Technological Development and Innovation; Selected Policy Implications

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ABSTRACT

Technological development is one of the main drivers in economic progress throughout the world and is strongly linked to the creation of new industries, jobs, and wealth. This thesis attempts to better understand how a specific technological field develops over time and to examine the policy implications resulting from that research. In order to research the specific field, we present a repeatable method to identify and describe the important innovations in an industry, using the solar photovoltaic industry as a case study. A set of 2484 patented inventions in the solar PV industry between 1961 and 2011 was selected and their metadata and textual information were analyzed using a mixture of qualitative, quantitative and objective tests. Within the patent set, a group of most highly cited patents was located and defined. We found that these highly cited patents improved on technologies across different technological hierarchy levels and that the hierarchy levels did not appear to follow any pattern over time. When compared with other patents in the set of 2484, the highly cited patents, contrary to some conjectures, did not apparently rely more on new scientific discoveries as they did not cite scientific literature more frequently than less cited patents. These findings support the theory that even the most important developments in a field are part of an integrated system and cannot be treated as standalone improvements. The work also indicates that ascribing the bulk of progress to "breakthroughs" is not seen in objective data. The thesis continues with an analysis of how these findings may apply to innovation polices in organizations. Finally, technological innovation strategies within MIT, Stanford and the United States Air Force are analyzed through the lens of the model constructed from the findings.

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Chapter 1
Introduction

The development of new technologies has enabled mankind to grow into the civilization that exists today. Industries of all kinds have created unprecedented new capabilities that would not have been possible without the advent of new technologies. In the past, many of the people who developed technologies were the ones using the technologies on a daily basis, but as specialization has increased, there are now many people who are devoted specifically to developing new technologies to further advance mankind and create the future. The very idea of attempting to understand how the future is created is a daunting challenge, and our only hope of doing so is to examine the past in order to understand how we got here today. This section will discuss why it is important to understand how technologies are developed and are critical not only to the survival of many individual firms and organizations, but for mankind as a whole advancing as well.

1.1 Importance Of Technological Innovation

The importance of technical innovations can be seen by the fact that nearly all of the net jobs created in the last 20 years have come from new firms (Kane, 2010). This trend is not something that has emerged in recent years. Robert Solow (1957) showed by economic analysis that up to 7/8 of the increased capital gains per man hour in the early part of the 20th century can be attributed to technical improvements. Joseph Schumpeter (1947) takes a similar stance, referring to entrepreneurship and technical change as the 'ultimate cause' of economic growth and development. Schumpeter also asserts that it is practically impossible to understand how the development will occur ex ante, something that has continued to be echoed in the years since. The idea that the technologies that will change the future cannot be predicted is a topic that will not be covered in this thesis, but rather the goal has shifted to understanding how to create a more fertile environment for those unpredictable improvements to occur. That is to say – under what circumstances can you make rapid technical change and therefore economic growth more probable? Many people believe that radical or breakthrough inventions lie at the center of wealth creation (Ahuja and Lampert, 2001). This thesis explores what is meant by radical invention and whether and how this concept helps answer the question about how best to tap into the economic effects of technological change.

It is important as a society to enable the effective creation of new technologies in order to allow new and disruptive firms to take root and become the engine of economic growth. While many companies that are forming today rely on business practice innovation, many of these particular innovations in business practices have come about due to the development of technical capabilities. For example, if one examines at many of the most innovative companies today – they rely on new technologies such as miniaturized computing, fast wireless data transmission capabilities, and energy storage capabilities. It is therefore imperative to develop technologies to enable the creation of new industries and the expansion of current industries.

1.2 Large Scale Systems' Interest in Innovation

Technological innovation is not only relevant for small organizations looking to create new industries, it is potentially more important for large scale systems and organizations to understand how technology is developed. This need arises becasuse the creation of new radical technologies is taking place in large organizations more than is generally believed (Ahuja and Lampert, 2001).

Technological development and innovation are very important today. Due to the fact that technologies are enabling more rapid change, the ability to develop technologies and innovate is only going to become more important in the next generation. Large scale systems are going to have even less time to be able to rely on competitive advantages from their initial innovations that propelled them into that state, and thus will need to rely on innovation more than ever. In particular they will need to be able to develop technologies quickly and appropriately and will need to make use of the newest tools and methods in order to keep up with the smaller challenging organizations.

It is for these reasons that as we progress throughout this century that large scale organizations will have shorter half lives than ever before, with the only organizations surviving being the ones that are able to effectively make themselves obsolete instead of waiting for a competitor to do so. This same logic holds true for companies and governmental organizations. For example, the military will no longer be able to rely on large scale technologies to win battles – they will find that newer tools will enable much smaller fighting forces to create effective technologies that have the potential of leveling the battlefield more than it has been in the last century.

Large-scale systems have two reasons to care particularly about the development of new technologies. Large organizations inherently have more to lose and are potentially less agile than their smaller counterparts. Large-scale organizations have the potential advantages of an established set of constituents, name recognition, and more resources than that of younger and smaller organizations. The balance between the advantages and disadvantages of being a large incumbent has shown that innovation has favored smaller organizations in more recent times (Kane, 2010). There have been examples of large scale organizations that prove effective in innovating and not being disrupted, therefore it is important to think about how large scale organizations can develop technologies in a way that plays to their inherent advantages.

1.3 Research Goals

The research goals of this thesis are to contribute to the understanding of how technological fields develop over time and in doing so gain a better understanding of some of the most effective methods for developing technologies. This includes understanding which inventions are more important than others and how they are different than the ones that may be less important. Understanding the distribution of importance for inventions can help guide us in technology development policy by elucidating how much effort should be focused on finding or creating the most important inventions in a field. Once we understand which inventions are more important and how they are more important, we aim to understand how to incent the creation of more important inventions in the future. The final aspect of this thesis is to look at a few case studies of large-scale systems and how they go about incenting innovation and provide recommendations for potential ways to increase the effectiveness of large-scale technological innovation.

1.4 Thesis Overview

This thesis begins in Chapter 2 with a literature review, which explores many of the ways that technological development has been studied, with a particular emphasis on the most prevalent methods that have been developed in the last 20 years. Chapter 2 will also discuss the lack of current research on the technical aspects of the field of technological development, which is currently dominated by the market and business components of technological innovation.

Chapters 3 and 4 explains the methodology used in this thesis. Chapter 3 presents the reasons for using Solar PV as a case study and why understanding how Solar PV technology has developed over the last 40 years is relevant. Chapter 4 explains the methodology for how we were able to create a repeatable, qualitative and quantitative method for characterizing the technological development of a given field.

Chapters 5 through 8 present the results of our research. Chapter 5 explores the continuum of importance of inventions and will discuss how these findings relate to the improvement curves of other technical fields. Chapter 6 goes deeper into the characteristics of the more important patents and will then discuss how they compare with the less important patents along a number of facets. Chapter 7 looks into how the different areas of the overall industry of solar PV change over time and how that applies to our understanding of how the focus of an industry may change over time.

Chapter 8 discusses the policy implications of this research and how it could be applied to large-scale organizations looking to incent innovation. This chapter will also explore the innovation strategies of MIT, Stanford, and the United States Air Force and provides general recommendations for technological development strategies.

Chapter 9 summarizes the findings of this thesis and will make recommendations for future work.

Chapter 2

Literature Review

The field of technological change has gained attention in recent years due to the more apparent results of what happens when a large organization does not innovate effectively and becomes overtaken by newer organizations with new technologies and practices. This occurrence of new firms replacing old ones is not new, but has been accelerated in recent years and thus made much more apparent, especially in high technology fields such as information technology. Clayton Christensen (1997) has popularized aspects of this field with his work on disruptive technologies and innovations. While his work is one of the most familiar to general audiences, there are many other theories and ideas around how technologies are developed. This section will explore many of the other methods of analyzing technological change. In addition, this Chapter will discuss the opportunity for more study on technological innovation through a technical, as opposed to business, lens.

2.1 Other Methods of Measuring Technological Change

One of the ways that people have attempted to understand technological development is to simply list a set of developments that are considered innovations. **Error! Reference source not found.** shows an example of this, with a list of important innovations throughout the last 300 years as determined by Girifalco.

Table 1: Example list of Innovations throughout History (Girifalco, 1991)

Innovation	Year
Seed Drill	1731
Watt Engine	1776
Rifle	1824
DC Motor	1872
Airplane	1903
Methyl Methacrylate	1935
Transistor	1947
Personal Computer	1974

It is clear that there are issues in deciding what constitutes an important invention. These issues stem partially from ambiguity about the *level* of innovation to be considered. For example, the transistor is often considered a breakthrough technology, at the same time so is the integrated circuit (an important way of utilizing and manufacturing transistors) and so has the personal computer (which depends directly on integrated circuits). It is also reasonable to consider the entire field of information technology (which relies on personal computers and many other technologies) the most important technological breakthrough of the latter half of the 20th century.

The ambiguity is further compounded by the fact that the described technological improvements can be collectively combined over varying time scales. In fact, this is often done to simplify communication about developments within a field. For example, the initial invention of the transistor was completed in a much shorter time than all of the ensuing and continuing changes in transistors. The same is true relative to the initial invention of the integrated circuit and the modern computer, which is only one aspect of the development of information technology. This overall lack of clarity about abstractions over time and level makes it very difficult to unambiguously describe the technical changes or inventions that contribute to the progress in a technical field, and thus to understand at an actionable level how to utilize the concept of breakthroughs.

Variation in technological hierarchy and the time period of consolidation can be seen by examining the set of innovations given by Girifalco (1991) shown in Table 2. Examining one of his cases more closely, the 'Watt Engine', James Watt's great improvement was the introduction of a condenser to the engine, not in creating the entire concept of the engine himself. Additionally, James Watt started working on his version of the engine in 1765, but it wasn't until 1774 that he was able to create accurate cylinders using John Wilkinson's boring mill, yet the Watt engine is dated to 1776 due to its first commercial sale in that year. Another example, methyl Methacrylate, a precursor to plexiglass, was first developed in a lab in 1930 by a graduate student in McGill University, but it wasn't commercialized until 1935 by Lucite, the year that is associated with the invention.

It is therefore not surprising that lists such as these have been criticized as potential sources of data due to their subjectively selected nature, lack of repeatability and reliance on a priori assumptions (Yu and Hang, 2009; Wang et al, 2010).

It is interesting to note that many design changes designated as significant improvements or breakthroughs appear to identify individual points of improvement. Thus, the list in **Error! Reference source not found.** would integrate well with the widely accepted conjecture that technological breakthroughs drive the overall improvements of a technology. The importance of breakthroughs is supported by Kaplan (1999), who states that

'substantial growth over the long horizon requires discontinuous innovation' (Kaplan, 1999).

A similar point of view is given by Ahuja and Lampert (2001) as they state that breakthrough inventions

'serve as the basis of new technological trajectories and paradigms and are an important part of the process of creative destruction in which extant techniques and approaches are replaced by new technologies and products'.

The idea that a small set of technological changes account for a large portion of the overall improvement has been echoed many times in regards to different aspects of technology.

With the apparently widespread acceptance of these related notions, it is important to be able to define a repeatable method to determine technologies that can be considered as breakthroughs. Currently, the definitions found in the literature are often not designed for broadly analyzing breakthrough technologies across time and technical fields. Some of the definitions that are provided tend to be most useful when considering technologies post-hoc, such as the definition provided by Sahal (1981)

'Major technological innovations represent technical advance so significant that no increase in scale, efficiency, or design can make older technologies competitive with the new technology '

Definitions like this are difficult to use on a repeatable basis due to the reliance on counterfactual analysis, post-hoc data, i.e. the size of the technical advances brought by a technology and on the lack of a means to assess the size of that change. In addition, the term "technology" in these definitions is unclear as to how much hierarchical (and time) consolidation is inherently assumed. The terms "breakthrough" and "radical" often imply singular inventions but no care is exercised in clarifying this in the definitions. Other definitions tend to be intentionally more broad, such as the one due to Mascitelli (2000)

'Discontinuous innovation, for example, typically refers to products that involve significant new technologies and are aimed at a market that is unfamiliar with the product class'

The term 'significant new technology' cannot easily be applied to diverse situations objectively but the term product does imply a specific new product. Other definitions seem too specific, in that they only pick out certain technologies subjectively, Markides (2006) does this with his definition:

'A second type of innovation that tends to be disruptive to the established competitors is radical innovation, which creates new-to-the-world products (e.g., the car, television, personal computers, VCRs, mobile phones)'.

There is some tendency in discussion of breakthroughs, radical or discontinuous innovations to be somewhat circular in the definition essentially saying that breakthroughs are important because they are significant. This analysis shows the need for a more robust and repeatable method for identifying the key technical changes than subjectively listing "important technologies".

