science policy. *Science and Public Policy*, 119-136.

Brandt Commission. (1980). *North-South: A programme for survival. The Report of the Independent Commission on International Development Issues under the Chairmanship of Willy Brandt.* London: Overseas Development Institute.

Brennan, T. J., Palmer, K. L., Kopp, R. J., Krupnick, A. J., Stagliano, V., & Burtraw, D. (2014). *A Shock to the System: Restructuring America's Electricity Industry.* Routledge.

Bridge, G., Bouzarovski, S., Bradshaw, M., & Eyre, N. (2013). Geographies of energy transition: Space, place and the low-carbon economy. *Energy Policy*, 331–340.

Brown, M., Protano, G., & Ulgiatib, S. (2011). Assessing geobiosphere work of generating global reserves of coal, crude oil, and natural gas. *Ecological Modeling*, 879–887.

Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., Fadika, L., & Singh, M. (1987). *Our Common Future ("Brundtland Report"): United Nations World Commission on Environment and Development .* Oxford University Press.

Budnitz, M. (2016). *Mobile Payments: Regulatory gaps, ambiguities, and overlap.* Pew Charitable Trust.

Burke, A. (2012, December 5). *Kurzweil at Techonomy: Artificial Intelligence Is Empowering All of Humanity*. Retrieved from Forbes: http://www.forbes.com/sites/techonomy/2012/12/05/kurzweil-at-techonomy-artificial-intelligence-is-empowering-all-of-humanity/#61baa80699d4

BusinessGreen. (2016, February). *Bill Gates: World will deliver 'clean energy breakthrough' within 15 years*. Retrieved from BusinessGreen: http://www.businessgreen.com/bg/news/2448179/bill-gates-world-will-deliver-clean-energy-breakthrough-within-15-years

Calvert, K. (2015). From ‘energy geography’ to ‘energy geographies’ Perspectives on a fertile academic borderland. *Progress in Human Geography*.

Carlisle, J. (2016). Utility-scale solar and public attitudes toward siting: A critical examination of proximity. *Land Use Policy*.

CDM. (2002). *Study on the Potential Applications of Renewable Energy in Hong Kong.* Hong Kong: The Government of the Hong Kong Special - Electrical & Mechanical Services Department.

Charmaz, K., & Belgrave, L. L. (2012). Qualitative Interviewing and Grounded Theory Analysis. In J. F. Gubrium, *The SAGE Handbook of Interview Research: The Complexity of the Craft* (pp. 347-352). SAGE Publications.

Chemnick, J. (2016, November 10). *Could Trump Simply Withdraw U.S. from Paris Climate Agreement?* Retrieved from Scientific American: https://www.scientificamerican.com/article/could-trump-simply-withdraw-u-s-from-paris-climate-agreement/

Chen, K., Edwards, G., Law, J., Loh, C., Mah, D., & Wu, W. Y. (2017, February 24). Renewable Energy: How Can it Thrive in Hong Kong? (R. So, Interviewer)

Chen, M. (2004). *Asian Management Systems: Chinese, Japanese and Korean Styles of Business.* Singapore: Thomson Learning.

Chontanawat, J., Hunt, L. C., & Pierse, R. (2006). *Causality between energy consumption and GDP: evidence from 30 OECD and 78 non-OECD countries.* Surrey Energy Economics Centre (SEEC), School of Economics, University of Surrey.

Chow, J., Kopp, R., & Portney, P. (2003). Energy Resources and Global Development. *Science*.

CIA. (2017, March 2). *CIA World FActbook*. Retrieved from U.S. Central Intelligence Agency: https://www.cia.gov/library/publications/resources/the-world-factbook/geos/xx.html

Clark, C. W. (1991). Economic biases against sustainable development. *Ecological economics: the science and management of sustainability*, 319-330.

Clark, W. C. (2007). Sustainability science: a room of its own. *Proceedings of the National Academy of Sciences* , 1737.

CLP. (2001). *CLP Holdings Annual Report 2001: Management's Discussion and Analysis - Financial Review.* Hong Kong: CLP Holdings.

CLP. (2017, March 4). *CLP: Supply Reliability & Power Quality*. Retrieved from CLP Power Hong Kong Limited: https://www.clp.com.hk/en/about-clp/power-transmission-and-distribution/supply-reliability-and-power-quality

CLP. (2017, March 5). *Tariff*. Retrieved from CLP: Energy for Life: https://www.clp.com.hk/en/customer-service/tariff

Coady, D., Parry, I., Sears, L., & Shang, B. (2015). *How Large Are Global Energy Subsidies?* International Monetary Fund.

Comello, S., & Reichelstein, S. (2016). The U.S. investment tax credit for solar energy: Alternatives to the anticipated 2017 step-down. *Renewable and Sustainable Energy Reviews*, 591–602.

Conti, J. J., Holtberg, P. D., Diefenderfer, J. R., Napolitano, S. A., Schaal, A. M., Turnure, J., & Westfall, L. D. (2014). Annual Energy Outlook 2014 with projections to 2040. *Annual Energy Outlook*.

Costello, K. W., & Hemphill, R. C. (2014). Electric Utilities' 'Death Spiral': Hyperbole or Reality? *The Electricity Journal*, 7-26.

Costello, M., & Jamison, S. (2015, October 4). *Is the utility death spiral inevitable for energy companies?* Retrieved from Utility Week: http://utilityweek.co.uk/news/is-the-utility-death-spiral-inevitable-for-energy-companies/1119642#.WLpXe_mGNEY

Croft, T. A. (1978). Nighttime images of the earth from space. *Scientific American*, 86-98.