2.2 The Business Focus of Prior Attempts

Yu and Hang performed an excellent review of disruptive innovation theory in 2010 (Yu and Hang, 2010), which described four perspectives of enabling potential disruptive innovation: internal, external, marketing and technology. They mentioned that of all of the perspectives, the technology perspective received by far the least amount of coverage by experts to date, even though technological change is one of the driving factors of disruptive innovation.

When the examples above are examined to determine how the prior literature attempts to define technical innovations, nearly all mention the social aspects and how the technology impacts society directly. The pieces mention the amount of units sold, or specific anecdotal bits of evidence are shown to prove that a specific technology has truly been an important innovation. The measures used are appropriate for their intended purposes, as the end result of technological change can be considered to be the improvement of the quality of life of people. The interesting aspect to note is that although technologies enable many of the improvements to the quality of life, the basic underlying technical aspects of a technological change are not as well studied.

One example of a measurement of a technical parameter is Moore's Law, which states that the number of transistors on a microchip will double every year moving forward, a law that has proven consistent over time (Schaller, 1997). While this is a more technical approach than looking at inventions post-hoc, this measure still comes short of what the technical development curves would look like to measure accurately the development of that field over time because the number of transistors on a chip does not account for a varying chip size, something that has greatly aided the continuation of Moore's Law. To move more into truly accurate technical specifications, it is important to have a measure that is as near technology agnostic as possible. Chris Magee (Magee, 2010) references a number of such measures in his papers that involve the basic competency (such as the amount of energy generated) of a technical field over a unit of cost (such as the weight or monetary cost required to achieve that competency). There is an opportunity to link together the ideas of technical development as have been explored by Magee and the underlying research in highly important inventions as has been popularized by Christensen (1997)

Chapter 3

Research Context

One of the goals of this thesis is to develop a repeatable method for understanding the technological development of an industry. In order to do this, it is important to use a representative industry as a case study that will both allow for interesting results, but also allow for scalability of the method beyond that particular industry. This chapter will discuss the selection of solar photovoltaics (PV) as an ideal case study for the research. This chapter will also explain a brief history of the development of the Solar PV field, so as to allow the reader to understand how the field developed over time through the lenses of experts familiar with the technology.

3.1 Solar PV as an Ideal Case Study

In the last 70 years, the field of solar photovoltaics has grown from an experiment in Bell Labs into a $20 billion dollar market in 2009 (U.S. DOE, 2009). Using a technical metric as described in the previous Chapter, it is possible to understand the growth of the particular industry on a technical level that is largely device agnostic. This growth can be tied to the improvement of the capability of the technology over time, as the capability to produce useful energy grew from 0.21 kWhr/$ in 1977 to 6.91 kWhr/$ in 2010 (Frost and Sullivan, 2011). Fig. 1 shows the improvement of this key metric has followed an exponential growth pattern as is famously demonstrated by Moore's Law, (Moore, 2005). Exponential dependence on time has been seen for almost all technological capabilities thus far studied (Koh and Magee, 2006).

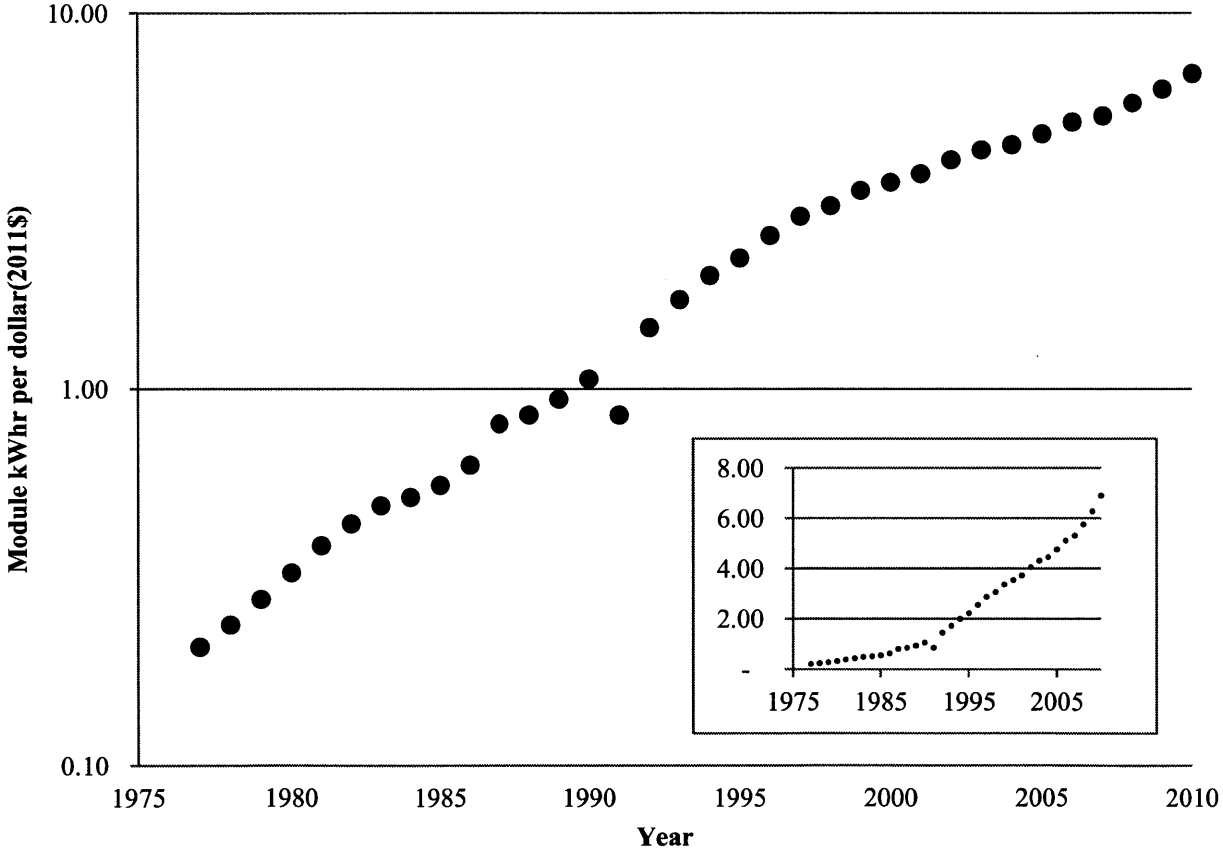

Figure 1: The exponential growth of kWhr/$ for solar PV from 1977-2010 is demonstrated by the logarithmic plot. The linear inset graph shows the continuously increasing slope.

Solar PV is an acceptable case study for the research because it has developed substantially over time, the time period in which it has developed is an acceptable length, and because the field does rely on patents to protect new inventions. As is shown in Figure 1, the development of the field of solar PV has been substantial, with capability increasing by almost two orders of magnitude. This is important for an appropriate case study because there is enough improvement over time so that it can be broken down and analyzed in parts. Additionally, the improvement over time is changing with time, which is important, as it will provide an opportunity to better understand the change in rate of improvement due to different factors in the inventions. Next, the time period of solar PV is ideal for a case study because it takes place largely in a time period for which the patent system has kept digital records. This makes a complete data set accessible, and therefore easily repeatable. This thesis is inherently forward looking, and the future of technological development research will rely on large amounts of accessible data, therefore it is important that the case study make use of such data, which the study on solar PV fulfills. Finally, it is important for the patenting rate of the case study to be relatively high so as to be sure that the inventions included in the research are representative of the overall set of inventions in a field. This factor is one of the main reasons why the information technology (IT) field would not make an ideal first case study of technological innovation, because the patenting rate in IT is low compared with the number of inventions occurring on a regular basis in the field (Kahin, 2008). The field of solar PV, however, continues to have an increasing rate of patenting (World Intellectual Property Organization, 2005) and still accounts for a large portion of the renewable energy patents filed around the world. It is for these three reasons that the field of solar PV is an ideal case study for the analysis of technological development.

In this thesis, we attempt to identify a finite set of the most important inventions underlying the rapid technological change occurring in the field of solar photovoltaics. In doing so, we analyze the required size of this finite set and examine the importance of singular inventions to the overall progress. Finally, we will characterize these very important inventions and attempt to differentiate them from the less important inventions in the same field. Our aim is to understand the overall technical change that has occurred in solar photovoltaics and the role of the most important inventions within this progress.

3.2 A Brief History of the Development of Solar PV

There have been previous attempts to understand the technical development of solar PVs over time. One example of this comes from the works of Martin Green (Wenham et al, 1994; Green, 1987, 1995). In his books, Green gives a description of the key changes that have occurred in silicon PV Cells over time as summarized in Table 2.

Table 2: Timeline of Solar Cell Development according to Martin Green (1995)

Date	Improvement
1941	Original Solar Cell
1954	dopant diffused p-n junction
1961	Contact Fingers and antireflection coating
1971	Violet Cells
1975	Pyramid cells (surface texturing)
1978	Oxide surface passivation
1985	PESC (Passivated Emitter Solar Cell)
1988	Rear point contact solar cell
1992	PERL cell

His list of improvements provides a structure for understanding how the technology has changed including a few specific improvements that have contributed to the increase in maximum efficiency of solar cells over time. Figure 2 below shows another way of visualizing the development of the technology, this time by mapping the increase in cell efficiencies over time. Keep in mind that these improvements in efficiencies are a measure for measuring technical progress, but not the primary one that we will continue to reference throughout the paper, for the cell efficiency does not take into account any sort of cost, such as weight, volume, or monetary costs.

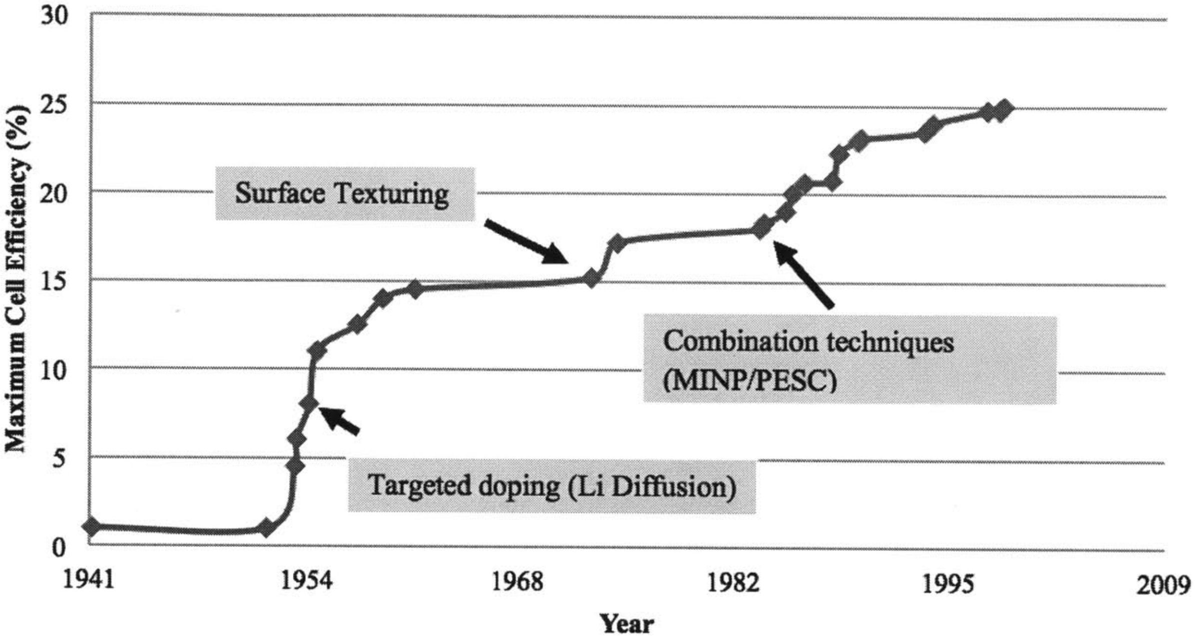

Figure 2: The Progression of Solar PV maximum cell efficiencies with certain developments labeled

In addition to Martin Green, there are several other experts in the field who have given short summaries of the development of solar PV, mostly along the lines of decade-by-decade improvement. The following lists show how other people understood the development of solar PV. A list from the thesis of Phech Colatat (2009) is paraphrased by decade below:

1960s – *Satellites*– annual market for solar cells was $5 million.

1970s – *Bulk terrestrial power motivated by the Arab Oil Embargo* - firms began making solar for terrestrial applications in 1972 – they began using solar for applications where they needed remote power – (oil rigs, forest ranger stations, lighthouses, buoys) – the goals were (1) – make the space cells cheaper and (2) cost effective commercial scale production – still mainly focused on mono-crystalline technologies

1980s – "Not a good decade for solar photovoltaic technology and industry" – this is supported by decreases in government funding, research staff, business tax credits and energy prices.

1990s – *Modest support and more modest growth throughout the 1990s* – reduce manufacturing costs, researching more in thin films – technology was not where it needed to be in order to be installed on the grid.