Curry, J., & Hanstedt, P. (2014). *Reading Hong Kong, Reading Ourselves.* Hong Kong: City University of Hong Kong Press.

Daly, H. E. (1997). *Beyond Growth: The Economics of Sustainable Development.* Beacon Press.

Daly, H., & Farley, J. (2004). The Fundamental Vision. In H. Daly, & J. Farley, *Ecological Economics - Principles and Applications* (pp. 22-29). Washington, DC: Island Press.

Dawson, J. F. (2013). Moderation in management research: What, why, when and how. *Journal of Business and Psychology*, 1-19.

del Ríoa, P., & Burguillob, M. (2007). Assessing the impact of renewable energy deployment on local sustainability: Towards a theoretical framework. *Renewable and Sustainable Energy Reviews*, 1325–1344.

Delmas, M., Russo, M., & Montes-Sancho, M. (2007). Deregulation and environmental differentiation in the electric utility industry. *Strategic Management Journal*, 189-209.

Denholm, P., O'Connell, M., Brinkman, G., & Jorgenson, J. (2015). *Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart.* National Renewable Energy Laboratory. Retrieved from http://www.nrel.gov/docs/fy16osti/65023.pdf

Denny, R., & Sundedrland, P. (2014). *Handbook of Anthropology in Business.* New York: Taylor & Francis.

Descartes, R. (1637). *Discours de la méthode pour bien conduire sa raison, et chercher la vérité dans les sciences.* Leiden.

Devine-Wright, P. (2011). Public engagement with large-scale renewable energy technologies: Breaking the cycle of NIMBYism. *Wiley Interdisciplinary Reviews: Climate Change*, 19-26.

Devine-Wright, P. (2011). *Renewable Energy and the Public: From NIMBY to Participation.* New York: Earthscan.

Dipaola, A. (2016, Septembere 19). *Cheapest Solar on Record Offered as Abu Dhabi Expands Renewables*. Retrieved from Bloomberg: https://www.bloomberg.com/news/articles/2016-09-19/cheapest-solar-on-record-said-to-be-offered-for-abu-dhabi

DOE. (2005). Report on the Basic Energy Sciences Workshop on Solar Energy Utilization . *Basic Research Needs for Solar Energy Utilization* (p. 3). Bethesda, Maryland: U.S. Department of Energy, Office of Science.

DOE. (2008). *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply.* US Department of Energy.

Domonoske, C. (2015, December 12). *2 Degrees, $100 Billion: The World Climate Agreement, By The Numbers*. Retrieved from NPR: http://www.npr.org/sections/thetwo-way/2015/12/12/459502597/2-degrees-100-billion-the-world-climate-agreement-by-the-numbers

Douglas, W. (1949). Stare decisis. *Columbia Law Review*, 735-758.

Drehobl, A., & Ross, L. (2016, April 20). *Lifting the High Energy Burden in America's Largest Cities: How Energy Efficiency Can Improve Low-Income and Underserved Communities*. Retrieved from American Council for an Energy Efficient Economy: http://aceee.org/research-report/u1602

Dungpo, S. (1084). *To know Mount Lu's true face (庐山真面目).* Jiujiang Shi.

Durkay, J. D. (2016, December 28). *STATE RENEWABLE PORTFOLIO STANDARDS AND GOALS*. Retrieved from National Conference of State Legislatures: http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx

Edwards, G. (2017, February 24). Presentation given at "Renewable Energy: How Can it Thrive in Hong Kong" conference.

EIA. (2007, August). *Energy and Economic Impacts of Implementing Both a 25-Percent Renewable Portfolio Standard and a 25-Percent Renewable Fuel Standard by 2025.* Retrieved from Energy Information Administration: http://www.eia.gov/analysis/requests/2007/eeim/pdf/sroiaf(2007)05.pdf

EIA. (2016, November 21). *Electric Power Annual*. Retrieved from Eneregy Infomation Administration: https://www.eia.gov/electricity/annual/

EIA. (2016). *International Energy Outlook 2016.* US Energy Information Administration.

EIA. (2017, March 01). *Frequently Asked Questions: How much does a person use in a year?* Retrieved from U.S. Energy Information Administration: https://www.eia.gov/tools/faqs/faq.cfm?id=85&t=1

Einstein, A. (1905). A Heuristic Viewpoint Concerning the Production and Transformation of Light. *Annalen der Physik* .

Elkington, J., & Trisoglio, A. (1996). Developing realistic scenarios for the environment: Lessons from Brent Spar. *Long Range Planning*, 762-769.

Elvidge, C. D., Baugh, K. E., Kihn, E. A., Kroehl, H. W., Davis, E. R., & Davis, C. W. (1997). Relation between satellite observed visible-near infrared emissions, population, economic activity and electric power consumption. . *International Journal of Remote Sensing*, 1373-1379.

EMA Singapore. (2016). *Singapore Energy Statistics 2016.* Singapore: The Energy Market Authority of Singapore.