2000s – *Environmental issues push governments to create PV end-markets* – focusing on lowering manufacturing costs and coming up with new technologies.

The themes of these decades are consistent with the themes described by Martin Green in Table 2 above. These examples also align with other lists by solar PV experts such as Lawrence Kazmerski (2006). In order to create an independent list of themes over the decades, many patents were read and some of the consistencies between patents in each decade are described in the list below.

1972-1982: **Advancing basic Photovoltaic Research-** This time period is interesting in that it uses the term photovoltaic often, even though some of the later decades take more caution in labeling it its own field. These patents generally take a lot of time to describe what a photovoltaic device is, and introduce the sun as a potential source of energy. Some of the patents in this decade seem to place more urgency on the need for a replacement of fossil fuels. The technologies created in this decade seem like they are forming 'best practices' for the solar PV industry in that they are experimenting with combined thermal and PV solar possibilities, and they are looking into novel contact materials and layouts and are discovering intricate doping techniques.

1982-1991: **Working outside of the field – increasing efficiencies to usable levels -** The patents in this time period discuss how conventional sources of energy are becoming scarcer and more expensive, but do not yet discuss the idea of solar being a generally accepted solution to this problem. The field of the invention in the earlier patent in this decade does not even mention photovoltaics as its own field, and instead talks about doped n-type and p-type semiconductors. The main focus of these patents is on increasing the efficiencies of the solar PV cells. They begin to address different material combinations and more novel ways of doping the silicon.

1992-2001: **Integrating solar technologies with the world -** This time period talks about how solar power is becoming a growing source of energy for the future. The prior art now is turning to discussing how to prepare solar PV for large scale use including beginning to discuss the cost and manufacturing problems associated with solar PV. The patents are involving making it easier to integrate with buildings or batteries. One of the important patents continues to work on improving the efficiencies of solar PV.

2002-Present: **Reducing costs and mass production, bringing solar to the masses -** This time period is unique in the fact that it starts to talk about the use of solar power as the future energy technology as a given. The prior art advances logically, now assuming that there are several different types of solar PV technologies on the market and the patents are not all focused on one type. The technologies in the patents themselves are particularly advanced and are starting to reach the efficiency limits proposed in the earlier decades. These technologies include plasma treatments and multi-junction cells.

This basic understanding of the field of solar PV will be helpful in understanding the analysis of the development of the technology over time that will be explored through the rest of the thesis.

Chapter 4

Framework for Analyzing Innovation

Until this point, much has been made about creating a repeatable method for understanding the development of a technological field. It has been shown that many of the repeatable methods are too quantitative and have very little applicability to actual situations, whereas the qualitative methods have shown to be more accurate and useable, but less repeatable and nearly impossible to perform ex ante, which is something that will be necessary to create an actionable methodology for developing more important technologies in the future. This Chapter will explore a repeatable methodology that is both quantitative and qualitative in its approach, and lends itself to a deep understanding of the most important patents along with a broad understanding of many of the inventions in the field of solar PV.

4.1 Using Patents as a Proxy for Innovation

One direct way to eliminate subjectivity over time is to utilize patents as the observed unit of development (Abraham and Moitra, 2001). Using patents or legally-recognized inventions is often considered a less subjective measure than the exogenous set of inventions (Biju and Soumyo, 2001). The patent database covers most fields of invention and it has information on nearly every invention in the last 200 years (Markides, 2006). Furthermore, the patent databases are accessible and include important metadata that can be used to gain more information about the patents and how they relate to technical progress as a whole. In particular, patent citation analysis has been used for assessing the importance of individual patents by Manuel Trajtenberg (1990), and has been used to validate the data sets of other studies in the field of technical innovation (Dahlin et al, 2004). Trajtenberg showed that

'patent citations may be indicative of the value of innovations and, if so, that they may hold the key to unlock the wealth of information contained in patent data'

Much of the analysis in this paper is built on the ideas of Trajtenberg et al. (1997) that the importance of patents as well as other useful measures can be determined by analyzing the citation data. We are not aware of any previous study that utilizes patent citation analysis to identify and analyze the nature of the most important patents in a given technological field but it appears to be a viable way to approach our research questions.

4.1.1 Why Patents Cite Other Patents

One of the reasons why the patent citation data is very accurate is due to the laws surrounding the submission of a patent to the USPTO. Each inventor is required to submit a complete list of the state of the art, which is penalized by future revocation of the patent if it is found that they missed any references. To prevent the risk of this, in practice, many inventors cite each and every patent that is even remotely relevant to the current invention (Michel and Bettels, 2001). In general, the citations show how the current invention is different from past inventions and the citations are the 'shoulders upon which the new claims stand in their attempt to advance technology (Harhoff et al, 1999).

4.2 Selecting the Data Set

In addition to the work done within a technological field, we will be interested in "spillover" of developments from other fields to the field of interest (Hur and Watanabe, 2001; Kwang and Chihiro, 2001; Griliches, 1992). Thus, we must specify the primary field of interest and differentiate it from others. In this study, a selection of patents from the solar photovoltaic technological domain was used to analyze the technological development in that field.

The first step was to populate a data set that was as narrow as possible on the PV field, but broad enough to capture many of the inventions that could have contributed to spillover. In order to do this, we explored several combinations of key words in the solar PV field (solar, cell, module, silicon, photovoltaic, electricity) as search terms in the US Patent database of issued US patents and compared the size and relevancy of the returned sets. A search of the term 'Solar Electricity' returned almost 7000 results. To ensure accuracy and that the data set was truly indicative of the solar PV field, subsets of the data were textually analyzed to determine if they were related to the PV field. The determination of being related to the solar PV field was done by a careful reading of the patents and discounting patents such as 'Solar powered smart card with integrated display and keypad' (5777903) and 'solid state electronic camera including thin film matrix of photosensors' (4788594) which are not directly related to the PV field, but could cause spillover.

A sampling of two selections of 150 patents from the search results of 'Solar Electricity' contained only 38% patents that were directly relevant to the solar PV field, and the sampling included many entirely irrelevant patents such as PN 5892900 '*Systems and methods for secure transaction management and electronic rights protection.*' The low occurrence of solar PV patents as well as the significant presence in this set of completely unrelated patents made the results from the search for 'Solar Electricity' not appropriate for the analysis of the solar PV field.

A more specific search for the term 'Photovoltaic Electricity' between 1970 and 2010 returned a data set of 2484 patents. Five selections of 150 patents across the data set (750 in total) were analyzed and showed that 62% of the patents in the set were related to the solar PV field, which provides an acceptable representation of the field of interest. The final data set was not cleaned of the discovered non-PV patents to allow for potential spillover and to increase repeatability since not all 2484 patents in the set were searched in detail.

4.3 Applicability of Patent Metadata

Using patents to study inventions allows us the opportunity to analyze the large amount of information stored in the metadata of each patent that is required by the US Patent and Trademark Office. This information, from the title to the number of citations, contains information on how the patents relate to each other and how the technology has changed over time. The forward, backward and non-patent citation data and patent classifications were extracted and used as comparing factors between selected examples of the inventions. In addition to the metadata, we also examined the text of each of the sections (Abstract, Prior Art, Summary of Invention) of a set of highly cited (see below) patents in order to gain another layer of quantitative and objective information on the patents beyond what the metadata includes.

The simple forward citation data is used as a proxy for importance throughout the paper. Some concerns have been raised about the applicability of simple citation counts due to the increasing patenting rates over time and the problem of truncation of the newer patents (Hall et al., 1995). In order to address this potential issue, we ran all of our tests using a method created by Dahlin et al (2004) that adjusts for these issues. We found that there was not a meaningful difference between the adjusted forward citation count and the simple citation count, especially among the most highly-cited patents. For the sake of ease of repeatability, the simple citation count was used, with the understanding that the increasing patenting rate and truncation problems are not significant in our comparisons.

In addition to their work on the importance of patents, Trajtenberg et al. (1997) also provide a method to analyze the relationship between patents and basic scientific research. His metric, which uses the patent's listing of non-patent literature (NPL), is referenced below as the NPL citation rate.

Through the metadata included in the patent database, we were able to construct a repeatable method of comparing inventions over broad periods of time and across numerous industries to help understand the technological development in a specific technical field. As was previously noted, the conclusions that are drawn from a purely quantitative approach tend to be more abstract, potentially ambiguous and thus difficult to reduce to immediate action.

4.1.1 Increasing Rate of Innovation and Changing Patenting Rates

One concern that may be raised concerning the data set is the changing rate of innovation and patenting over time, as the number of inventions patented per year rises over time and thus may disturb our data set (Dahlin et al, 2004). Dahlin et al describe a method (2004) that corrects for the changing rate of patenting and for the truncation effect that does not allow newer patents to be cited as often as older patents due to the fast that they have not been available long enough to be patented as often as older patents. This methodology described by Dahlin et al produces a measure that is ultimately an adjusted citation count. In order to ensure that the data was reliable, all of the tests were performed using the simple forward citation count and the adjusted citation value created by Dahlin et al. Ultimately there did not appear to be a significant difference between the Dahlin et al (2004) values and the simple citation count for our purposes and thus chose to use the simple citation count for this research in the name of simplicity.

4.4 Separating the Patents into Subsets

With these factors taken into account, several subsets of the 2484 patents were read in depth and qualitatively analyzed to understand them and their direct relationships to other patents. These subsets were picked to allow comparison across time and importance. Three sets of 12 patents each were selected, varying with number of forward citations, resulting in a set of highly cited patents, a set of moderately cited patents, and a set of least cited patents. Table 3 shows the statistical analysis of the citation data of the three sub-sets. These sets varied across time, with 3 patents coming from each of the last 4 decades (1971-1981, 82-91, 92-2001, 02-11). For example, to form the set of 12 'most cited' patents, the most highly cited solar PV patents from each of the last 4 decades starting in 1971 were selected. Unlike the data set as a whole, these three subsets were cleaned of non-PV related patents to assure relevance of the analysis to the solar PV field.

Table 3: The mean, variation and range of the forward citations of the 3 patent subsets

Type	N	Mean	Stdev	Min/Max
Very Important	12	86	45	57/163
Moderately Important	12	15	1.8	11/17
Less Important	12	2	0	2/2

As mentioned above, each patent's forward citation rate will act as a representation for their importance. The rationale behind this is that if a patent is cited more often, then they are at least more important to future patent activity than a similar, yet less cited patent. Trajtenberg (1990) uses the citation data as an approximation for the social value of an invention. In contrast, this study is also interested in the technical value of the inventions. The purpose of citations is to give credit for previously created value and thus citations are at least as strongly related to technical value than they are to social value. Throughout the remainder of the paper, we will assume that citation rate and importance are correlated and will refer to the three sub-sets of patents as 'very important' patents, 'moderately important' patents, and 'least important' patents as shown in Table 3.

These three sub-sets of patents were read thoroughly in order to understand the initial intent of the patents and why they were cited in the future in an attempt to clearly define the qualitative relationships between each patent, how it improved on the past and how it affected the future. Through the combination of quantitative and qualitative patent analysis we were able to arrive at a richer understanding of how solar PV technology has changed over time. This methodology will allow us to analyze the patents and break them down into manageable sets from which to compare. The following Chapters will explore more deeply the quantitative portions of this repeatable method.

Chapter 5
Continuity of Technological Progress

This Chapter will map the inventions in the solar PV field over the past half-century utilizing citation analysis. This will allow us to see clearly the distribution of importance of the inventions over time and, in particular, look for inventions that are discontinuously important that may be considered as breakthrough or disruptive innovations. Additionally, this section will explore how the results shown in our theory of continuous technical importance relate to other models of technological trends.

5.1 Mapping the Continuity of Inventions

As noted above, Trajtenberg (1990) showed that the importance of an invention can be quantified by the number of citations that a patent receives. Figure 3 shows the distribution of the most cited to the least cited patents in the data set of 2484 solar PV patents. There is clear evidence of patents that are cited much more highly than others, there are 57 patents that are cited at least 50 times each, inventions that can be considered important to the technological development of solar PV. There are also many patents that are moderately important, with over 600 patents being cited between 10 and 20 times. Finally, there is a clear tail with 522 patents being cited zero times, an indicator of less important patents. Figure 3 shows that despite the enormous difference between the most highly cited and the least cited patents, there is no discontinuity in citation rate within the entire set of patents –the distribution is relatively continuous.