Energy Matters. (2017, February 28). *(Another) World's Largest Lithium Ion Battery Installation*. Retrieved from Energy Matters: http://www.energymatters.com.au/renewable-news/lithium-battery-project-em5927/

EPA. (2014). *Global Greenhouse Gas Emissions Data*. Retrieved from US Environmental Protection Agency: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

Euractiv. (2015, October 12). *'Sanctions' and 'punishment' barred from COP21 vocabulary*. Retrieved from EURACTIV.com with Reuters: https://www.euractiv.com/section/climate-environment/news/sanctions-and-punishment-barred-from-cop21-vocabulary/

Fairley, P. (2014, August 28). *Germany's Grid: Renewables-Rich and Rock-Solid*. Retrieved from IEEE Spectrum: http://spectrum.ieee.org/energywise/energy/the-smarter-grid/germanys-superstable-solarsoaked-grid?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+IeeeSpectrum+%28IEEE+Spectrum%29&utm_conten

Farmer, D., & Lafond, F. (2016). How predictable is technological progress? *Research Policy*, 647–665.

Fischer, C. (2010). Renewable portfolio standards: when do they lower energy prices? *Energy Journal*.

Fischer, C., & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. . *Journal of Environmental Economics and Management*, 142-162.

Florini, A., & Sovacool, B. K. (2009). Who governs energy? The challenges facing global energy governance. *Energy Policy*, 5239–5248.

Foran, B., Lenzen, M., Dey, C., & Bilek, M. (2005). Integrating sustainable chain management with triple bottom line accounting. *Ecological economics*, 143-157.

Forbes. (2015, November 9). *The World's Most Influential Business Thinkers 2015*. Retrieved from Forbes: http://www.forbes.com/sites/susanadams/2015/11/09/the-worlds-most-influential-business-thinkers-2015/#2acf48c16a77

Fowler, G., & Allison, K. (2008). Technology and Citizenry: A Model for Public Consultation. *Jouornal of Evolution & Technology*, 1-14.

Frenette, G., & Forthoffer, D. (2009). Economic & commercial viability of hydrogen fuel cell vehicles from an automotive manufacturer perspective. *International Journal of Hydrogen Energy*, 3578–3588.

Fthenakis, V., Mason, J. E., & Zweibel, K. (2009). The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US. *Energy Policy*, 387-399.

Fuller, B. (1938). *Nine Chains to the Moon, An Adventure Story of Thought.* Philadelphia: Lippincott.

Fuller, B. (1940, February). World Energy: A Map by R. Buckminster Fuller. *Fortune*, pp. 50-63.

Fuller, B. (1957). A comprehensive anticipatory design science. *Journal - Royal Architectural Institute of Canada*, 357.

Gagnon, P., Margolis, R., Melius, J., Phillips, C., & Elmore, R. (2016). *Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment.* National Renewable Energy Laboratory.

Gallup. (2013, March 10). *Americans Want More Emphasis on Solar, Wind, Natural Gas [Tables]*. Retrieved from Gallup: http://www.gallup.com/poll/161519/americans-emphasis-solar-wind-natural-gas.aspx

Gallup. (2016, March 24). *Gallup Politics*. Retrieved from Gallup: http://www.gallup.com/poll/190268/prioritize-alternative-energy-oil-gas.aspx

Gallup, J. L., Sachs, J. D., & Mellinger, A. D. (1999). Geography and economic development. *International regional science review*, 179-232.

Gibson, B., Hassman, S., Tansey, J., & Whitelaw, G. (2013). The Basic Sustainability Assessment Decision Criteria. In B. Gibson, S. Hassman, & J. Tansey, *Sustainability assessment: criteria and processes* (pp. 235-236). Routledge.

GovHK. (2014). *Hong Kong: The Facts: Population.* Hong Kong: Information Services Department, Hong Kong Special Administrative Region Government.

GovHK. (2016, December 26). *HONG KONG : THE FACTS - Country Parks and Conservation*. Retrieved from GovHK: http://www.afcd.gov.hk/english/country/cou_lea/the_facts.html

GovHK. (2016). *Hong Kong Energy End-Use Data 2016.* Hong Kong: The Goverenment of Hong Kong Special Administrative Region - Electrical & Mechanical Services Department.

GovHK. (2016). *Hong Kong: The Facts: Country Parks and Conservation.* Hong Kong: Agriculture, Fisheries & Conservation Department, The Government of the Hong Kong Special Administrative Region.

GovHK. (2016, December 30). *Mainland and Hong Kong Closer Economic Partnership Arrangement (CEPA)*. Retrieved from Trade and Industry Department: The Government of the Hong Kong Special Administrative Region: https://www.tid.gov.hk/english/cepa/

GovHK. (2017, March 5). *Cleansing Services*. Retrieved from The Government of the Hong Kong Special Administrative Region - Food and Environmental Hygiene Department: http://www.fehd.gov.hk/english/pleasant_environment/cleansing/clean1.php

GovHK. (2017, March 5). *Energy Calculator*. Retrieved from The Government of the Hong Kong Special Administrative Region - Electrical and Mechanical Services Department: http://www.energylabel.emsd.gov.hk/en/cal/cal.php

GovHK. (2017, March 4). *Resources & Publications: Agreement: Energy: Scheme of Control Agreement (SCA) with:*. Retrieved from The Government of Hong Kong Special Administrative Region - Environment Bureau: http://www.enb.gov.hk/en/resources_publications/agreement/

GovHK. (2017, March 5). *Vision & Mission*. Retrieved from The Government of the Hong Kong Special Administrative Region - Environmental Protection Department: http://www.epd.gov.hk/epd/english/about_epd/vis_miss/about_epd.html

Graffy, E., & Kihm, S. (2014). Graffy, E., & Kihm, S. *Energy*.

Grant, W., & Wilks, S. (1983). British Industrial Policy: Structural Change, Policy Inertia. *Journal of Public Policy*, 13-28.

Green, A. (2005). Climate Change, Regulatory Policy and the WTO: How Constraining Are Trade Rules? *Journal of International Economic Law*, 143-189.

Groom, B. (2015). Natural Capital: Valuing Our Planet. *Journal of Economic Literature*, 1043-1045.

Harrison, G., KcKinnon, J., Panchapakesan, S., & Leung, M. (1994). The Influence of Culture on Organizational Design and Planning and COntrol in Australia and the United States Compared with Singapore and Hong Kong. *Journal of International Financial Management and Accounting*, 242-261.

Harvey, F. (2015, December 14). *Paris climate change agreement: the world's greatest diplomatic success*. Retrieved from The Guardian: https://www.theguardian.com/environment/2015/dec/13/paris-climate-deal-cop-diplomacy-developing-united-nations

Henderson, J. V., Storeygard, A., & Weil, D. N. (2012). Measuring economic growth from outer space. *The American Economic Review*, 994-1028.

Herche, W. (2017). Solar energy strategies in the U.S. utility market. *Renewable and Sustainable Energy Reviews*, 1-6.

Herche, W. (2017). Utility Death Spiral. In S. Remington-Doucette, *Sustainable World: Approaches to Analyzing and Resolving Wicked Problems 2nd Edition.* Kendall Hunt Publishing.

Hill, C. W., & Rothaermel, F. T. (2003). The performance of incumbent firms in the face of radical technological innovation. *Academy of Management Review*, 257-274.

HKE. (2017, March 4). *HKE: Supply Reliability*. Retrieved from Hong Kong Electric Investments: https://www.hkelectric.com/en/our-operations/supply-reliability

HKE. (2017, March 5). *Home > Customer Services > Billing, Payment & Electricity Tariffs > Residential Tariff*. Retrieved from Hong Kong Electric: https://www.hkelectric.com/en/customer-services/billing-payment-electricity-tariffs/residential-tariff

HK-EMSD. (2003). *Protecting Public Safety: Monitoring a Safe and Reliable Supply of Electricity.* Hong Kong: The Government of the Hong Kong SPecial Administrative Region - Electrical and Mehanical Services Department.

Hofstede, G. (1983). National Cultures in Four Dimensions: A Research-Based Theory of Cultural Differences among Nations. *International Studies of Management & Organization*, 46-74.

Hofstede, G. (1993). Cultural constraints in management theories. *Academy of Management Executive*, 81-94.

Hofstede, G. (2001). *Culture's consequences: Comparing values, behaviors, institutions, and organizations across nations, second edition.* Sage Publications.

Hofstede, G. (2017, March 5). *What about Hong Kong?* Retrieved from Geert Hofstede: https://geert-hofstede.com/hong-kong.html

Holland, J. (2002). Complex adaptive systems and spontaneous emergence. In J. Holland, *Complexity and industrial clusters* (pp. 25-34). Physica-Verlag HD.

Holley, C., & Lecavalier, E. (2017). Energy governance, energy security and environmental sustainability: A case study from Hong Kong. *Energy Poilcy*, 379-389.

Hong Kong Environment Bureau. (2014). *Future Fuel Mix for Electricity Generation: Consultation Document.* Hong Kong: Hong Kong Environment Bureau.

Hong Kong Environment Bureau. (2015). *Report on the Public Consultation on Future Fuel Mix for Electricity Generation in Hong Kong.* Hong Kong: The

Government of the Hong Kong Special Administrative Region - Environment Bureau.

Höök, M., & Tang, X. (2013). Depletion of fossil fuels and anthropogenic climate change - A review. *Energy Policy*, 797-809.

Hubbard, G. (2009). Measuring organizational performance: beyond the triple bottom line. *Business Strategy and the Environment*, 177-191.

Hui, S. C. (1997). rom Renewable Energy to Sustainability: The Challenge. *Proceedings of the POLMET '97 Conference* (pp. 1-8). Hong Kong: Hong Kong Institution of Engineers.

IEA. (2015). *World Energy Outlook 2015– Electricity Access Database.* Interrnational Energy Agency.

IPCC. (2011). *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.* Abu Dhabi: Intergovernmental Panel on Climate Change.

Jackson, J. (2000). The Role and Effectiveness of the WTO Dispute Settlement Mechanism. *Brookings Trade Forum*, 179-236.

Jacobson, M. Z., & Delucchi, M. A. (2010). Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of Infrastructure, and materials. *Energy Policy*.

Jefferson, M. (2015). There's nothing much new under the Sun: The challenges of exploiting. *Energy Policy*, 804-811.

Jefferson, M. (2015). There's nothing much new under the Sun: The challenges of exploiting and using energy and other resources through history. *Energy Policy*.

Kahn, G. (2003). The Fate of the Kyoto Protocol under the Bush Administration. *Berkeley Journal of International Law*, 548-571.

Kant, I. (1785). *The Categorical Imperative.*

Kazmerski, L. (2005). Solar photovoltaics R&D at the tipping point: A 2005 technology overview. *Journal of Electron Spectroscopy and Related Phenomena*, 105-135.

Keisuke, I. (2004). Is WTO Dispute Settlement Effective? *Global Governance: A Review of Multilateralism and International Organizations*, 207-225.