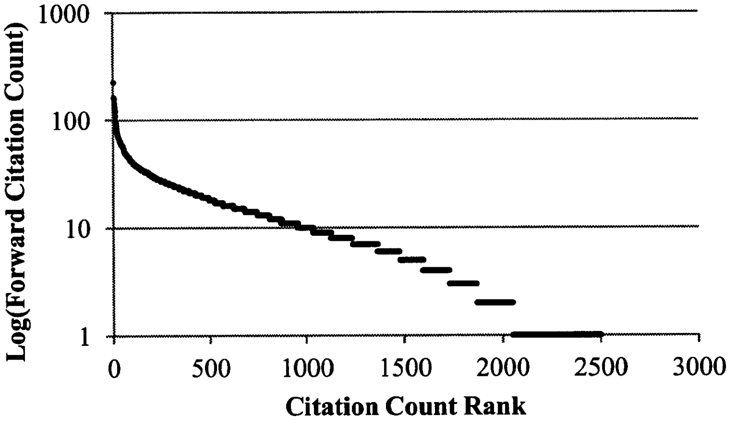

Figure 3: Distribution of patents by forward citation count

5.2 Lack of Discontinuities in Curve

The graph in Figure 3 shows a very interesting take on how technological fields develop as a whole considering the technical importance of individual inventions in the field. It indicates no singular breakthroughs or disruptive inventions when they are analyzed by their technical merit. This is a rather large departure from the way that many people think about technologies in that there are not a discrete number of very important inventions that drive the overall development of an industry. This curve points to the idea that all inventions are of varying importance and that while some are more important than others, the goal of research and development should be to develop a wide set of more important inventions rather than a much smaller set of discontinuously important breakthroughs.

It is important to keep in mind that this graph is looking at the relative technical importance of these inventions. This is separated from other attempts that use patent citation count in an attempt to judge societal or monetary importance of inventions. It is also differentiated from attempts that use other metrics such as patent renewal rate to judge the non-technical value of an invention. This particular aspect is what Yu and Wang (2010) were referring to when they discussed the technical perspective of technological innovation had a large gap. The graph does show a distribution of *technical* importance of most of the inventions in the solar PV field and allows us to see how the field has developed technically. This, along with the graph in Figure 1 provide a greater understanding of the progress of technical capabilities of a technology that enable the creation of disruptive or discontinuously important inventions.

Another way of visualizing this curve is to show the distribution of importance by year that the patents for the inventions were granted. Figure 4 shows that there seems to be no pattern for the distribution of important patents over time. For this particular test, the adjusted forward citation count method described earlier by Dahlin et al. (2006) is used to allow for newer patents to be accounted for. Although the aforementioned methodology does help with the problems of increasing patent rates and truncation, keep in mind that the most recent patents may have lower citation counts due to truncation. This data does not support the idea that important inventions come at critical points throughout the lifetime of an industry, but rather that important inventions are created nearly continuously, along with a slew of less important inventions.

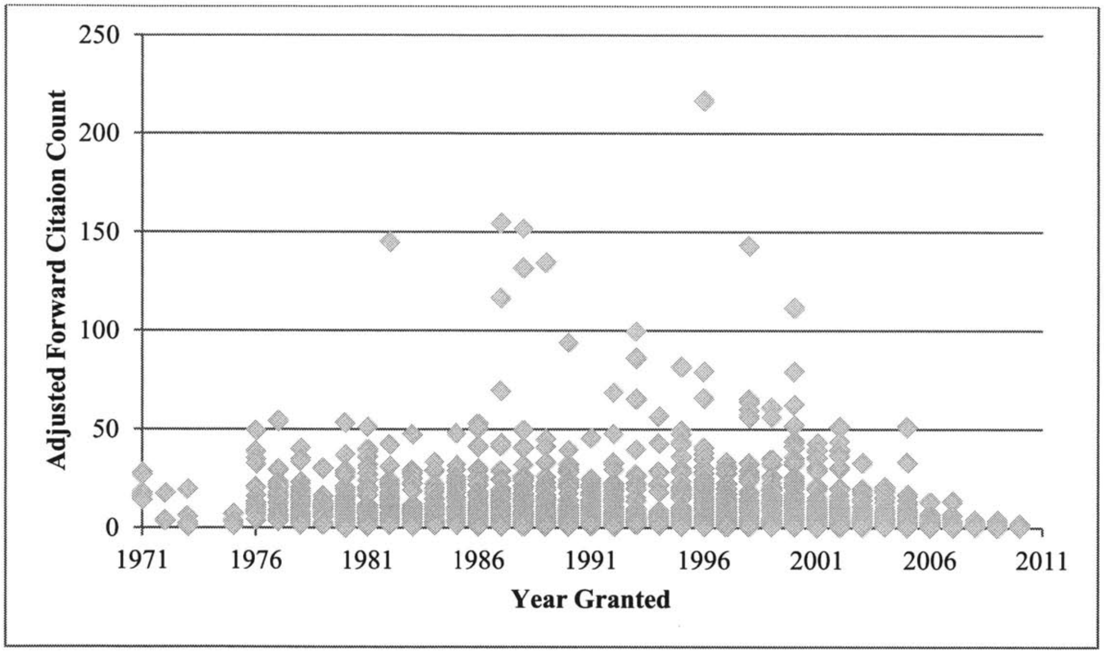

Figure 4: Citation count of Solar PV patents by year

5.3 Comparing the Curve to other Inventions

The curve in Figure 3 does not show discontinuously important technical inventions over time. Rather, it shows that all inventions lie on a scale of importance and are part of a large interconnected system that ultimately results in technical improvement over time. This information, although it is not the most widespread opinion among experts, is consistent with many other theories of technological development. This section will explore how this theory of all inventions resting on a continuum of importance relates to some of the other models of technological development.

One of the most well known theories in technical development comes from Gordon Moore and states that the number of transistors placed upon an integrated circuit will double approximately every two years. This law has remained mostly true for the last 40 years since he first posited the theory (Moore, 2005). Moore wrote in his original paper (Moore, 1965):

> *The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain constant for at least 10 years.*

The interesting part to note about Moore's prediction is that it is inherently device agnostic. He did not look ahead and take note that there would be significant breakthroughs that would happen at certain points. Moore's law suggests that there is an integrated system of inventions and developments that will continually increase our technical capabilities. This is consistent with the data that we present in that we see ever increasing technical capabilities that are caused by the accumulation of many inventions of varying importance. Schaller (1997) builds upon Moore's law to show what particular products and socially useful technologies have come about due to the increased technical capabilities brought about by the improvements in the semiconductor and integrated circuit industries. His list includes distributed personal computing workstations in 1981, internet connected computers in 1998 and he is even able to predict phone and videophone capabilities for the year 2010. This idea that the technical capabilities of a field are continuously increasing and enable the creation of discontinuously important inventions is consistent with the results of our study.

The technical curves created by Magee and Koh (2006; 2008) show that technologies of all kinds develop continuously over time in a nearly exponential fashion. These curves, like the curve from Moore's law, are device agnostic, meaning that a technical field can maintain its progress through several different iterations or dominant designs. One example of this is the continually increasing nature of information storage in megabits per cubic centimeter; the trend follows a nearly exponential path from handwriting to punch cards to modern day magnetic hard drives. This work is consistent with our findings from the solar PV field and with the theory that there are no discontinuously important technical improvements, only ones that are more important than others. As was shown earlier, the graph of PV development over time follows a nearly exponential path through much iteration and many different kinds of devices. These devices have ranged from very expensive, high efficiency silicon cells to less expensive but lower efficiency thin film solar cells, but the exponential technical growth remains consistent throughout. As the exponential growth curves in PV were shown to be similar to other industries, it is reasonable to assume that the lack of discontinuously technical important invention can also be extrapolated to other industries, such as information technology or energy storage. Within each technical field, however, there are certainly inventions that are more important technically than others, which is shown in the roughness of the logarithmic curves. On a short time scale, each of the technical development curves show a wide range of improvements, with some inventions showing more progress than others. The consistency of our results with that of Magee (2010) lends to the idea that the theory of continuous technical importance of inventions could be applicable to fields other than solar PV as well.

The model we present is also consistent with the idea of disruptive innovations. The concept of disruptive innovations was originally introduced by Clay Christensen (1997), where he explains how large organizations become disrupted by smaller ones with new ideas or technologies that are inferior to the status quo on one dimension, but are superior in another dimension, as shown in Figure 5, which was taken from his book.

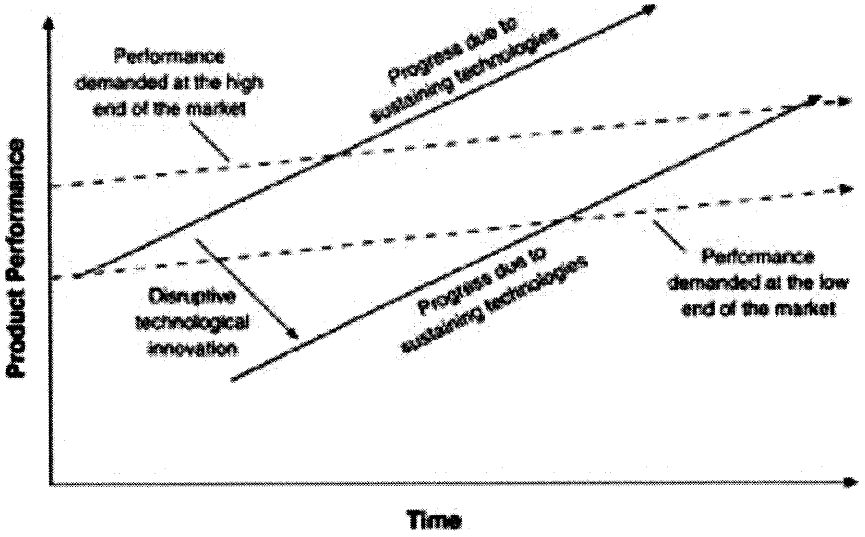

Figure 5: A comparison between sustaining and disruptive innovations (Christensen, 1997)

Christensen explains his theory using the disk drive industry as an example. He explains that disk drive manufacturers were very focused on the large sized disks and improving the dominant critical parameters, cost/byte (lower) and overall storage (higher) to serve their main market. They underestimated the impact of allowing for smaller architectures and therefore smaller devices with perhaps more expensive cost per byte initially, but could serve the new market of personal workstations. He goes on to show that the development of the smaller disks 'disrupts' the larger disk makers. The idea of disruptive innovations shows that there are certainly products that are discontinuously more useful to society. The difference between a societally important product and improving technical capability is a critical distinction to make for this analysis (Magee and Devezas, 2011). The data that we have shown indicates that there are no discontinuously *technically* important inventions, meanwhile, Christensen (1997) has clearly shown that there are discontinuously *societally useful* inventions.

Christensen also discusses how many of the disruptive innovations are technologically straightforward and are often made from off the shelf components put together in a new way. This aligns with the idea that the technologies are the enablers of the new disruptive products or inventions. This is to say that the underlying technical capabilities advanced to a point where they could be fit together to make a discontinuously useful invention, one that was likely impossible in previous times. As an easy to imagine example, consider portable MP3 players that became very popular in the early 2000s. These devices became useful because of advances in technical fields such as energy and data storage, which enabled a new combination of technologies to be combined to create discontinuously useful products.

5.4 Summary of Results

In this chapter we ranked 2484 patented inventions in the solar PV field by importance and found that there were no discontinuously important technical inventions. The inventions, however, do vary greatly in importance, but none seem worthy to be considered 'breakthroughs'. The results shown are consistent and complementary to much of the prior work in the study of technological development. In particular, the theory presented is consistent with Moore's Law and his idea of continuous exponential improvement in a particular technical field, while remaining device agnostic. The agreement with the work of Magee shows that the theory shown in the field of solar PV may likely be applicable to other fields due to the exponential improvement of technical curves across many areas of study such as information technology. Finally, our results align with those of Christensen and his theory on disruptive innovations, as consistent technical improvement makes discontinuous improvement in the usefulness of devices possible.

Chapter 6

Comparison of More Important and Less Important Inventions

If we accept the idea that there are no discontinuously important inventions, and that there are certainly inventions that are more important than others. What are the characteristics of those inventions that are the most important? This chapter will explore in depth a set of the most important inventions in the field of solar PV and will look to see what value they added as well as what problem they were initially solving. Next, the citations of the more and less important patents will be compared to understand what they are building off of. Ultimately the goal is to understand how the important patents were developed in order to determine a strategy for creating more important technical inventions in the future.

6.1 Detailed Analysis of Important Patents

This sub-section analyzes the set of 12 'very important' patents in an attempt to understand their role in the technological development of solar PV with the results summarized in Table 4. The fourth column in Table 4 describes the specific way these highly cited patents improved on the previous state of the art. In order to determine this, we examined the prior art section of each patent and looked for statements about shortfalls of existing technological approaches and for specific statements about what is superior in the method decribed in the patent over the existing technologies.

For example, patent number 5747967 (row **D**) cites the following problem in the 'Prior Art' section of the patent:

'Once the optimal operating conditions have been determined, the systems intentionally change the operating conditions to non-optimal operating conditions and restart the process of determining the optimal operating conditions. Therefore, the disclosed systems do not provide for extended or sustained operation at the optimal operating conditions once the optimal operating conditions have been determined, which causes a loss in efficiency of the disclosed systems and reduces the power delivered by the photovoltaic device to a battery or load. Consequently, in spite of the well-developed state of solar array and photovoltaic array technology, ***there is still a need for a peak power tracker for a photovoltaic array that is simple to construct, operates the photovoltaic array at peak power output for significant periods of time****, and allows the electric energy and electric power produced by the photovoltaic array to be stored in a battery.'(Bold type added)*

This section can be reduced down to a condensed form of the need for the invention. This simplified need for the invention can then be combined with components from the abstract and/or the 'Summary of Invention' section of the patent. In this case, the abstract provides a clear summary of how the invention addresses that problem:

'A method and apparatus for maximizing the electric power output of a photovoltaic array connected to a battery where the voltage across the photovoltaic array is adjusted ***through a range of voltages to find the voltage across the photovoltaic array that maximizes the electric power generated by the photovoltaic array*** *and then is held constant for a period of time. After the period of time has elapsed, the electric voltage across the photovoltaic array is again adjusted through a range of voltages and the process is repeated. The electric energy and the electric power generated by the photovoltaic array is delivered to the battery which stores the electric energy and the electric power for later delivery to a load.' (bold type added)*

These two statements were combined to provide a concise interpretation of the technical improvements disclosed in the patent.

There is a need for a peak power tracker for a photovoltaic array that operates the photovoltaic array at peak power output for significant periods of time (achieved by an apparatus that optimizes voltages to operate at peak power)

Table 4 gives these concise interpretations for the sub-set of 12 'very important' patents. This qualitative information gave us a clear indication of what the authors believed were the most important improvements that they were making on the existing state of the art. Although the statements of improvement were more clear in some patents than others, overall it was possible to describe the technological change inherent in the invention as believed by the inventor at the time of invention.

Table 4: Summary of 12 'Very Important' Patents and how they relate to prior and subsequent patents.

atent Number - Patent Title (year)	Hierarchy #	Improvement on Prior Technologies from Prior Art section	In Text/ Total Citat	Summary of in-text citations
441298 - Surface-plasmon enhanced photovoltaic evice (2002)	3	Current devices are not stretchable and do not conform to the shape of surfaces used in many electrical devices.	0/56	No In-Text Citations
878871 - Nanostructure and nanocomposite ased compositions and photovoltaic devices 2005)	2	Current photovoltaic devices or cells employ thin layers of semiconductor material, e.g., crystalline silicon, gallium arsenide, or the like, incorporating a p-n junction to convert solar energy to direct current - their efficiency has been somewhat limited.	7/57	Photovoltaic devices having layer structures that include inorganic nanostructures
340788 - Multijunction photovoltaic cells and anels using a silicon or silicon-germanium active ubstrate cell for space and terrestrial applications 2002)	1	For the multiple-cell PV device, efficiency is limited by the requirement of low resistance interfaces between the individual cells	2/42	Multiple graded buffer layers placed between upper and lo subcells to provide maximum flexibility in subcell lattice constant and band gap
747967 - Apparatus and method for maximizing ower delivered by a photovoltaic array (1998)	4	There is a need for a peak power tracker for a photovoltaic array that operates the photovoltaic array at peak power output for significant periods of time	1/67	No In-Text Citations
350644 - Photovoltaic cells (1994)	1	It is important that the titanium dioxide film be coated with a photosensitizer which harvests light in the wavelength domain where the sun emits light.	16/64	Graetzel et al reported solid- dye-sensitized mesoporous TiO.sub.2 solar cells with up 33% photon to electron conv efficiencies.
092939 - Photovoltaic roof and method of naking same (1992)	3	What is needed is an economical system for constructing a roof structure that uses the flexibility of thin film photovoltaic materials	5/62	A roof structure comprising in which a photovoltaic layer been incorporated
698234 - Vapor deposition of semiconductor naterial (1987)	2	Applicants' low band gap (1.45eV) semiconductor alloy material is of the same high quality (with respect to the number of defect states in the band gap thereof and the photoconductivity thereof) as the best 1.75 eV	0/162	No In-Text Citations

		material heretofore produced (and far superior to any low band gap semiconductor alloy material heretofore produced).		
775425 - P and n-type microcrystalline emiconductor alloy material including band gap idening elements, devices utilizing same (1988)	1	A method of fabricating wide band gap microcrystalline n-type silicon alloy material to which have been added a band gap widening element.	3/161	Microcrystalline silicon semiconductors used in p-typ n-type semiconductor layers i solar cells of a pin structure u amorphous i-type semiconduc layer
309225 - Method of crystallizing amorphous aterial with a moving energy beam (1982)	2	Method does not require that the semiconductor material be heated to a temperature above the melting point of the crystalline material to achieve crystallization. It is in fact preferred to carry this method out completely as a solid phase transformation.	4/155	Technique for improving the crystallinity of semiconducto by laser annealing and doping films.
021323 - Solar energy conversion (1977)	5	The invention is particularly concerned with the efficient conversion and storage of solar energy, and with the efficient use of materials for that purpose.	22/66	Semiconductor elements are placed in contact with an electrolytic fluid. This results solar energy converter (semiconductor module) whe electrolysis of the electrolyte place when illuminated with sunlight.
234352 - Thermophotovoltaic converter and cell r use therein (1980)	4	Photons having less energy are either not absorbed or are absorbed as heat, and the excess energy of photons having more than 1.1 electron volts energy creates heat. These and other losses limit the efficiency of photovoltaic cells in directly converting solar radiation to electricity to the order of 10-20%.	14/60	A cell described therein inclu back surface reflector for refl incoming below band gap en radiation back out of the cell.
281208 - Photovoltaic device and method of anufacturing thereof (1981)	2	In order to be light transmissive, the film needs to be thinner; however, it is extremely difficult to control the film thickness of such a film and to attain good reproducibility.	15/67	A photovoltaic device which comprises a TCO front electr semiconductor layer, and a b electrode stacked on a transp insulative substrate such as a plate is described

Understanding the technical advancements of each of the patents allows us to discern how these patents relate to the overall changes in the solar PV field. At a preliminary level, these 12 'very important' patents are seen as definite technological improvements, but their importance is not obvious from the titles or abstracts. Moreover, beyond being technologically deep, they are different from one another in a number of underlying factors. In particular, two factors were examined regarding the 12 'very important' patents: the variation that important inventions show in their level in a technological hierachy that proceeds from materials to components to systems; and the relationship of citations to important patents to the technological improvement they specified in their patent.

6.2 Levels of Technological Hierarchy

Using the descriptions in the fourth column of Table 4, (and more detailed study of the patents) the technological hierarchy levels of the 12 'very important' patents were determined. A method of characterizing the technological hierarchy of an invention was described by Magee (2010) that places inventions into one of 6 technological levels in a hierarchy ranging from *Materials and Process Improvement* which is the lowest level in the hierarchy through *Compnent Redesign, etc.* up to *System Phenomenon Change* where the actual scientific phenomenom in the technology is affected. Table 5 shows the 6 levels of hierarchy along with their relative positions for this analysis (slightly modified for this thesis).

Table 5: Levels of technological hierarchy along with example technological changes for information transmission adapted from Magee (2010)

Hierarchy	Example in information transmission	Level
Materials/Process Improvement	Coatings on glass fibers	1
Materials/Process Substitution	Glass fibers replacing metallic conductors	2
Component Redesign	Optical 'solitons'	3
System Redesign	Optical amplification	4
System Operation Change	TCP/IP; wavelength division multiplexing	5
System Phenomenon Change	Wireless vs. wired transmission	6

The third column in Table 4 show the hierarchy levels (numbers given on the right hand side of Table 5) applied to the 12 'very important' patents. Our estimates of the hierarchy levels can be ambiguous but not by more than a single level (from a 1 to a 2 or a 3 to a 4). As an example of a non-ambiguous characterization, patent number 6878871 (Row B) replaces a polymer layer with a layer containing inorganic nanostructures, making it level 2: material substitution.

Of the 12 'very important' patents, 7 were either hierarchy levels 1 or 2, and none of the important patents involve changes at (the most "radical" change) level 6. The highest level change was observed in patent number 5747967 (Row D), which is a change at the system operation level with the addition of a component that allows the solar pv system to operate at the peak power for more of the time thus generating more electricity. A second result evident in the hierarchy column in Table 4 is that the occurrence of changes at various levels is not systematically related to time. There are low and high hierarchy levels across the 4 decades, with early inventions such as patent number 4021323 (Row J) in 1977 which involves the redesign of the system (level 4) to produce liquid fuel instead of electricity and patent 4281208 (Row L) in 1981 which has a hierarchy level of 2 and introduces a new process for creating a electrically conductive and light transmissive layer on the solar cell. Later patents such as patent number 5747967 (Row D) and 6878871 (Row B) also represent a wide range of technical hierarchy levels that do not form any pattern over time, thus, one does not first get higher level changes and then only lower level changes later (or vice versa). Another result to notice is that three of the 'very important' patents that were of technology level hierachy 1 or 2, patents number 4698234 (G) , 4775425 (H) and 4309225 (I), are all cited over 150 times and are low technological hierarchy levels.

6.3 Relationship between Inventors Intentions and Results

A second aspect of determining the basic technical improvement provided by a patent was examined by analysis of wording in patents that cited these important patents. Although these important patents were each cited by large number of patents, there are only few of these that are in-text citations that can give specific insight into why a patent is being cited. The fourth column in Table 4 shows the number of in-text citations for each of the 12 'very important' patents, with approximately 11% of the citations being in-text. Of the 12 'very important' patents three were not cited in-text at all, conversely, patent number 4021323 (J) was cited in-text 22 times out of 67 forward citations. The 5th column of Table 4 shows a summary of the in-text citations that a patent received. The method we used to create these summaries is similar to that of the creation of the technical improvement summaries in column 2. For example, patent number 5350644 (E) was cited in-text by 16 different patents. Two example in-text citations are shown below:

CITED BY 6649824 - Graetzel et al. (J. Am. Chem. Soc. 115(1993) 6382, U.S. Pat. No. 5,350,644) also reported that performance as high as that of a silicon solar cell was achieved by improving dye and a semiconductor electrode. There, a ruthenium type coloring agent was used as dye and an anatase type porous titanium oxide (TiO.sub.2) was used as a semiconductor electrode.

CITED BY 6929970 - A wet type solar cell having a porous film of dye-sensitized titanium dioxide semiconductor particles as a work electrode was expected to surpass an amorphous silicon solar cell in conversion efficiency and cost. These fundamental techniques were disclosed in 1991 by Graetzel et al. in Nature, volume 353, pages 737-740 and in U.S. Pat. Nos. 4,927,721, 5,350,644 and JP-A 05-504023. ***Graetzel et al reported solid-state dye-sensitized mesoporous TiO.sub.2 solar cells with up to 33% photon to electron conversion efficiencies.***

These in-text citations were condensed into a qualitative and concise statement:

Graetzel et al reported solid-state dye-sensitized mesoporous TiO.sub.2 solar cells with up to 33% photon to electron conversion efficiencies.

All 16 in-text citations that referred to patent number 5350644 (E) mentioned the dye sensitized solar cell that was claimed in the patent. In general almost all of the in-text citations were consistent with each other, meaning that the patents were cited for almost the exact same thing. There were only 2 patents that had clear separations between the citing patents. Patent number 4234352 had citations both for its back scatter reflector and for the more general idea of a concentrator solar cell. Patent number 4281208 had an even more divergent set of citing patents, with 8 patents citing the transparent conductive layer while the other 7 patents cited its potential use as an anti-counterfeiting tool. For the purposes of this study, the patents that had diverging sets of in-text citations used the citations that were more specific to the solar PV field for the summary of in-text citations.

It is interesting to compare the summaries of technical improvement that are reflective of the orignal inventor with the summaries of the in-text citations that are indicitive of the acknowledged contributions of the patents. Of the 9 patents that were cited in-text, six show a nearly verbatim correlation between the technical improvement as stated at the time of invention and the future in-text citations. Patent number 5350644 (E) shows an example where the technical improvement is the addition of a dye to the titanium dioxide film that is used in solar cells to help absorb light in the visible spectrum, which is consistent with the citations that refer to the use of dye sensitized titanium dioxide cells in order to increase efficiency. The remaining three patents (4775425 (H), 4309225(I), 4234352(K)) also have consistency between claims and citations, but require a deeper reading to discover the relationship. For example, 4309225 (I) is cited in text about the laser annealing of a semiconductor film, which is a clear indicator of a solid state transition (not melting or phase change) that is mentioned in the original patent as an improvement over the prior art.