Kenning, T. (2016, November 2). *20GW by 2025: Behind Taiwan's big solar numbers*. Retrieved from PV Tech: http://www.pv-tech.org/features/20gw-by-2025-behind-taiwans-big-solar-numbers

Kuehne, L. M., & Olden, J. D. (2015). Opinion: Lay summaries needed to enhance science communication. *Proceedings of the National Academies of Sciences of the United States of America*.

Kuhn, T. (1962). *The Structure of Scientific Revolutions.* Chicago: University of Chicago Press.

Kurzweil, R. (1999). *The Age of Spiritual Machines.* Viking Press.

Lacey, S. (2014, March 4). *This Is What the Utility Death Spiral Looks Like*. Retrieved from Greentech Media: https://www.greentechmedia.com/articles/read/this-is-what-the-utility-death-spiral-looks-like

Lane, J. E. (2016). Are The Cop21 Objectives Implementable? *Business and Management Horizons*, 86-120.

Lazard. (2016). *Lazard's Levelized Cost of Energy Analysis - Version 10.0.* Lazard.

Lee, B., & Mok, H. (2010). Potential of wind and solar energy in Hong Kong. *Symposium on E-Management - Challenges and Opportunities* (pp. 1-12). Hong Kong: Hong Kong Observatory.

Legco.gov.hk. (2016). *House Committee Papers*. Retrieved from Legislative Council of the Hong Kong Special Administrative Region of The People's Republic of China: http://www.legco.gov.hk/yr15-16/english/hc/papers/hc_ppr.htm#toptbl

Loh, C., Close, J., Lai, A., Shannong, C., & Valentine, S. (2014, March 20). Future of Energy Policy in Hong Kong. (H. Chiverton, & E. Wong, Interviewers)

Lu, L., Yang, H., & Burnett, J. (2002). Investigation on wind power potential on Hong Kong islands—an analysis of wind power and wind turbine characteristics. *Renewable Energy*, 1-12.

Luker, K. (2008). *Salsa dancing into the social sciences: Research in an age of info-glut.* Harvard University Press.

Lund, P. D. (2011). Boosting new renewable technologies towards grid parity – Economic and policy aspects. *Renewable Energy*, 2776–2784.

Lyon, T. P., & Yin, H. (2010). Why Do States Adopt Renewable Portfolio Standards?: An empirical investigation. *Energy Journal*, 133-157.

Ma, T., Yang, H., Lu, L., & Peng, J. (2014). Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong. *Renewable Energy*, 7-15.

Mah, D. (2017, February 24). Presentation given at "Renewable Energy: How Can it Thrive in Hong Kong" conference.

Mah, D. (2017, February 24). Renewable Energy: How can it thrive in Hong Kong?

Marchetti, C., & Nakicenovic, N. (1979). *The Dynamics of Energy Systems and the Logistic Substitution Model.* Laxenburg: International Institute for Applied Systems Analysis.

Matson, P., Clark, W., & Andersson, K. (2016). *Pursuing sustainability: A guide to the science and practice.* Princeton University Press.

McDonald, F. (1958). Samuel Insull and the Movement for State Utility Regulatory . *Business History Review*, 241-254.

McNall, S. G., & Basile, G. (2013). How to create a new narrative for sustainability that will work: And why it matters (part 2). *Sustainability: The Journal of Record*.

Mekhilef, S., Saidur, R., & Safari, A. (2011). A review on solar energy use in industries. *Renewable and Sustainable Energy Reviews*, 1777-1790.

Metayer, M., Breyer, C., & Fell, H.-J. (2015). *New EWG study: International Energy Agency holds back global energy transition.* Berlin: Energy Watch Group. Retrieved from http://energywatchgroup.org/new-ewg-study-international-energy-agency-holds-back-global-energy-transition/

Miles, T. (2016, September 16). *India loses WTO appeal in U.S. solar dispute*. Retrieved from Reuters: http://www.reuters.com/article/us-india-usa-solar-idUSKCN11M1MQ

Miller, T. (2013). Constructing sustainability science: emerging perspectives and research trajectories. *Sustainability Sciences*.

Moore, G. E. (1965). Cramming more components onto integrated circuits. *Electronics Magazine*, 4.

Morris, P., & Scott, I. (2010). Educational reform and policy implementation in Hong Kong. *Journal of Education Policy*, 71-84.

Mumford, L. (1934). *Technics and Civilization.* Chicago: University of Chicago Press.

Mumford, L. (1971). *Technics and Human Development: The Myth of the Machine, Vol. I.* Harvest Books.

Munsell, M. (2015, October 22). *The United States Is a Top 5 Country for New Solar-Module Manufacturing*. Retrieved from Green Tech Media: https://www.greentechmedia.com/articles/read/the-united-states-is-a-top-5-country-for-new-solar-module-manufacturing

Nakicenovic, N. (1998). Global Energy Needs: Past and Present. In N. Nakicenovic, A. Grubler, A. McDonald, A. Grubler, M. Jefferson, N. Makarova, . . . G. Fischer, *Global Energy Perspectives* (pp. 11-20). Cambridge University Press.

NASA. (2016). *Surface meteorology and Solar Energy (SSE) Release 6.0 Methodology - Version 3.2.0.* US National Aeronautics and Space Administration.