6.4 Reliance on Scientific Literature

In addition to the detailed analysis of 12 of the 'very important' patents in solar PV, it is useful to look at a broader comparison of important patents to a more general selection of patents in order to examine how important inventions differ from the rest. Besides being cited more frequently than the other inventions, the 'very important' patents can differ from or be similar to other sets of patents in interesting ways. This study will compare the three patent sub-sets of varying importance across three categories of differences: the reliance of patents on basic scientific research, the variety of fields from which patents draw information and other comparisons between highly cited and moderately cited patents

The comparison of the reliance on scientific research for important and non-important patents was analyzed through examination of the citations of the different subsets of patents. Patents not only cite other patents but also cite non patent literature (NPL), which in almost all cases is basic scientific literature. For instance, patent number 6441298 cites 50 other patents and has 6 citations of non-patent literature, all of which are scientific journal articles. In particular, patent 6441298 cites articles such as "Theory of Diffraction by Small Holes" (Beth, 1944) in *Physical Review* and "Extraordinary optical transmission through sub-wavelength hole arrays" (Ebbesen et al., 1998) in *Nature.* We infer that a patent with more NPL citations is more likely to be based on pure science as compared to patents that have fewer NPL citations. This inference has previously been made by Trajtenberg et al(1997).

The first four columns of Table 6 show the analysis of NPL citaitons for the 12 important patents that were analyzed in depth in the preceding section. The important patents on average have a 16% NPL citation rate.

Table 6: Comparison between the NPL citations of the three sub-sets of patents with outliers removed

Very Important	Backward Citations	NPL Citations	NPL Ratio	Mod Important	Backward Citations	NPL Citations	NPL Ratio	Least Important	Backward Citations	NPL Citations	NPL Ratio
6441298	41	6	15%	6924164	179	3	2%	6700057	8	1	13%
6878871	52	2	4%	6936761	24	2	8%	6472296	3	0	0%
6340788	14	5	36%	6531653	8	0	0%	6452090	6	1	17%
5747967	8	0	0%	5391236	6	0	0%	5479043	10	6	60%
5350644	9	5	56%	6118572	4	0	0%	5458695	4	0	0%
5092939	6	0	0%	5821597	16	5	31%	5401331	10	6	60%
4698234	0	0	0%	4612409	9	1	11%	4707561	6	0	0%
4775425	6	2	33%	5019177	8	0	0%	4412091	1	0	0%
4309225	11	0	0%	4658086	4	0	0%	4348545	2	0	0%
4021323	8	2	25%	4177083	5	0	0%	4228315	13	5	38%
4234352	7	4	57%	4254546	3	0	0%	4188239	2	1	50%
4281208	8	1	13%	3982265	12	4	33%	4156310	4	0	0%
Average	14.17	2.25	16%	Average	23.17	1.25	5%	Average	5.75	1.67	29%

Table 6 also shows the results of the NPL analysis of the 'moderately important' patents and the 'least important' patents. The three different samples vary between an average of 5% NPL citations and 29% of citations to the scientific literature. In order to determine if the three sets of data are statistically different, a Single Factor ANOVA tests was run on the three sets of NPL citation ratios. The P-value of the ANOVA test was .226, much higher than the P-value of .05 that would be required to indicate with 95% confidence that the 3 sets of data are statistically different. Although the ratios vary, the three samples are **not** statistically significantly different, suggesting that important patents do not rely more on NPL or scientific findings than patents of moderate or low importance.

6.4 Intra vs Inter Field Citations

Another analysis possible from the backward citations of patents is to identify the patent categories that the citing patents built upon for their inventions. This is possible because each patent is required to have a category, which can be used as a proxy for a technical field. Examples of these categories range from 'Structures' to 'Batteries, Thermoelectric and Photoelectric'. A purality of the patents in the overall list of 2484 were classified in the 'Batteries, Thermoelectric and Photoelectric', as the field we are studying is solar photovoltaics. The primary patent classes of the citations of the important patents were analyzed in order to understand which fields impacted these important patents. Table 7 shows the distribution of the 20 most highly cited fields by the overall set of 2500 patents. In order to achieve a more accurate representation of the cited fields, a larger sample size was used to represent the important patents in this comparison. The final column in Table 7 shows the distribution of those same 20 fields within the patents cited by only the top 250 patents.

The most cited field for both the 250 important patents and the overall set was 'Batteries: thermoelectric and photoelectric', the same field in which most of the patents are classified. It is interesting to note that the 250 important patents cite the 'Batteries…' class at a rate 2 times that of the full list of patents. Beyond this, the top 4 most cited classes are the same for the overall set of patents and the 250 important patents. When the complete lists of citation rate by class are compared using a t-test, the results show that the two distributions are not significantly different, with a P-value of 0.9, very far from the P-value of 0.05 needed to claim significantly different distributions with 95% confidence.

Table 7: Comparison of top 10 most highly cited patent classes between the overall set of 2484 patents and the 250 most highly cited patents

Patent Class Name	All 2484 Patents	Top 250 Patents
Batteries: thermoelectric and photoelectric	11%	20%
Semiconductor device manufacturing: process	5%	6%
Radiant energy	4%	6%
Active solid-state devices (e.g., transistors, solid-state diodes)	4%	5%
Stoves and furnaces	3%	1%
Communications: electrical	3%	2%
Illumination	2%	1%
Optical: systems and elements	2%	4%
Electricity: battery or capacitor charging or discharging	2%	1%
Stock material or miscellaneous articles	2%	1%

6.5 Other Differences between Important and Less Important Patents

In addition to these initial tests, a battery of tests was performed comparing important patents to other sets within the data. The actual text of the patents were parsed and analyzed in an attempt to better understand the make-up of the important patents as compared to the moderately important set. Table 4 shows the difference in length of abstract (in number of characters) between the important and moderately important patents and found that the less important patents actually have slightly longer abstract lengths than the important Type 1 patents. This difference is potentially statistically significant, with a P-value of 0.08. Ultimately the data does not establish that more important inventions having longer or shorter abstracts.

Another test involved searching through the text of the patents and counting the number of different embodiments of inventions in each patent. Table 8 shows the comparison between the embodiment counts of the important and less important patents. The two data sets are not statistically different, with a P-value of .13. There is not evidence in this study that more important patents have a different number of embodiments of invention than other patents.

Finally, the length of the text in the prior art sections was compared, showing no significant difference, with a P-value of 0.14. The data does not indicate that the more important patents have a significantly shorter or longer description of prior inventions. Table 8 shows a summary of the other tests performed on the important and moderately important patents.

Table 8: Other comparisons between the 3 sub-sets of patents

Very Important	Abstract Length	Embodiment Counts	Prior Art Lengths	Less important	Abstract Length	Embodiment Counts	Prior Art Lengths
6441298	723	0	2705	6924164	663	6	5285
6878871	743	38	2878	6936761	906	3	6395
6340788	461	11	6071	6531653	835	1	6724
5747967	723	0	6834	5391236	732	1	2025
5350644	395	0	2001	6118572	870	2	4795
5092939	883	3	2533	5821597	1016	0	7524
4698234	452	0	87442	4612409	449	0	4290
4775425	298	7	21798	5019177	491	0	9747
4309225	224	0	5148	4658086	578	1	4171
4021323	552	0	N/A	4177083	464	0	1155
4234352	759	1	3241	4254546	458	0	4098
4281208	668	2	6341	3982265	895	1	1495
Average	573.4	5.2	13362	Average	696.4	1.3	4808

6.6 Summary of Results

This chapter analyzed the differences between the most important and the less important inventions so as to understand more about how the more important technical inventions are created. The most important inventions tend to be cited for what they are attempting to fix in their own problem statement, not pointing to the notion of the randomly created breakthrough invention. The important patents come in a variety of technological hierarchies, inventions involving system level changes and small detail changes can both can have a large technical benefit for a field. The important inventions also don't tend to cite basic scientific journals more than their less important counterparts, leading us to believe that all inventions are grounded in fundamental science. Finally, the important inventions tend to cite more within their field than the less important inventions, but only at rate of 20%, meaning that most inventions do draw knowledge from other fields, but the important inventions draw twice as much from their own field than the average of 10% from all inventions studied.

Chapter 7

Industry Evolution Over Time

This chapter discusses how the focus of an industry can change over time and simultaneously how it can stay consistent. Previous chapters have discussed how the technological capability of a basic function underlying an industry follows a reasonably continuous exponential growth curve, even while devices and even whole industries undergo upheavals . Next we seek to understand if a particular industry may change its focus as the technology or devices change drastically. In particular, we are interested in the solar PV case to see if the patenting patterns change as new technologies such as thin film solar PV are introduced.

7.1 Overall Industry Citation Patterns

Overall, nearly 25000 patents were cited by this group of 2484 solar PV patents, and the distribution of the classes of the cited patents is shown in Figure 6. The comparison between the sample set of 2484 patents and the approximately 25000 cited patents show that there is complete overlap between the two sample sets in terms of the most represented patent classes. The top five most prevalent patent classes are the same in both the set of 2484 studied patents and the set of nearly 25000 patents that were cited by the sample set, it is not until the 6th most prevalent patent class that a difference occurs, with the 6th ranked class for the sample set of 2484 being 'Communications: electrical' and 'Optical: systems and elements' for the cited set of ~25000.

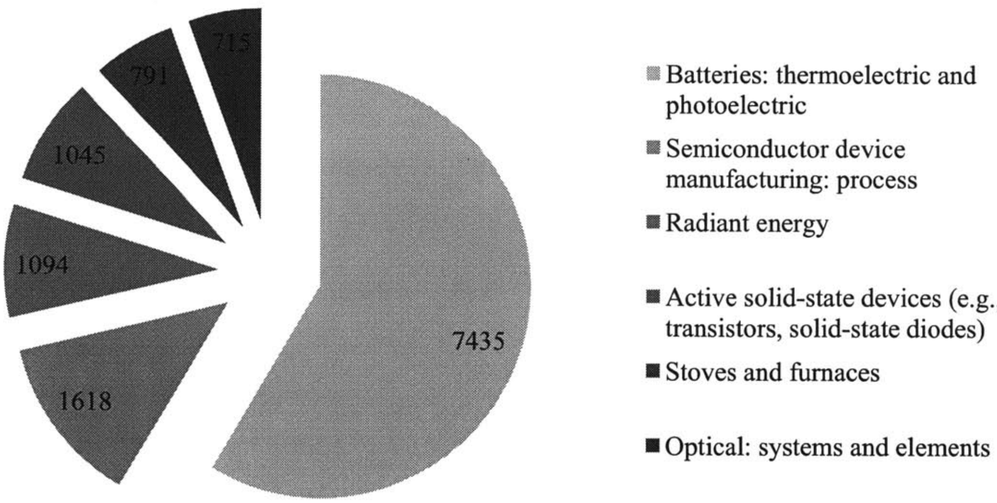

Figure 6: Top 6 most frequent patent classes of ~25000 patents cited by the sample set of 2484

In addition the breakdown of the most cited classes in an industry, it is interesting to examine how the trends of the industry have changed over time. Figure 7 show the number of patents cited by the set of 2484 solar PV patents sorted by the 5 most prevalent patent class and by decade. When this set of ~25000 patents that were cited by the solar PV patents is sorted this way, it shows which ideas the solar PV industry built off of during each decade. The data is very noisy when it moves from year to year, but when it is smoothed out over time it gives a reasonably clear picture about the technical trends of the industry. Please note that the data point for the decade lies on the initial year, so that the average of the decade including the years 2000-2010 lies solely on the 2000 data point. Figure 7 only shows the five most cited patent classes, which account for almost 50% of the citations. Including all categories precludes clear visualization of the changes over time. Figure 7 shows that the *Stoves and Furnaces* class is most cited in the early years and tapers off, and that all of the other classes tend to trend higher over time before dropping at the end, presumably due to the lack of recent citations due to the truncation effect mentioned previously.

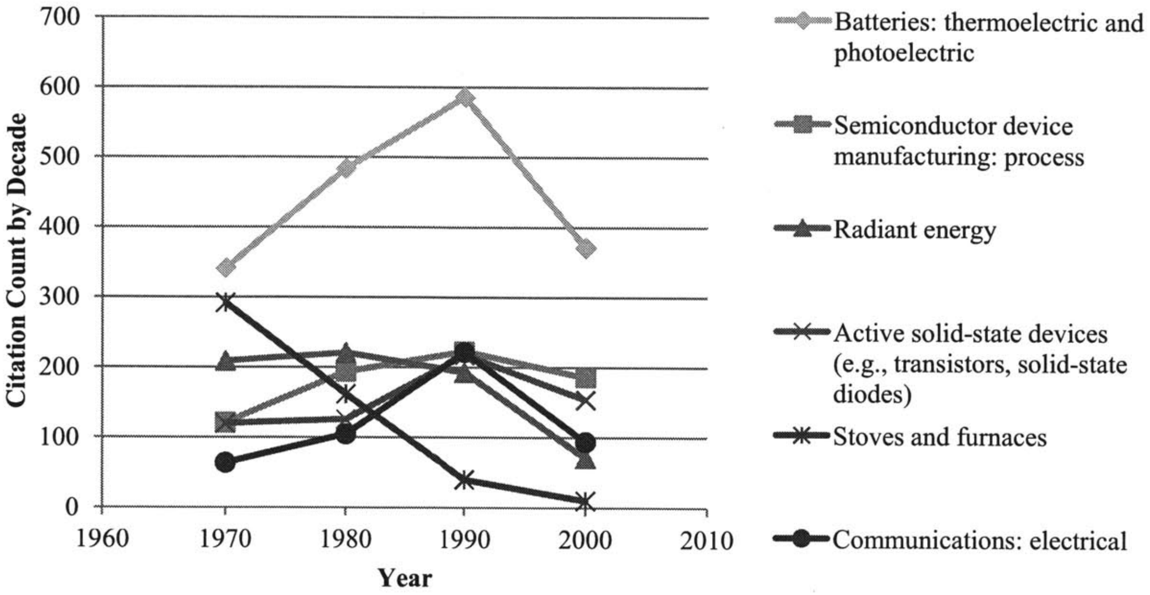

Figure 7: Number of cited patent classes per decade, sorted by the most cited classes

With one exception, the distribution of cited patent areas stays relatively consistent over time. This is interesting to note, as the industry has changed considerably from the 1970s till the 2000s moving from an advanced research project to a power source for the masses that is looking to compete with traditional energy sources such as natural gas and coal. During such a massive change in an industry it would seem to make sense for the early years to cite more in the theory-based patent classes such as 'Batteries' and 'Active Solid-State Devices', and the later years to cite more in the practical classes such as 'Semiconductor manufacturing process', but this is not the case. Instead, the patents for the industry consistently cite in both the research and manufacturing fields through the entire development of the technology.

7.2 Time Dependent Citation Patterns

While the majority of the field is consistently cited over time, there is one exception in the 'Stoves and Furnaces' patent class. The stoves and furnaces patent class is the 5th most cited class by the sample set, but the majority of the citations for the class come in the first two decades and trails off considerable in the 1990s and 2000s. This particular example seems like an outlier in the data set, but its lack of congruity with the rest of the information leaves some room for an exploration of explanations. This section will explore a possibility of why the 'Stoves and Furnaces' patent class shows a non-consistent citation pattern in the development of the field of solar PV.

A potential reason for the drop off in the citation of the 'Stoves and Furnaces' patent class is that in the beginning of the solar PV industry solar energy was associated with thermal energy, which would make the citing of solar thermal devices appropriate. Solar thermal energy gathering is considerably older than solar PV energy gathering, therefore it would be logical to assume that when the solar PV technology was first being developed, it would cite more heavily with the prior art in the solar energy collection space. Within the major patent class of 'Stoves and Furnaces' one of the major subclasses is 'Solar Heat Collector'. This reference to solar thermal energy indicates that the solar PV field was more closely linked with the solar thermal field in the early days of the industry, but as the fields developed further, they started to become more clearly separated. As PV technology developed into its own distinct industry, it became very clear that the two technical fields, while related in raw energy input, were very distinct in their uses and capabilities, thus leading to separate fields.

One potential flaw in this reasoning is that as the solar PV market moved more into the mass market with consumer applications, their began to be a gradual increase over time in the activity around developing photovoltaic/thermal hybrid (PVT) solar systems (Chow, 2009). Solar PVT energy collectors have increased as a topic of research over the last two decades and therefore more citations of thermal solar in the 'Stoves and Furnaces' field could be apparent in recent years. This is not the case, and there were significantly less citations of the 'Stoves and Furnaces' field in recent years than in the past, leaving this particular outlier as a potential area for future research.

7.3 Summary of Results

Our evidence does not show that a particular Industry (in this case solar PV) will change the focus of it patent citations over time. We analyzed the number of patents in each class by year in the solar PV field and found that the proportion of specific classes in the solar PV field does not change year over year. This is to say that they don't focus on one particular aspect of a technology at one time and the industry changes to another aspect at another time. For example, the solar PV industry might be conjectured to focus on the active solid-state device part of the technology early on, then shift to semiconductor manufacturing, and conclude with static structures on which to mount the solar arrays. Our data shows that all of the aspects of this technology tend to develop consistently across time except for the 'Stoves and Furnaces' class, which can be linked to solar thermal energy. The reasoning for the time dependency of the solar thermal related class has yet to be fully explained and is an area that needs further investigation.

Chapter 8

Policy Applications

A theory of technological innovation has been presented thus far along with several conclusions. This Chapter will explore how this theory can inform policy applications in government, universities and other organizations. In addition, a review of several innovation-oriented programs will shed light on how the lessons learned from this theory could be applied directly to programs in the near and long term future.

8.1 Innovation as a Driving Factor in Economic Development

The currency of the 21st century is innovation. In order to remain competitive, a country or an organization needs to be economically vibrant, and much of this comes through the development and exploitation of new technologies. There has been much said about why this is important, with some of the most notable work being discussed in Section 2. This section will use some of the observations about the technological development of one particular field to discuss a modified way of thinking about innovation and how to create high impact technologies.

There are many examples in the literature about incenting innovation that are looking in particular for 'breakthroughs', this work suggests that instead of looking for a 'silver bullet' to invest in a range of approaches that can all have potential to result in high value inventions. . One potential path is to create a fertile environment full of many high impact inventions across many different aspects of an individual field. Once this happens, the overall field should continue to develop rapidly until it hits a certain tipping point in which it becomes useful to a broad range of people. This is a different approach from attempting to create a disruptive invention from within the lab. Instead of aiming to get a to a certain unknown point, ensure that many aspects of the field are all developing at a rapid pace, even though one may not be aiming towards a particular disruptive invention, that end result may come faster if the goal is to develop high quality inventions in an important field (such as solar PVs).

This brings us to the question of how to develop very important inventions and technologies? It is unfortunate that the answer to that question remains a mystery and may perhaps always be one step ahead, as the future is inherently unpredictable due to the infinitely large and unconstrained world that real world technologies are developed in.

8.2 Policy Considerations for Spurring Innovation

We did not see a trend towards a specific time dependence of the technological hierarchy in the most important patents. This means that if one is looking to develop technically important inventions in order to create actually useful breakthrough products, then one should work to develop technologies across all levels of technical hierarchies – invest both in the small details and the system phenomenon changes. This is different than many people have considered before – because it may appear logical to believe that technologies that rely on a new scientific phenomenon are more likely to change the landscape, but this idea is not supported by development in the solar PV field.

The next idea is to look at the reliance of the important inventions on basic scientific literature. Solar PV development showed that the more important inventions actually did not rely more on basic scientific literature than average. If we make the logical connection that much of basic research that is published in Journals is related to university research (World Intellectual Property Organization, 2005) it is important to maintain research in both the Academic settings and through investing in commercial research in order to incent more important innovations.

Our analysis of the solar PV industry points to the fact that inventions are typically cited for what they claim they are solving in their background statements. This indicates that contrary to some ideas, it does not seem to be the case that Inventors 'stumble' randomly upon very important solutions. The policy implications of this lead us to believe that if you are looking to incent important inventions you should find the very specific 'pain points' that need to be addressed to advance the technology. This means specific things such as creating a more receptive passivation layer and not a goal as broad as 'increase the efficiency of solar PV cells'. Therefore it is important to define exceptionally clear goals for the development of a particular technology. This may seem in contrast with some of the earlier recommendations that argue that it is important to incent many great inventions as there does not seem to be any technologies that are discontinuously important, therefore it is important to define many specific improvements across a wide variety of aspects of a particular technology.

One particular example of recent note of a 'breakthrough' that has not proven to be as impactful as hoped is the Solyndra solar cell. This was supposed to be a 'breakthrough' technology that could utilize cylindrical solar cells in order to create cells without the use of silicon, thus making them significantly less expensive and easier to produce and install on rooftops (Martin, 2011). In this particular example the goal was to place a large 'bet' on one invention proving to be the key to the future of solar PV. Using the methodology described above, the strategy would be to invest in this company and many others – across many other fields to spur the creation of a large group of technically important inventions in order to create a fertile environment for the creation of a socially important product, what many would call a 'breakthrough' technology.

8.2.1 Top-Down Policy Measures

Policies for developing new technologies for large organizations such as a the United States Air Force (USAF) are often decided and managed by top ranking officials (Fino, 2010). These large systems often have large entry costs and it can be difficult to contain the benefits of innovation without the high-level control associated with 'top-down' approaches. This is largely consistent with the policy recommendations above – as it is clear that socially valuable innovations come from the accumulation of many important inventions across all fields of technology. Additionally, many of the cumulative effects of these important inventions are only entirely captured at the system level, as they inherently create many side benefits such as spillover technologies and workforce training. The top down approach has the benefit of viewing things as "system of interconnected intuitions to create, store, and transfer the knowledge, skills and artifacts that define new technologies'. It is the ability to work at a system level and coordinate resources and capture the value that makes the top down approach to innovation policy effective.

One potential drawback of top-down policy measures is that the high level officials making the decisions of which technological paths to pursue are not often personally well versed in the specific technical intricacies of the individual projects, which can lead to improper selection of technical priorities, and example of this occurring in the USAF is presented in section 8.3.4. It is therefore important for the top-level policy makers to set a research agenda for particular *areas* of interest, but leave some leeway for the technical experts to select the most appropriate individual projects to pursue.

8.2.2 Grassroots Movements

Looking at innovation from a different point of view, there have been many grass-roots organizations that have made significant advancements in the way that technology is developed (Methe et al, 1997). The organizations that pursue technological development from a bottom-up approach tend to be smaller and have the added advantage of flexibility that can sometimes plague the large scale top-level led initiatives and organizations. Examples of organizations that are attempting to change the way that technologies are developed are the incubators and co-working spaces that have sprouted up in major cities in the last few years (Chen, 2011). These new businesses are trying to use new tools make it possible to create entirely new disruptive products with very few resources.

One new tool that has been used in both small and large organizations is user-led innovation. User-led innovation helps alleviate the problem of inflexibility and lack of technology-market fit that can lead to the creation a technology that is not helpful to the end user. An example of this is the Air Force allowing units to retrofit their aircraft with machine guns in the Vietnam war when they were only originally designed to be equipped with missiles (Fino, 2010). These lessons demonstrate that it is important to keep the end user in mind and to work with a degree of flexibility while creating technological development strategies.

8.3 A review of Innovation Systems

Ultimately it will require a mixture of top down and bottom up approaches to enable organizations to keep up with the pace of innovation. This section will provide a review of real world innovation and technological development systems and policies that span from small start-up companies to large governmental organizations. Through this, we are attempting to more clearly explore how these lessons can be applied across a multitude of organizations with varying goals, resources, and sizes.

8.3.1 Technology and Company Incubators and Accelerators

In the last several years, there has been a resurgence of technology incubators and accelerators that have popped up all around the United States and the world. The idea behind a technology incubator is that they provide the resources and advice for very early stage companies so that they can survive the tough early days of the creation of a business when they are the most vulnerable (Aernoudt, 2004). These technology incubators have popped up lately to help out younger and younger startups with less capital than ever before. There have been some great successes that have come out of incubators in recent years. One prime example is the company DropBox, which was founded by an MIT graduate and incubated in the Y-Combinator program. The company took on a technically difficult problem, and solved a societal important need.

The interesting part about many of the technology incubators is that they don't rely very heavily on cutting edge scientific discoveries. They instead fulfill the prediction of Clay Christensen (1997) when he mentions that disruptive products are often built using technologically straightforward or off-the-shelf components. This is shown dramatically in the incubator settings as off the shelf components or coding languages are used in new ways to create successful products and businesses. These incubators, like our model suggests, do rely on the development of the underlying technologies, however. Tools such as increases in battery storage, computing power, data transfer rates, and manufacturing techniques enable these incubators to put relatively small amounts of capital into new ventures that can take advantage of the capabilities offered by the underlying technological development and create useful novel products. The lesson learned from this new breed of incubators is that world changing products can and do come from relatively small teams with small amounts of capital that take advantage of a useful network and the capabilities afforded by the development of the core technological competencies.

8.3.2 University Technological Development

Universities have long been a place where technologies have been developed, and MIT has been a leader in this for many years. Through basic scientific research, high end academic teaching, a focus on practical problem solving and other activities, the alumni of the university have created companies that employ 3.3 million people, and generate approximately $2 trillion worth of sales every year (Roberts, 2009). In this section, we will not focus on the basic scientific research, but will explore the options for technologies to become businesses through association with the institution.