National Aeronautics and Space Administration. (2000, October 23). *http://visibleearth.nasa.gov/view.php?id=55167.* Retrieved from Visible Earth : A catalog of NASA images and animations of our home planet: http://visibleearth.nasa.gov/view.php?id=55167

Nelson, R. (1977). *The Moon and the Ghetto: An Essay on Public Policy Analysis.* W. W. Norton & Company.

Noble Media AB. (2017, February 20). *The Nobel Prize in Physics 1921*. Retrieved from NoblePrize.org: http://www.nobelprize.org/nobel_prizes/physics/laureates/1921/

NREL. (2008). *Solar Resources by Class and Country*. Retrieved from National Renewable Energy Laboratory - Open Energy Information (OpenEI): http://en.openei.org/datasets/dataset/solar-resources-by-class-and-country

NREL. (2016, Feb). *Distributed Generation Renewable Energy Estimate of Costs*. Retrieved from National Renewable Energy Laboratory - Energy Analysis : http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html

Obama, B. (2017). The irreversible momentum of clean energy. *Science*.

OECD. (2017, March 4). *Prices and purchasing power parities (PPP)*. Retrieved from OECD Better Policies for Better Lives: http://www.oecd.org/std/prices-ppp/

Ohbayashi, M. (2016, May 25). *Asia Super Grid Workshop organized by Renewable Energy Institute.* Retrieved from Renewable Energy Institute: http://www.renewable-ei.org/en/activities/events_20160525.php

Owen, A. (2006). Renewable energy: Externality costs as market barriers. *Energy Policy*, 632–642.

Pachauri, S. P., van Ruijven, B. J., Nagai, Y., Riahi, K., van Vuuren, D. P., Brew-Hammond, A., & Nakicenovic, N. (2013). Pathways to achieve universal household access to modern energy by 2030. *Environmental Research Letters*, 5.

Pasqualetti, M. J. (2011). Social barriers to renewable energy landscapes. *Geographical Review*.

Pasqualetti, M. J. (2011). The Geography of Energy and the Wealth of the World. *Annals of the Association of American Geographers*, 972-980.

Pasqualetti, M. J., & Brown, M. A. (2014). Ancient discipline, modern concern: geographers in the field of energy and society. *Energy Research & Social Science*.

Pasqualetti, M. J., & Sovacool, B. K. (2012). The importance of scale to energy security. *Journal of Integrative Environmental Sciences*.

Perez, R., Rábago, K. R., Trahan, M., Rawlings, L., Norris, B., Hoff, T., . . . Perez, M. (2016). Achieving very high PV penetration – The need for an effective electricity remuneration framework and a central role for grid operators. *Energy Policy*, 27–35.

Pew. (2015, April 15). *Cell Phone Ownership Surges in Africa*. Retrieved from Pew Research Center: http://www.pewglobal.org/2015/04/15/cell-phones-in-africa-communication-lifeline/africa-phones-7/

Pew. (2015, April 14). *Few Own Smartphones in Africa, But Cell Phones Common*. Retrieved from Pew Research Center: http://www.pewglobal.org/2015/04/15/cell-phones-in-africa-communication-lifeline/africa-phones-5/

Porter, M. (1980). *Competitive Strategy: Techniques for Analyzing Industries and Companies.* New York: Free Press.

Posner, R. (1969). Natural Monopoly and Its Regulation. *Stanford Law Review*, 548-643.

Preiser, W. F., & Smith, K. (2011). *Universal Design Handbook: 2nd Edition.* McGraw-Hill.

Rader, N. A., & Norgaard, R. B. (1996). Efficiency and sustainability in restructured electricity markets: the renewables portfolio standard. *The Electricity Journal*, 37-49.

Ravetz, J. (1971). *Scientific Knowledge and its Social Problems.* Transaction Publishers.

Rittel, H. W., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, 155-169.

RMI. (2015). *THE ECONOMICS OF LOAD DEFECTION: HOW GRID-CONNECTED SOLAR-PLUSBATTERY SYSTEMS WILL COMPETE WITH TRADITIONAL ELECTRIC SERVICE, WHY IT MATTERS, AND POSSIBLE PATHS FORWARD.* Boulder: Rocky Mountain Institute.

Robinson, D., Hockley, N., Cooper, D., Emmett, B., Keith, A., Lebron, I., . . . Whalley, W. (2013). Natural capital and ecosystem services, developing an appropriate soils framework as a basis for valuation. *Soil Biology and Biochemistry*, 1023-1033.

Roosevelt, F. D. (1937). Extemporaneous remarks at Harve, Montana. *Collection FDR-PPF: Papers as President, President's Personal File, 1933 - 1945*.

Rose, A. K. (2004). Do We Really Know That the WTO Increases Trade? *The American Economic REview*, 98-114.

Roser, M. (2016). *Energy Production & Changing Energy Sources*. Retrieved from OurWorldInData.org: https://ourworldindata.org/energy-production-and-changing-energy-sources/

Russo, M. (2003). The Emergence of Sustainable Industries: Building on Natural Capital. *Strategic Management Journal*, 317-331.

Russo, M. V. (2003). The emergence of sustainable industries: building on natural capital. *Strategic Management Journal*.

Sarewitz, D. (2004). How science makes environmental controversies worse. *Environmental Science & Policy*, 385-403.

Sarewitz, D. (2004). How science makes environmental controversies worse. *Environmental Science & Policy*, 385–403.

Sarewitz, D. (2011, September 27). *Two Approaches to Climate Change: Why Technology Unites While Science Divides*. Retrieved from Nextagenda.com: https://www.youtube.com/watch?v=fKxyyAI4H_0

Scheffer, M. (2009). *Critical Transitions in Nature and Society .* Princeton University Press.