There are countless organizations within MIT that aim to encourage entrepreneurship and in doing so encourage the creation of products of societal importance from technically important inventions. These organizations include the Trust Center for MIT Entrepreneurship, the Deshpande Center for Technological Innovation and many others including a range of student clubs and organizations that have popped up to encourage innovation and entrepreneurship. Figure 8 shows some of the organizations at MIT on their orientation of either grassroots (bottom up) or administration run (top down) and how much they place emphasis on theory vs practice of innovation.

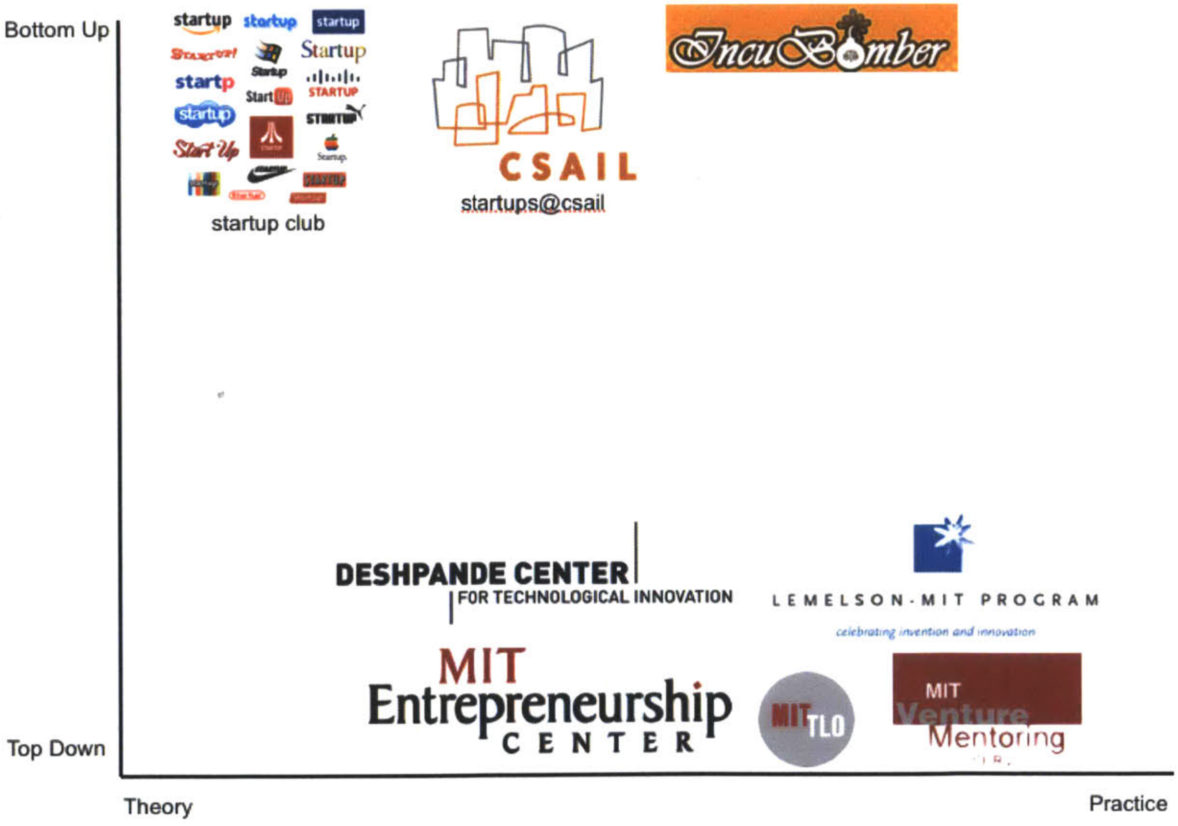

Figure 8: Summary of Entrepreneurial Organizations within MIT

The first thing to note about Figure 8 is that the MIT ecosystem does a great job of providing a spectrum of opportunities along the theory/practice spectrum, or what we call Mens/Manus at MIT. This has created an effective ecosystem for people to both learn and do things regarding developing new innovations. Figure 8 also shows that there are many organizations at both ends of the organizational direction spectrum – that either pop up due to students creating it themselves or because a wealthy alumni donated money to ensure a program occurs. One interesting observation that can be made from this chart is that there are relatively few organizations that lie in the middle, that pair the drive and cultural understanding of the students with the resources and bigger picture view of the administration or alumni. This may represent an important gap in the overall effectiveness of the system.

A similar review of entrepreneurial organizations was performed at Stanford University, who has also been a leader in entrepreneurial impact in the world. Figure 9 shows what their entrepreneurial ecosystem looks like from the author's perspective after a week-long visit of the entrepreneurial organizations of Stanford University.

Figure 9: Summary of entrepreneurial organizations at Stanford University

Using this admittedly limited view of Stanford's ecosystem, Stanford apparently has a different approach to that at MIT, with many organizations that are student driven and administration supported, providing them a significantly different ecosystem than the one at MIT. Stanford also places a larger emphasis on creating things than MIT. Stanford has managed to create a vibrant ecosystem that creates many businesses every year. The lesson learned from the comparison between

MIT and Stanford is that it is important to have a mix of lower-level engagement and upper-level support for an initiative. In this particular example, it is important to involve the students, who will be the end users, in the decisions made by the upper level administrators, who have the resources to direct the entrepreneurial direction of the universities.

8.3.3 The StartLabs Experiment

Throughout the course of this research, the author decided to experiment by creating an organization that would be separate from MIT and would be both student driven and administration backed. StartLabs was founded by a group of four students who were interested in the entrepreneurial activities at MIT, and through a series of meetings and proposals became supported by several departments and the chancellor of the university, who provided strategic guidance, administrative support and fundraising connections for the organization. The organization is an experiment in understanding how young and technically competent teams can create valuable new products and companies. Additionally, it is interesting to see how this quasi-independent organization fits in with the rest of the entrepreneurial ecosystem at MIT. This organization's goal is to 'Create the next generation of technical entrepreneurs' and does so by encouraging students to drive the organization, with guidance from faculty, and support from the administration. Figure 10 shows the updated MIT entrepreneurial ecosystem with StartLabs included.

Figure 10: Updated map of MIT entrepreneurial ecosystem to include StartLabs

In the first year, StartLabs attracted over 200 students to its networking event, and 31 teams applied to form companies over the Independent Activities Period (IAP). Of the 31 teams that applied, 7 teams were accepted and formed companies in the 24 day period of the Concept to Company program run by StartLabs. At the end of this program, 100% of the participants said they would recommend the program to a friend. This preliminary information shows that the students were very receptive to the idea and the organization. This could have been caused by the fact that the program was also run by other students, and simply supported by industry, faculty and the administration. This unique blend proved especially convincing to those in the entrepreneurial community who were interested in seeing young, talented minds create new visions for the future.

The Concept to Company program had a wide variety of companies and people. The program included 4 web-based companies and 3 hardware companies, along with a diverse group of people ranging from freshman to PhD to alumni of the university. The technical difficulty of the domains represented by the companies also varied considerably, from a social network to a miniaturized mass spectrometer. Despite the wide range, all of the companies successfully completed the program and are moving forward, providing preliminary agreement with the idea that the technical importance of an invention is not necessarily tied with the social importance of a resulting product or service, but that the technical development does enable the entrepreneur to create the useful products. This was demonstrated very clearly in the concept to company program. The main lesson learned by the StartLabs experiment is that a link between the grassroots and top-down movements can be created and that it is helpful in creating an innovation friendly environment.

8.3.4 Military Technology and Development

The military is an example of a large organization where many technologies are developed and put to use with customers. Like other large organizations, the products that the military develops are designed for specific customers within the organization and are not as focused on creating new companies or wealth for the country. The military is also an interesting case study because they have been at the cutting edge of technology for hundreds of years, moving from muskets to F-22s over that duration. Despite their overall goals, the military has created many technologies that have greatly impacted society and have played an important role in developing America into the technical position it occupies today (Smith, 1985).

It is interesting to note, however, that the military is not always supportive of new technologies that are being developed and are sometimes supportive of new technologies that are not appropriate for use by the ground level warfighters (Fino, 2010). This can come from a mismatch in expectations between the bottom up and the top down approaches to the development of new technologies. Because the Air Force is segmented into many different arms, the technologies developed are sometimes not useful to the warfighter. At the same time, some technological solutions are simply scraped together to solve a problem by the ground level warfighter. Stephen Fino (2010) mentions an example of this when the Air Force decided to equip the pilots in Vietnam with aircraft only outfitted with missiles, as they were sure that missiles were going to be the future of air combat. This decision caused problems within the flying forces as their tactics were limited without the use of a gun on board the aircraft. In an example of user innovation, the flying units mounted other guns to their aircraft in a non-intended way. The result was a much more effective aircraft for the flying force, which soon caused units all across the air force to rig their planes up with mounted guns. This particular example shows that it is important to understand and match the top-down and bottom-up approaches so as to allow for the core technologies to be developed into useful products.

The Air Force is attempting new innovation strategies with these new ideas in mind. They have set up a new laboratory called the Center for Rapid Product Development (CRPD) outside of the Air Force Research Labs in Dayton, Ohio. This new center is bringing in smaller teams that have significant technical expertise and working with known problems from ground level warfighters to create exceptionally useful products while utilizing the core capabilities of the advanced underlying technologies. This brief case study of the USAF shows once again the importance of tying the top-down development of the underlying technologies with the grassroots development of socially useful products.

8.4 Summary of Recommendations

This chapter described lessons learned from several different large and small-scale organizations about how to develop technical capabilities and socially important inventions. These lessons include, using a top-down approach for the core fundamental technological goals – that invest a significant amount of money into flexible technological bases that can be easily adapted. Eliminate barriers for small grass-roots organizations to take advantage of these flexible technologies and adapt them to their particular needs. Finally, create a network between those who develop the long term important technically important inventions and those who can and will work to use those technical inventions to create socially important innovations.

Chapter 9

Conclusion

This chapter will explain the main points that should be take from this thesis. The goal is that the points will be concise and actionable and that the thesis should provide the additional depth for exploring any of these points further. Recommendations for additional work will also be presented, as the research in the technical aspects of technological innovation is in its earliest stages.

9.1 Summary of New Insights into Technological Development

The conclusions that can be drawn from this paper can be summarized in three points, two that are theory based, and one that is aimed at influencing policy.

The most important conclusion of this thesis is that there are no inventions of discontinuous technical importance. Another way of putting this is that there are not technical breakthroughs. This is a departure from some previous notions, which may have come about due to the confusion of technical and societal importance. Ultimately the development of the core technical capabilities comes from an additive effort of many inventions of varying importance, but none that cause the change alone.

The second takeaway from this research is that the most important inventions are not generally different from the less important inventions in many ways. The important inventions do not rely more on scientific literature, negating the idea that more important technical improvements come from more academic science. The important inventions also come in a wide variety of technical hierarchies, which would not point to the idea that more important technical contributions come from a change in the basic science or fundamental principles upon which the devices relies. Finally, they also tend to be cited for the problem they intended to solve, disagreeing with the notion of the 'lucky' inventor.

The final conclusion comes in the form of a policy recommendation for organizations and claims that the mixture of top-level support combined with end user engagement within innovation policies will create a fertile ground for innovation. The reasoning behind this is because the high ranking officials are able use their large resources and can capture the externalities of a large group of inventions that when combined will ultimately improve the technical capabilities of a field that provide the driving force for new innovations. The bottom-up approach tends to be more effective in taking advantage of new technical capabilities in novel and creative ways due to their flexibility and lack of reliance on the status quo, and will ultimately be the ones who can create the next set of societally important innovations.

The combination of these conclusions explains effective innovation systems by noting that despite the distinct separation of the inventor and the entrepreneur, they are at the same time entirely dependent on each other for inventing the future.

9.2 Future Work

While this research provides a good starting point, there is still a significant amount of work to be done in understanding how the inventions contribute to the increases in the overall technical capability of a field. This thesis is a first approximation, using already known techniques of defining importance and relationships between inventions. In the future, it would be useful to dive deeper into understanding how to measure technical importance more accurately in a repeatable manner while still providing useful results.

Another aspect that could be further developed is understanding of the diference between important inventions and less important ones. In this thesis we found many results to show that they were not different, which, while interesting, could be significantly aided by more clear differentiated factors between the two.

Finally, the work that was started with the StartLabs experiment should be continued to see if an organization that is grassroots driven, midlevel guided, and top-level supported can be an effective way to innovate. As this experiment expands, it will also provide more insight into how the new technological capabilities can enable younger and less experienced founders of companies to create the next great products and services.

9.3 Final Remarks

While this thesis is an important milestone for my academic career, and the academic research is interesting and important, much of the work in this field must be done by actually going out and trying to innovate. The work of inventing the future will not be done solely in the mind, but in a match between the theory and practice. The next phase of this research will involve even more empirical evidence of how the next generation of technologies and entrepreneurs will change the world.

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