Schumacher, E. F. (1973). *Small is beautiful: A study of economics as if people mattered.* RAndom House.

Schumacher, E. F. (1973). *Small Is Beautiful: Economics as if People Mattered.* Blond & Briggs.

SCMP. (2014, July 8). *Beijing to raise rooftop solar power subsidies by up to 55pc*. Retrieved from South China Morning Post: http://www.scmp.com/business/commodities/article/1549220/beijing-raise-rooftop-solar-power-subsidies-55pc

Seba, T. (2014). *Clean Disruption of Energy and Transportation: How Silicon Valley Will Make Oil, Nuclear, Natural Gas, Coal, Electric Utilities and Conventional Cars Obsolete by 2030.*

Seyfang, G., & Smith, A. (2007). Grassroots innovations for sustainable development: Towards a new research and policy agenda. *Environmental Politics*.

Sheng, E. (2017, January 24). *The Five Most Expensive Cities in the World*. Retrieved from Forbes: https://www.forbes.com/sites/ellensheng/2017/01/24/the-five-most-expensive-cities-in-the-world/#536a5bb61648

Shu, Z., Li, Q., & Chan, P. (2015). Statistical analysis of wind characteristics and wind energy potential in Hong Kong. *Energy Conversion and Management*, 644-657.

Shwom, R. (2009). Strengthening sociological perspectives on organizations and the environment. *Organization & Environment*, 271-292.

Siemens. (2014, October 1). *Optimizing Energy Systems: How to Save a Fortune*. Retrieved from Siemens: https://www.siemens.com/innovation/en/home/pictures-of-the-future/energy-and-efficiency/power-transmission-facts-and-forecasts.html

Simon, H. (1969). *The sciences of the artificial.* Cambridge: Cambridge.

Simons, B. (2012, February 10). *Africa's Chance to Leapfrog the West*. Retrieved from Harvard Business Review: https://hbr.org/2012/02/africas-leapfrogging-opportuni

Smil, V. (1994). *Energy in World History.* Boulder: Westview Press.

Smil, V. (2014). The Long Slow Rise of Solar and Wind: The great hope for a quick and sweeping transition to renewable energy is wishful thinking. *Scientific American*, 52-57.

Solangib, K., Islamb, M., Saidura, R., Rahimb, N., & Fayazb, H. (2011). A review on global solar energy policy. *Renewable and Sustainable Energy Reviews*, 2149–2163.

Solar Energy HK. (2017, March 5). *Solar Energy Supply in Cloud-prone Areas of Hong Kong*. Retrieved from Solar Energy Supply in Cloud-prone Areas of Hong Kong: http://www.solarenergyhk.tk/index.html

Solow, R. (1956). A Contribution to the Theory of Economic Growth. *The Quarterly Journal of Economics, Vol. 70, No. 1*, 65-94.

Sovacool, B. (2009). Rejecting renewables: The socio-technical impediments to renewable electricity in the United States. *Energy Policy*.

Starr, C., Searl, M., & Alpert, S. (1992). Energy Sources: A Realistic Outlook. *Science*, 981-987.

Stigler, G. J. (1958). Economies of Scale. *The Journal of Law and Economics*, 54-71.

Stokes, L., & Warshaw, C. (2017). Renewable energy policy design and framing influence public support in the United States. *Nature Energy*, 1-6.

Strauss, A., & Corbin, J. (1997). *Grounded Theory in Practice.* New Delhi: SAGE Publications.

Swanson, R. M. (2006). A vision for crystalline silicon photovoltaics. *Progress in photovoltaics: Research and Applications*, 443-453.

Taplin, R. (2013). Greenhouse: An Overview of Australian Policy and Practice. *Australian Journal of Environmental Management* .

Thayer, R. L., & Freeman, C. M. (1987). Altamont: Public perceptions of a wind energy landscape. *Landscape and Urban Planning*, 379-398.

The Atlantic. (2015, November). *We Need an Energy Miracle: Bill Gates has committed his fortune to moving the world beyond fossil fuels and mitigating climate change.* Retrieved from The Atlantic: http://www.theatlantic.com/magazine/archive/2015/11/we-need-an-energy-miracle/407881/

The Cincinnati Enquirer. (1937, October 4). p. 19.

The Economist. (2012, April 28). *Press 1 for modernity: One business where the poorest continent is miles ahead*. Retrieved from The Economist: http://www.economist.com/node/21553510

The Economist. (2012, November 21). *The World in 2013:Sunny Uplands*. Retrieved from The Economist: http://www.economist.com/news/21566414-alternative-energy-will-no-longer-be-alternative-sunny-uplands

The Economist. (2015, June 6th). *The leapfrog continent*. Retrieved from The Economist: http://www.economist.com/news/middle-east-and-africa/21653618-falling-cost-renewable-energy-may-allow-africa-bypass

The World Bank. (2017, March 5). *Access to electricity (% of population)*. Retrieved from The World Bank : http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?end=2012&locations=HK&start=1990&view=chart

The World Bank. (2017, March 5). *GDP per capita*. Retrieved from The World Bank: http://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=HK&view=chart

The World Bank. (2017, March 2). *World Bank Staff estimates based on United Nations, World Urbanization Prospects.* Retrieved from The World Bank: http://data.worldbank.org/indicator/SP.RUR.TOTL.ZS

Tobler, W. R. (1970). A Computer Movie Simulating Urban Growth in the Detroit Region. *Economic Geography*, 234-240.

UNFCC. (2017, March 2). *The Paris Agreement*. Retrieved from United Nations Framework Convention on Climate Change: http://unfccc.int/paris_agreement/items/9485.php

Unruh, G. (2000). Understanding Carbon Lock-in. *Energy Policy*.

Unruh, G. (2002). Escaping carbon lock-in. *Energy Policy*.

US Department of the Treasury. (2016, September 30). *Recovery Act 1603 Program: Payments for Specified Energy Property in Lieu of Tax Credits*. Retrieved from US Department of the Treasury: https://www.treasury.gov/initiatives/recovery/Pages/1603.aspx

USGS. (2015, January 1). *Lithium: U.S. Geological Survey, Mineral Commodity Summaries, January 2015.* Retrieved from U.S. Geological Survey: https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2015-lithi.pdf

Van Aken, J. E. (2005). Management Research as a Design Science: Articulating the Research Products of Mode 2 Knowledge Production in Management. *British Journal of Management*, 19-36.

Van der Horst, D. (2007). NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies. *Energy Policy*, 2705–2714.

Waldholz, R. (2017, February 23). *Start-up gambles time is right for Alaska solar power*. Retrieved from KTOO Public Media: http://www.ktoo.org/2017/02/23/start-gambles-time-right-alaska-solar-power/

Webber, M. (2013, April 16). Changing the Way Business Thinks About Energy. Retrieved from https://www.youtube.com/watch?v=eu3Vouff2h4&feature=youtu.be

Weinberg, A. (1972). Science and Trans-Science. *Minerva*, 209-222.

Wesley-Smith, P. (1994). *The Sources of Hong Kong Law.* Hong Kong: Hong Kong University Press, HKU.

Wesoff, E. (2015, June 26). *Solar Star, Largest PV Power Plant in the World, Now Operational*. Retrieved from Greentech Solar: https://www.greentechmedia.com/articles/read/Solar-Star-Largest-PV-Power-Plant-in-the-World-Now-Operational

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., . . . Banerjee, B. (2011). Tipping toward sustainability: emerging pathways of transformation. *A Journal of the Human Environment*, 762-780.

Wettengel, J. (2016, August 16). *Volatile but predictable: Forecasting renewable power generation*. Retrieved from Clean Energy Wire: https://www.cleanenergywire.org/factsheets/volatile-predictable-forecasting-renewable-power-generation

Wiek, A., Withycombe, L., & Redman, C. L. (2011). Key competencies in sustainability: a reference framework. *Sustainability Science*, 203-218.

Wittmayer, J. M., & Schapke, N. (2014). Action, research and participation: roles of researchers in sustainability transitions. *Sustainability Science*, 483-496.

Wong, M. S., Nichol, J. E., Zhi-Zhao, L., Lin, L., Tang, Z.-q., Yip, T. P., . . . Luo, N.-n. (2015). *A Remote Sensing Study of Solar Energy Supply in Cloud-prone Areas of Hong Kong.* Hong Kong: Public Policy Research Funding Scheme from the Central Policy Unit of the Hong Kong Special Administrative Region Government Project No.: 2013.A6.024.13A.

Wright, T. P. (1936). Factor's affecting the cost of airplanes. *Journal of the aereonautical sciences*, 122-128.

WTO. (2016, October 14). *DS456: India — Certain Measures Relating to Solar Cells and Solar Modules*. Retrieved from World Trade Organization: https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds456_e.htm

Yin, H., & Powers, N. (2010). Do state renewable portfolio standards promote in-state renewable generation? *Energy Policy*, 1140-1149.

Yoo, S.-H., & Kwak, S.-Y. (2010). Electricity consumption and economic growth in seven South American countries. *Energy Policy*, 181–188.

York, J. G., & Lenox, M. J. (2013). Exploring the sociocultural determinants of de novo versus de alio entry in emerging industries. *Strategic Management Journal*.

Young, H., & Freedman, R. (2015). *University Physics with Modern Physics (14th Edition) .* Pearson.

Zank, B., Bagstad, K. J., Voigt, B., & Villa, F. (2016). Modeling the effects of urban expansion on natural capital stocks and ecosystem service flows: A case study in the Puget Sound, Washington, USA. *Landscape and Urban Planning*, 31-42.

APPENDIX A

IRB RESEARCH APPROVAL (STUDY C)

ASU Knowledge Enterprise Development

EXEMPTION GRANTED

Wesley Herche
OKED: Global Security Initiative (GSI)
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Dear Wesley Herche:

On 1/4/2017 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	A Measured Approach Towards Solar as a Distributed Energy Resource in Hong Kong
Investigator:	Wesley Herche
IRB ID:	STUDY00005488
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Herche_HongKong_2017-InterviewGuide.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Herche_HongKong_2017-RecruitmentScript.pdf, Category: Recruitment Materials; • Herche_HongKong_2017-HRP-502c - TEMPLATE CONSENT DOCUMENT -SHORT FORM.pdf, Category: Consent Form; • Herche_HongKong_2017_HRP-503a-TEMPLATE_PROTOCOL_SocialBehavioralV02-10-15.docx, Category: IRB Protocol; • Herche_HongKong_2017-InternationalHumanResearchStandards .pdf, Category: Other (to reflect anything not captured above);

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 1/4/2017.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: