From Smart Grids to the Internet of Energy

An Investigation into the Disruptive Capacity of the Smart Grid

Scott Weiler

A Major Paper submitted to the Faculty of Environmental Studies to fulfill the requirements for the Master in Environmental Studies,
York University Ontario, Canada.

Student's Signature

Supervisor's Signature

Acknowledgments

I would like to thank my wife for her enduring support of my academic endeavors that began over a decade ago. Without her support I would not have been able to return to school. I also need to thank my children who I am really looking forward to spending more time with now that I have completed my studies. Nicholas and Chloe, 6 and 3, only know me as an FES student since they were both born during my time at York. Nicholas is looking forward to my career as an "inventor". I also need to thank all the grandparents who have provided babysitting and proofreading support on numerous occasions.

I would like to thank my Supervisor, Mark Winfield for his guidance and endless patience. His *Energy and the Environment* undergraduate course inspired me to focus my research on sustainable energy. I would like to thank my Advisor, José Etcheverry. His enthusiasm for renewable energy is contagious. I would also like to thank Peter Love for energizing me about energy conservation. Finally, I would like to thank the Social Sciences and Humanities Research Council of Canada and everyone who helped with my application for this scholarship; Gail Fraser, Arlene Gould, and Mark Winfield. Without the financial support from SSHRC it would not have been possible to pursue my master's degree.

I have really enjoyed my time at York and completing my studies is bittersweet. Completing a Master's degree, as well as being awarded the SSHRC scholarship is great source of pride, particularly for someone who has struggled with learning challenges in the past. I am truly grateful to all those who have provided family, financial, and academic support for this achievement.

Abstract

Globally, electricity systems are undergoing rapid modernization as they transition into the digital era of the '*Smart Grid*'. By integrating information and communication technology with the electricity grid, the smart grid will become a highly automated network with two-way flows of electricity and information. This research questions whether the smart grid will be an *evolutionary* technology that enhances grid operations, but maintains the existing institutional order, or will the smart grid be a *revolutionary* technology that disrupts the natural monopoly of electricity utilities. This research also explores the potential for the smart grid to cause a broader transformation in energy systems that will bring about a sustainable energy transition.

Foreword

This Major Research Paper satisfies the learning objectives outlined in my Plan of Study and Major Research Proposal. It also encompasses many of my learning interests from both my undergraduate and graduate studies in the Faculty of Environmental Studies. These interests have coalesced around climate change and energy policy. The goal of this research was to understand how to bring about a sustainable energy transition.

My research set out to understand the impact that the smart grid may have on energy systems. Intuitively the smart grid appears to have many similarities to the Internet. The Internet is understood to be a highly disruptive technology. This research explores these similarities and questions whether the introduction of Internet technology to the electricity system will have disruptive impact on energy institutions, similar to what occurred in the telecommunications industry.

Furthermore, this research questions whether the smart grid could be a catalyst for a sustainable energy transition. My studies have shown that renewable energy technologies have great potential to supply our energy needs. Yet we seem to be locked into using fossil-fuels when it is increasingly clear that they are having a significant impact on our environment.

Despite the apparent resistance to change, energy transitions have occurred in the past and will undoubtedly occur in the future. This research explores the history of energy transitions to understand the processes that drive disruption and innovation. Complexity science is used to provide a framework for understanding the process of institutional lock-in and disruptive innovation.

Table of Contents

1. Introduction

Globally, electricity systems are undergoing rapid modernization as they transition into the digital era of the '*Smart Grid*'. This modernization will see the electricity grid *evolve* from a servo-mechanical, paper driven system, to a modern, highly automated network that incorporates sensors, monitoring, and communications to improve the flexibility, security, efficiency, and reliability of the grid.[1] The smart grid will enhance every facet of the electricity delivery system, including generation, transmission, distribution and consumption; it will energize utility initiatives that encourage consumers to modify patterns of electricity use; it will empower consumers to become active participants in their energy choices; and it will offer two-way visibility and control over the electricity system.[2] The smart grid will include central and distributed generation connected through transmission and distribution networks with the expectation that there will be many more points of generation such as micro-hydro-electric, bio-energy as well as wind and solar generation. The addition of these new elements will require new communication and control systems that are capable of managing two-way flows of electricity and information.[3] This modernization will provide a powerful tool for utilities and system regulators to monitor and manage an increasingly complex grid and also enable a transition to a low-carbon energy system.

Some argue that the smart grid is something much bigger than simply a new electricity system management tool. Through the convergence of information communication technologies (ICT) and distributed energy technologies, grid modernization may bring about a *revolutionary* shift in how energy is created and shared. Information and communication technologies are recognized to be disruptive innovations that are transforming the information landscape from centralized and closed to distributed

[1] IESO. (2009). *Enabling Tomorrow's Electricity System: Report of the Ontario Smart Grid Forum*. Independent Electricity System Operator. P 1.
[2] U.S. DOE. (2008). *The Smart Grid: An Introduction*. Litos Strategic Communication. Prepared for the U.S. DOE.
[3] Sood et al. (2009). *Developing a communication infrastructure for the smart grid*. IEEE. Electrical Power & Energy Conference..

and open, and driving profound social and economic changes.[4] By integrating ICTs with the electricity grid, the smart grid may be the frontier for a paradigm shift that will transform the energy landscape and disrupt the natural monopoly of power utilities.[5] In essence, this convergence may be laying the foundation for an *Internet of Energy*[6] that would see the 20th century grid, dominated by large centralized utilities, replaced with a 21st century network of independently-owned and widely dispersed renewable energy generation and energy storage technology that would bring the economic benefits of widely dispersed ownership.[7] However, this revolutionary vision of the smart grid contrasts sharply with the traditional centralized utility model[8] and may be perceived by incumbent energy institutions as a disruptive force that will erode the dominance of their century old monopoly.[9]

1.1. Research Objective

This research has two objectives. Firstly, this research seeks to understand how the smart grid may be a catalyst for a sustainable energy transition. Secondly, is seeks to understand the disruptive capacity of the smart grid on the existing energy institutions and the centralized utility model. In this context it asks whether grid modernization may be laying the foundation for an *Internet of Energy*. This research frames the disruptive capacity of grid modernization in *evolutionary* versus *revolutionary* terms where;

- *Evolutionary* modernization sees the smart grid as the integration of modern communication and control technology into the grid infrastructure that is centrally managed and controlled by the existing regulatory and intuitional order and;

[4] Tapscott & Williams. (2009). *Wikinomics: How Mass Collaboration Changes Everything*. Portfolio.
[5] Collier. (2012). *A Good Offense Is the Best Defense*. The Energy Collective.
[6] Zeller. (2011). *Jeremy Rifkin: The "Democratization Of Energy" Will Change Everything*. Huffington Post.
[7] Farrell. (2011). *Democratizing the Electricity System: A Vision for the 21 st Century Grid*. New Rules Project. Institute for Local Self Reliance Pub.: Washington DC, ….
[8] *Renewable Distributed Energy Generation Installations Will Reach Nearly $86 Billion in Market Value by 2017*. (2012) Wall Street Journal.
[9] Collier. (2012). *A Good Offense Is the Best Defense*. The Energy Collective.

- *A revolutionary* transition sees grid modernization as a disruptive force, like the Internet. Described herein as the *Internet of Energy*, this vision will disrupt the existing institutional order and completely transforms how energy is generated, distributed, and used.

1.2. Methodology

This research reviews the opportunities and barriers to the *Internet of Energy* from technological, regulatory, and economics perspectives. The convergence of the "Internet of Things" with distributed energy technology is compared to the disruptive nature of the Internet.

Energy systems are recognized as complex socio-technical systems. They are the product of a co-evolutionary process that is influenced by interactions between technologies, policies, institutions, resource availability, and cultural norms. Energy systems are tightly coupled, and deeply embedded within social systems. This interaction between social and technical systems not only makes them complex, but also makes them difficult to reform. Transitions in energy systems require not only the emergence of new technologies, but also changes in other systems.

To understand the disruptive capacity of grid modernization, this research uses complexity science to investigate the electricity system by looking at the relationships between social, institutional, and technological systems. It draws on complexity research undertaken by Trist, Homer-Dixon, Tainter, Waltner-Toews, Geels, and Dobson, to provide a framework for analyzing the disruptive nature of the smart grid and energy system transitions. Complexity science provides theoretical frameworks for investigating transitions.

1.3. Key Findings

From an evolutionary perspective, the electricity system is recognized as a socio-technical system. It has several features that create techno-institutional lock-in that resists innovation and a transition towards sustainable energy. Operated as a regulated monopoly for over a century, power utilities have developed 'institutional inertia' due to a combination of social, regulatory and technological lock-ins:

a. *Conservatism & Risk-aversion:* There is an inherent conservatism within the industry that is risk-averse and prefers incremental change to radical innovation.
b. *Scale Economies:* The pursuit of scale economies presents a considerable barrier to innovation since new market entrants are less capable of competing at the same scale.
c. *Standards:* The development of smart grid standards for interoperability and privacy provides an opportunity to utilities and regulators to erect barriers to competition.
d. *Information Control:* Smart Meters act as a form of lock-in. Control over smart meter and smart grid data makes utilities a 'gate keeper' for access to smart grid market.

From a revolutionary perspective, there are several forces at play that seem to be working synergistically to overwhelm these lock-in mechanisms.

a. *Utility Brittleness*: The centralized utility model is becoming increasingly brittle from a technological, economic, and institutional perspective. They will be unable to maintain and manage the increasing complexity of the grid. When centralized systems become too complex, they lose their resilience and expose the risk of cascading failures.
b. *Changing Economics*: Momentum appears to be shifting towards distributed energy systems. Smaller distributed resources are proving to be more agile and competitive than centralized systems. In some places solar PV has reached 'grid parity' meaning it costs the same or less the conventional energy systems.
c. *Emerging Technologies*: New technologies and technological configurations have emerged to present a disruptive challenge to the centralized utility business model. Most importantly is innovation with integrated solar PV plus storage. This undermines the centralized utility model's primary value proposition of reliability.
d. *Internet of Energy*: The disruptive nature of the Internet is converging with the centralized utility model and exposing the contrast between the two paradigms. While the slow moving regulated utility is bogged down in a regulatory quagmire for interoperability standards and privacy regulations, innovation is doing an end-run around utilities by providing energy services in the smart home. Through the convergence of the Internet of Things in the smart home, an *Internet of Energy* is being developed using the open platform of the Internet rather than proprietary networks. This innovation is occurring behind-the-meter, and outside of the regulatory control of system operators.

2. Background

Heightened awareness of the environment and energy security is presenting significant challenges to our energy landscape. Climate change, rising costs for fossil fuels, the dependency on both energy imports and exports, and the inevitability of a carbon tax are presenting significant economic and regulatory challenges globally and here in Canada.[10] Furthermore, the electricity grid that has served us well for over a century is plagued with aging infrastructure that will require significant investment over the next 20 years to ensure the security and reliability of the electricity system.[11] These are formidable challenges, but taken together they may also offer a unique opportunity to rapidly implement far-reaching measures that will bring about a sustainable energy transition.

2.1. Energy

Energy is an indispensible commodity for our complex society. For almost two centuries, this energy was derived from cheap and abundant non-renewable carbon based resources: coal, oil, and natural gas.[12] These resources have fueled exponential economic growth, driven global development, and propelled enormous prosperity and well-being. They have quadrupled both agricultural yields and global population over the past century.[13] They power machines and factories, provide mobility, and heat and cool our buildings. Fossil fuels are the keystone resource that makes industrial civilization and the globalized economic system possible. However, this has created a direct relationship between energy consumption, economic activity, and prosperity.[14] To maintain the prosperity derived from this

---

[10] Beltrame. (2012). *Canada Dutch Disease? OECD Says Yes*. The Huffington Post.; Block et al. (2010). *Internet of Energy: ICT for energy markets of the future*. Federation of German Industries (BDI) publication No. 439.; "Carbon Tax: Canada Will Inevitably See One, Conference Told." (2013) The Huffington Post.

[11] Utility Dive. (2014). *The State of the Electric Utility: 2014*. Utility Dive.

[12] Pardy. (2009). *Climate Change Charades*. Windsor Review of Legal and Social Issues.

[13] T Homer-Dixon. (2011). *Carbon Shift: How Peak Oil and the Climate Crisis Will Change Canada (and our lives)*. P. 16 & P. 27.

[14] Pardy. (2009). *Climate Change Charades*. Windsor Review of Legal and Social Issues.

energy regime requires a constant flow of energy[15] from ever expanding supplies of fossil fuels.[16] This dependence is perhaps the foremost defining characteristic of our time.[17] This is the 'carbon age'.[18]

Despite the expanding supply fossil fuels, we are paradoxically threatened by both the abundance and scarcity of these resources. The scarcity, and thus the rising cost of 'conventional' resources, poses a serious threat to economic and geopolitical stability. Yet this scarcity also hastens the development of the extraordinary abundance of 'unconventional' sources, since higher prices make them economically viable. Developing these resources will greatly increase the threat of climate change, not only because of their abundance, but also since 'heavy oil' is more carbon-intensive than conventional oil.[19] Estimates of unconventional reserves vary widely depending on many assumptions,[20] but it would appear that we have sufficient coal, natural gas, and unconventional oil to power our fossil-fuel driven society at our current burn rate for somewhere between four hundred and eight hundred years.[21]

However, there is accumulating evidence showing that CO_2 emissions associated with burning fossil fuels are already disrupting the global climatic system. This has increased the frequency and severity of extreme weather around the world and in Canada.[22] Fully exploiting unconventional resources would release enough carbon to push atmospheric concentrations of CO_2 to over ten times pre-industrial levels.[23] This would have profound implications on national economic welfare,[24] security and stability,[25] and cause global political unrest.[26]

---

[15] T Homer-Dixon. (2011). *Carbon Shift: How Peak Oil and the Climate Crisis Will Change Canada (and our lives)*. P. 14.
[16] Jiusto. (2009). *Energy transformations and geographic research*. Blackwell Publishing Ltd. A companion to environmental geography.
[17] Pardy. (2009). *Climate Change Charades*. Windsor Review of Legal and Social Issues.
[18] Klare. (2013). *The Third Carbon Age: Nonrenewable "Unconventional" Oil and Gas*. Centre for Research on Globalization. Global Research.
[19] Biello. (2013). *How Much Will Tar Sands Oil Add to Global Warming?* Scientific American Inc.
[20] Jaccard. (2011). *PEAK OIL AND MARKET FEEDBACKS: Chicken Little versus Dr. Pangloss*. Random House Canada. Carbon Shift: How Peak Oil and the Climate Crisis Will Change Canada (and our lives). P. 70.
[21] T Homer-Dixon. (2011). *Carbon Shift: How Peak Oil and the Climate Crisis Will Change Canada (and our lives)*. P. 42.
[22] McBean. (2012). *Telling the Weather Story: Prepared by the Institute for Catastrophic Loss Reduction for the Insurance Bureau of Canada*. Insurance Bureau of Canada.
[23] Keith & Homer-Dixon. (2009). *Dangerous abundance*. Random House Canada. Carbon Shift: How Peak Oil and the Climate Crisis Will Change Canada (and our lives). P. 39.
[24] Hertel et al. (2010). *The poverty implications of climate-induced crop yield changes by 2030*. Global Environmental Change.

Climate change and fossil fuel dependence expose the socio-ecological contradictions that are increasingly apparent with our conventional energy systems:[27] our current globalized economic system is built on the back of fossil energy[28] yet extreme weather events have resulted in social and economic consequences for individuals, governments, and businesses.[29] Additionally, the global economy is so interconnected with fossil fuels that the recent global economic crisis and the global climate crisis cannot be separated. They are both symptoms of the breakdown of an all-encompassing global system.[30] These forces are combining to create a perfect storm that threatens our security and prosperity and, as some have argued, has led us to the door of collapse.[31]

2.2. Electricity

The electrical power delivery system, or the electricity grid, is regarded as the greatest engineering achievement of the 20th century. Affordable and reliable electricity is considered critical for quality of life, social stability, and economic growth.[32] Over the past century, the grid has evolved into an immensely complex and tightly coupled system. At its inception, power utilities were municipally owned and operated and only supplied power to the local community. The system has expanded extensively to create a highly integrated North American transmission network that supplies bulk power to over 340 million people, with a capacity of 1 million megawatts of generation, and nearly 500,000 miles of high voltage transmission lines.[33]

---

[25] The CNA Corporation. (2007). *National Security and the Threat of Climate Change*.
[26] Lagi et al. (2011). *The Food Crises and Political Instability in North Africa and the Middle East*.
[27] Jiusto. (2009). *Energy transformations and geographic research*. Blackwell Publishing Ltd. A companion to environmental geography.
[28] Weinrub. (2012). *Labor's Stake in Decentralized Energy*. Trade Unions for Energy Democracy.
[29] McBean. (2012). *Telling the Weather Story: Prepared by the Institute for Catastrophic Loss Reduction for the Insurance Bureau of Canada*. Insurance Bureau of Canada.
[30] Weinrub. (2012). *Labor's Stake in Decentralized Energy*. Trade Unions for Energy Democracy.
[31] Keith & Homer-Dixon. (2009). *Dangerous abundance*. Random House Canada. Carbon Shift: How Peak Oil and the Climate Crisis Will Change Canada (and our lives).
[32] Rosenfield. (2010). *The smart grid and key research technical challenges*. Ieee. 2010 Symposium on VLSI Technology.
[33] CEA. (2013). *The Integrated Electric Grid: Maximizing Benefits in an Evolving Energy Landscape*. Canadian Electricity Association (CEA).

However, electricity generation is currently responsible for 41% of global energy-related carbon dioxide emissions. This share is projected to rise to 44% in 2030, mainly due to the increasing share of electricity in energy consumption, and the continuing reliance on coal in both developing and developed countries.[34] In the United States, the electricity sector represents 33% of GHG emissions.[35] Canada's electricity sector emissions are skewed downward by an abundance of hydro resources, and also higher than average emission in other sectors due to a resource intensive economy, greater transportation demands, and a colder climate.[36] Nationally electricity sector GHG emissions in Canada represent 13%[37] and in Ontario they are 9%.[38]

Furthermore, the industry faces significant financial challenges with the need to replace aging infrastructure. In the U.S this investment is estimated to be between $1.5 to $2 trillion over the next 20 years in order improve energy security and meet increasing demand.[39] In Canada, the required national investment in electricity infrastructure is estimated to be $347.5 billion.[40] Ontario is expected to spend more than all other provinces and territories with an investment of over $100 billion[41] to replace or refurbish 80% of its electricity system over the next 20 years.[42]

---

[34] Shum. (2010). *Renewable Energy Technology—Is It a Manufactured Technology or an Information Technology?* Sustainability.
[35] U.S. EPA. (2013). *Sources of Greenhouse Gas Emissions*. U.S. Environmental Protection Agency.
[36] Environment Canada. (2014). *Canada's Sixth National Report on Climate Change: 2014*. Environment Canada.
[37] Environment Canada. (2013). *Greenhouse Gas Emissions by Economic Sector*. Environment Canada.
[38] ECO. (2013). *Failing Our Future: Review of the Ontario Government's Climate Change Action Plan Results*. Environmental Commissioner of Ontario (ECO).
[39] AAA&S. (2011). *Beyond Technology: Strengthining Energy Policy Through Social Science*. American Academy of Arts and Sciences.
[40] Coad et al. (2012). *Shedding Light on the Economic Impact of Investing in Electricity Infrastructure: Report February 2012.* Conference Board of Canada. P. 4.
[41] *Ibid*.
[42] Ontario Ministry of Energy. (2011). *Results-based Plan Briefing Book: 2011-2012*.

2.3. Sustainable Energy

Concern over climate change and energy security has stimulated governments, entrepreneurs, and civil society to seek alternatives to the conventional energy system.[43] Given energy's centrality in global development, economic activity and the evolution of social and political systems, energy system sustainability is essential to any larger vision of sustainable development.[44]

Proponents of renewable energy technologies argue that wind, solar, and hydro have virtually unlimited capacity to provide for our energy needs, while emitting no greenhouse gases.[45] Moreover, these renewable resources can be found in almost every part of the world in one form or another. However, the intermittent nature of these resources pose a management challenge when integrated with the conventional electricity system. In this respect, the smart grid is considered to be the enabling technology for integrating and managing energy from renewable sources.[46]

2.4. Energy Transitions

Even with the increasing awareness of the unsustainable nature of our conventional energy systems, analysts are forecasting 'business as usual' with continued growth in fossil fuel production and consumption. This reflects the entrenched socio-economic power of the conventional energy regime. Conventional energy regimes have co-evolved with policies, institutions, social practices, and cultural norms.[47] As they become more embedded within society, they enjoy greater institutional support and

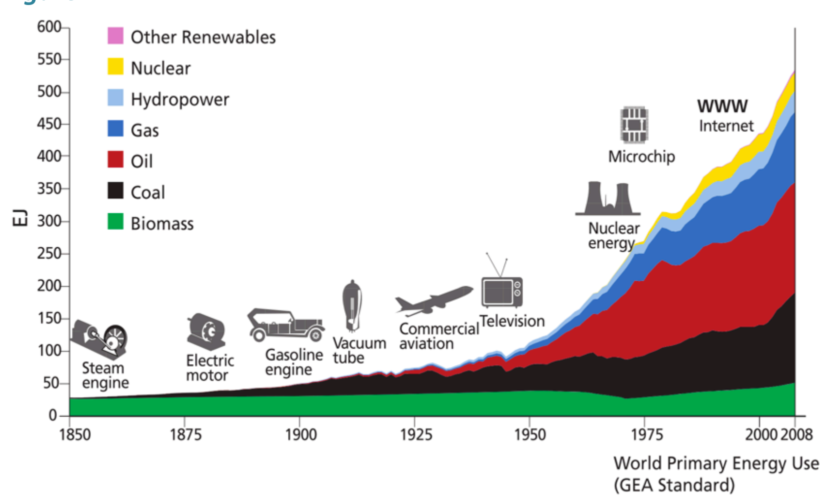
[43] Stephens & Jiusto. (2010). *Assessing innovation in emerging energy technologies: Socio-technical dynamics of carbon capture and storage (CCS) and enhanced geothermal systems (EGS) in the USA*. Energy Policy.
[44] Jiusto. (2009). *Energy transformations and geographic research*. Blackwell Publishing Ltd. A companion to environmental geography.
[45] Denholm & Mehos. (2011). *Enabling Greater Penetration of Solar Power via the Use of CSP with Thermal Energy Storage*. NREL.
[46] Sood et al. (2009). *Developing a communication infrastructure for the smart grid*. IEEE. Electrical Power & Energy Conference.
[47] Jiusto. (2009). *Energy transformations and geographic research*. Blackwell Publishing Ltd. A companion to environmental geography.

political legitimacy.[48] Over time, energy systems develop their own institutional inertia making it difficult to alter their course. Therefore, a transition to a sustainable energy system will not only require the adoption of new technologies, but also changes in markets, social practices, policies, and cultural meanings. A sustainable transition will not come about easily.[49]

However, despite the appearance of insurmountable barriers and the tendency for unsustainable lock-ins, the long view of economic history reveals that disruption is inevitable. Joseph Schumpeter argued in his seminal work on business cycles in 1939, that the history of capitalism is studded with violent bursts and catastrophes. Economic evolution is "lopsided, discontinuous, disharmonious by nature"; it is a "disturbance of existing structures… more like a series of explosions than a gentle… transformation."[50]

History has shown that energy transitions and innovations occur in the face of scarcity or environmental limitations. Over the past two hundred years, developed countries have experienced several energy transitions. Energy consumption in the United States shifted from 70% wood in 1870, to 70% coal in 1900, to 70% oil and gas in 1960. These changes were accompanied by changes in energy technologies and the provision of new energy services like heating, cooling, lighting, and mechanical power.[52] See Figure 1.

Figure 1



Evolution of primary energy shown as absolute contributions by different energy sources (EJ).

Source: Global Energy Assessment[51]

[48] Smith & Stirling. (2008). *Social-ecological resilience and socio-technical transitions: critical issues for sustainability governance*. STEPS Centre.
[49] F. W. Geels. (2010). *Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective*. Elsevier B.V. Research Policy.
[50] Schumpeter. (1939). *Business Cycles: A Theoretical, Historical and Statistical Analysis of the Capitalist Process*. McGraw-Hill.. P. 100.
[51] GEA. (2012). *Global Energy Assessment: Toward a Sustainable Future*. Cambridge University Press. P. 4.
[52] O'Connor. (2008). *Energy transitions*. Encyclopedia of Earth.

Experience suggests that the provision of energy services is not dependent on any one fuel or technology and innovation has occurred largely when energy technologies emerge that can offer substantial improvements in the quantity or quality of energy services they provide. These emergent energy technologies have generally been more flexible and offered significant efficiency improvements over their predecessor.[53] Future energy transitions will be driven by the constraints imposed by climate change and depleting conventional energy supplies. This will create a push for developing new resources and energy technologies that not only provide better service, but also protect the environment.

2.5. Smart Grid

Globally, utilities are in the process of implementing smart grid technologies and the associated processes to modernize their operations and information systems. With the deployment of advanced metering infrastructure (AMI), and other information and communication technologies, utilities hope the smart grid will enable them to monitor, analyze, and synchronize their networks to improve reliability, and increase efficiency of the grid.[54]

However, defining the smart grid is a difficult task as it represents different visions to different stakeholders.[55] Its definition is further complicated by the fact that smart grid technology is rapidly evolving, as is the regulatory and institutional environment in which it is emerging. This imposes a classic chicken-or-egg dilemma; the regulatory structure surrounding the smart grid will inform how it develops and the shape it takes in the process, which in turn, will inform the regulatory structure.[56] In

---

[53] O'Connor. (2008). *Energy transitions*. Encyclopedia of Earth.
[54] Pike Research. (2012). *Smart Grid Data Analytics*. Navigant Research.
[55] CEA. (2010). *THE SMART GRID: A Pragmatic Approach*. Canadian Electricity Association.
[56] Quinn & Reed. (2010). Envisioning the Smart Grid: Network Architecture, Information Control, and the Public Policy Balancing Act. U. Colo. L. Rev. U. Colo. L. Rev.

many ways, defining smart grid before it is fully formed may be similar to trying to define Google or Facebook before the Internet has been created. Generally speaking, the smart grid is understood as a collection of concepts, technologies, and operating practices intended to bring the electric grid into the 21st century.[57]

There are two related but different objectives that the smart grid is trying to achieve: modernize the electricity system's antiquated architecture; and provide consumers with dynamic new ways to produce, use, and conserve electricity. Electricity is a product on which modern life depends, but the electricity industry is the last major network to hold out against fundamental change. Transforming the industry into a dynamic energy ecosystem could enable interactive consumer applications that would create immense environmental and economic benefits. This would yield technological breakthroughs, create entirely new industries and consumer uses far beyond what is presently envisioned. The smart grid has the potential to be a resilient, secure, multifunctional network that would provide a critical response to climate change and bring together numerous generation sources and energy-saving technologies in a seamless network.[58]

However, the smart grid is being built on top of the existing utility regulated monopoly. This would be analogous to developing the Internet with just one computer company, instead of a competitive marketplace of hardware and software providers we have today. Developing the smart grid therefore requires new technologies as well as a new regulatory environment and business model.[59]

Form an *evolutionary* perspective, utilities and regulators see the smart grid as the entire electricity infrastructure from generation to consumption. It is an integrated system with advanced metering,

[57] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.
[58] *Ibid*.
[59] *Ibid*.

sensors, and controls throughout the existing grid as well as customer side devices and services.[60] The objective of the smart grid is to enhance the electricity system with digital technologies that can monitor and manage the flows of electricity and information. It will provide a powerful tool to co-ordinate generation, grid operations, end-users and the electricity market, while minimizing costs and environmental impacts and maximizing system reliability and stability.[61]

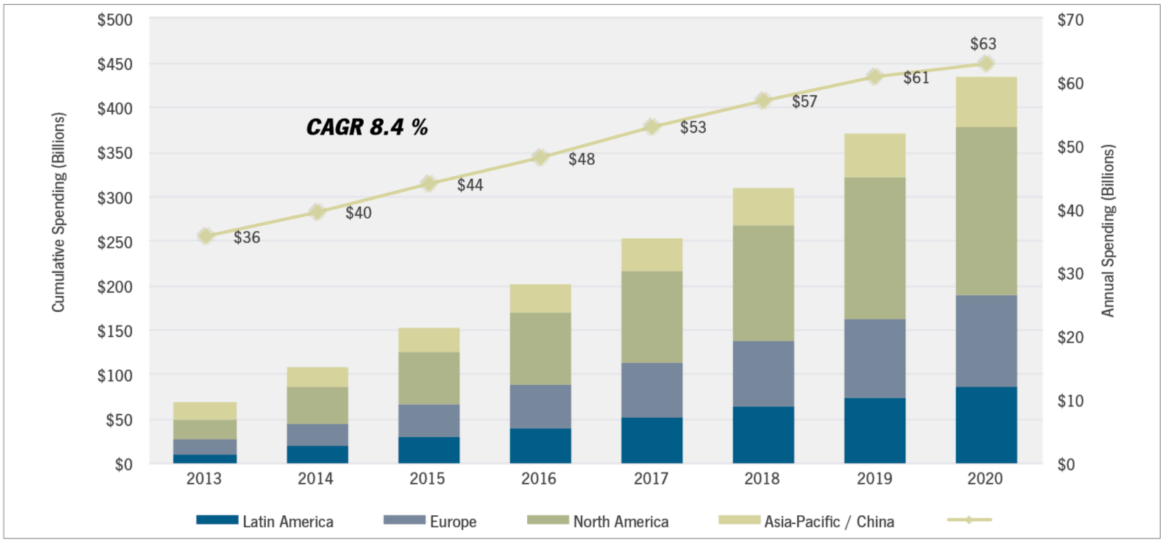
From a *revolutionary* perspective, a broader view sees the smart grid as an attempt to integrate the fast-paced, disruptive information and communication technologies into the slow and reliable infrastructure of the traditional grid. This view requires a "systems-within-systems" approach in order to integrate the volatile and complex social, economic, and political systems of our world with the top-down centralized culture of a regulated monopoly. All these systems together will determine what the smart grid will look like in the future.[62]

Furthermore, just like how the Internet connected commerce, banking, entertainment, digital media, voicemail, and many other information systems, it is anticipated that the smart grid will connect or integrate all of the systems and community assets that consume or produce electricity.[63] Cisco Systems anticipates that the smart grid will "eclipse the size of the internet" by 100 or 1000 times.[64] According to GTM research, investment in smart grid has an annual growth rate of 8% with the cumulative value of the market is expected to surpass $400 billion by 2020.[65] See Figure 2.

[60] Knight et al. (2010). *How Does Smart Grid Impact the Natural Monopoly Paradigm of Electricity Supply? Part I Knight-Brownell*.
[61] IEA. (2011). *Technology Roadmap: Smart Grids*.
[62] "Smart Grid 2025." (2011) Institute for the Future.
[63] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.
[64] Lamonica. (2009). *Cisco: Smart grid will eclipse size of Internet*. CNET News.
[65] Groarke et al. (2013). *Global smart grid technologies and growth markets 2013-2020*. Greentech Media Inc.

Figure 2

Smart Grid Regional Forecast 2013-2020



Source: GTM Research[66]

The smart grid will comprise many things and use ICT to expand the capabilities of the electricity grid to provide benefits like reliability, information, efficiency, and customer control.[67] Despite the competing visions, it is possible to look at some the key infrastructure components that make up the smart grid. See Table 1 for details.

Table 1

Hard infrastructure	*Soft infrastructure*	*Characteristics of Smart Grid*
• Smart meters	• Interoperability standards	• Demand response
• Networked devices	• Cyber security protocols	• Facilitation of distributed generation
• Energy storage	• 1.8 Ghz spectrum	• Facilitation of electric vehicles
• Smart appliances	• Stakeholder engagement	• Optimization of asset use
• Centralized Generation	• Planning Models	• Problem detection
• Renewable Generation	• Information Control	• Self healing
• Electric Vehicles		• Two-way flow of information and energy
• Smart Chargers		

Source: Canadian Electricity Association[68]

[66] Groarke et al. (2013). *Global smart grid technologies and growth markets 2013-2020*. Greentech Media Inc.
[67] IESO. (2014). *The Smart Grid in Ontario*.
[68] CEA. (2010). *THE SMART GRID: A Pragmatic Approach*. Canadian Electricity Association.

3. Complexity

Within the *evolutionary* versus *revolutionary* framework, this research seeks to understand how the smart grid may either reinforce the existing techno-institutional structure of the electricity grid, or disrupt it, and potentially bring about a sustainable transition for energy systems. Complexity science offers powerful analysis tools for conceptualizing and understanding this tension. This field of analysis arose because the traditional reductionist approach - gaining understanding from the study of individual parts – of 'conventional' science was proving inadequate for problem solving in an increasingly complex and interconnected world. Simply put, complexity science is the recognition that that systems behave as a whole and that this behaviour cannot be understood through analysis of the individual elements.[69] *The whole is greater than the sum of its parts.*

3.1. What is Complexity

Complex systems have features that distinguish them from simple systems: they usually have many components that have a high degree of interconnectivity; they are often open systems with many inputs and outputs with the surrounding environment; they exhibit novel properties and unexpected behaviours. Furthermore, complex systems have flows of energy, material, and information between components in the system and between the system and its surrounding environment. This makes it difficult to define a clear boundary and draw a causal relationship between a complex system and its surroundings.[70]

[69] Waltner-Toews et al. (2008). *An Introduction to Systems Thinking*. Columbia University Press. The Ecosystem Approach: Complexity, Uncertainty, and Managing for Sustainability.
[70] Thomas Homer-Dixon. (2011). *Complexity Science*. Oxford Leadership Journal.

Complex systems are distinct from simple systems, or even something that may be described as complicated. Simple systems are easily defined, the boundaries are clear, and they have minimal interaction with their surrounding environment. They also exhibit predictable and repeatable behaviour where it is easy to draw simple causal links between cause and effect. A complicated system can be carefully dismantled and then reassembled and it will work in exactly the same way. In contrast, complex systems exhibit characteristics that defy simple linear causality, and behaviours that make them adaptive to their external environment. Within complex systems, interactions between its components are not fixed or clearly defined, and have on-going co-adaptations that spontaneously generate their own order.[71]

Characteristics of complex systems include feedbacks, non-linearity, cascading failures, emergent or novel properties, resilience, self-organization, brittleness, threshold behaviour, and uncertainty and surprise. Complexity researchers have developed several methods to conceptualize how these characteristics influence the behaviour of complex systems including *techno-institutional lock-in* and *socio-technical transitions*. These characteristics and concepts are detailed below.

Feedbacks: Complex systems have mechanisms that create circular relationships or feedbacks. Typically complex systems exist in what is called dynamic equilibrium where negative feedbacks work to stabilize the system from external forces. However, sometimes external forces trigger positive feedbacks that cause sudden and often unexpected change. Positive feedback loops can amplify the initial force (think Jimi Hendrix) where the effect becomes the cause of further change. Typically this results in a system transition towards a new state of equilibrium.[72]

[71] Newell. (2008). *The class as a learning entity (complex adaptive system): An idea from complexity science and educational research*. SFU Educational Review.
[72] Waltner-Toews et al. (2008). *An Introduction to Systems Thinking*. Columbia University Press. The Ecosystem Approach: Complexity, Uncertainty, and Managing for Sustainability.

Climate change provides a good example of feedbacks. The greenhouse gas emissions from energy systems are causing warming that is melting polar ice caps. This sets off a positive feedback since the snow and ice have a high albedo (reflectivity) that reflects some of the solar radiation back into space. With melting ice, more solar energy is absorbed by the dark seawater that, in turn, causes further warming, and more melting. However, global warming also triggers a negative or stabilizing feedback since warming causes more cloud cover that increases albedo.[73] However, it is expected that the positive feedbacks will overwhelm the stabilizing feedbacks.

Non-linearity: Simple systems behave in a linear causal fashion where inputs cause a proportional linear effect. Complex systems, in contrast, defy linear causality due to the feedback mechanisms described above. These feedbacks induce disproportionality between cause and effect, or non-linearity: positive feedbacks amplify small perturbations and lead to big changes or system collapse; or negative feedbacks dampen and absorb large perturbations with little impact to the system.[74]

Cascading failures: As complexity increases so does the vulnerability to cascading failures. This characteristic of complexity results from systems that are increasingly interconnected and tightly coupled. These factors increase the risk that a small perturbation in one sector can propagate outwards and have a ripple effect on other systems. [75]

Emergence: This is perhaps the most important characteristic of complex systems for the purpose of this research. Emergence is an interplay of both positive and negative feedbacks that creates the dynamic balancing of opposites. Formally emergence refers to the formation of coherent structures,[76] but in practical terms emergence is the creation of novel properties or behaviours from systems that

[73] Ormand. (2013). *Introduction to Complex Systems: What Constitutes a Complex System?* Science Education Resource Centre.
[74] Thomas Homer-Dixon. (2011). *Complexity Science*. Oxford Leadership Journal.
[75] Oldreive et al. (2012). *Managing Current Complexity: Critical Energy Infrastructure Failures in North America*. Dalhousie Journal of ….
[76] Lichtenstein. (2000). *The Matrix of Complexity: A Multi-Disciplinary Approach for Studying Emergence in Coevolution*. P.3.

could not be understood or predicted from looking at the individual parts.[77] There are five conditions required for emergence to occur: internal diversity; redundancy; decentralized control; organized randomness; and neighbor interactions.[78]

Resilience: A resilient system is able to adapt to a changing external environment and withstand shock without catastrophic failure. Diversity and redundancy within a system determine how it will respond to the external environment and maintain its established coherence.[79] Resilience may be either positive or negative depending on the context.[80] It is typically conceived as a good characteristic for reliability in the electricity system or for ecological systems exposed to disturbances. However, if the objective is to change a system or bring about a transition, resilience can be a negative characteristic.

Self-organization: Self-organization is the coherent patterns of relationships that form the internal structure of complex systems. This property of complex systems causes surprising and counterintuitive system behaviour and is what gives a system its identity.[81] For instance a *school* of fish or a *murmuration* of starlings describe the behaviour of the system rather than the individual components - fish or bird. With system behaviour, organizational control is uniformly distributed, which makes the system more resilient when compared to centralized top-down control structures.[82]

Murmuration of Starlings

Source: The Fab Web[83]

Brittleness: As systems become increasingly complex, they get to a point where they are no longer resilient and lose their ability to innovate and their capacity for novelty. This happens when they have a

[77] Thomas Homer-Dixon. (2011). *Complexity Science*. Oxford Leadership Journal.
[78] Newell. (2008). *The class as a learning entity (complex adaptive system): An idea from complexity science and educational research*. SFU Educational Review.
[79] *Ibid*.
[80] Smith & Stirling. (2008). *Social-ecological resilience and socio-technical transitions: critical issues for sustainability governance*. STEPS Centre.
[81] Waltner-Toews et al. (2008). *An Introduction to Systems Thinking*. Columbia University Press. The Ecosystem Approach: Complexity, Uncertainty, and Managing for Sustainability.
[82] Ajmone-Marsan et al. (2012). *The emerging energy web*. The European Physical Journal Special Topics.
[83] Monika. (2013). *Murmuration of Starlings in Netivot, Isreal*. The Fab Web.

declining redundancy of critical components, making systems less resilient and more prone to cascading failures. We are getting a rise in brittleness because of the enormous energy requirements that are required to maintain our global technologies and societies while we are trying to deal with a whole range systemic stresses from food production and climate change, while trying to provide ever more energy for human kind.[84]

Thresholds: As complexity increases, systems develop threshold behaviour in response to feedbacks, resilience, and non-linearity. They tolerate external disturbances for a period of time while maintaining their system structure, often with minimal indication that the system is under stress. But at a certain point they reach a threshold and the system suddenly flips to a new state of equilibrium. This can be seen with the collapse of the East Coast Fishery and the collapse of the global economy in 2008, and no body could have predicted these events.

Uncertainty and surprise: The preceding characteristics of complex systems make them difficult to understand let alone manage. Complexity creates situations where numerous different future outcomes are possible, some may be desirable, some not, but all of which have an inherent and irreducible level of uncertainty of actually coming to fruition. Complexity gives the impression that there is no right way looking at complex systems. But the problem with traditional approaches to complexity lies in the singularity of their conception of trying to find the "right" answer.[85]

3.2. Socio-Technical Systems

The focus of this research is on the processes that bring about a technological change. A systems thinking approach recognizes that technologies do not develop in bubble, but are the result of a co-

[84] Thomas Homer-Dixon. (2011). *Complexity Science*. Oxford Leadership Journal.
[85] Waltner-Toews et al. (2008). *An Introduction to Systems Thinking*. Columbia University Press. The Ecosystem Approach: Complexity, Uncertainty, and Managing for Sustainability.

evolutionary process between technologies, cultural, social, political institutions, infrastructure, industrial networks, and everyday activities associated with the technology. A socio-technical systems perspective allows us to understand technological development in terms of complex systems and adaptive processes that form the interdependencies between the material and social realms.[86] The concept of socio-technical systems was developed by Eric Trist and others from the Tavistock Institute in the 1960s. Trist later became a Professor of Organizational Behaviour and Social Ecology, in the Faculty of Environmental Studies at York University.[87] In contrast to “technological determinism”, his work viewed organizational behaviour as the meeting of two systems, technological and psycho-social.[88] Simply put, Trist’s socio-technical systems perspective refers to the interrelatedness between social, institutional, and technological systems.

Often socio-technical systems cause unexpected (emergent) uses of artifacts that are enabled by technological changes. Once this process starts, technologies experience increasing adoption and diffusion through social systems (positive feedbacks). As a result, some transitions can occur very rapidly, or they may take decades, and for others, they may never be complete.[89] In response to feedbacks these systems experience resilience and emergence resulting in the following behaviours:

Techno-institutional lock-in

Through stabilizing feedback mechanisms, techno-institutional lock-in (lock-in) creates a persistent state (resilience) for systems by presenting market and policy barriers to technological alternatives or innovation. Lock-in is amplified by increasing returns to adoption; the more a technology is adopted – the more experience is gained – the more the technology is improved – the more it is adopted.[90] Path-

[86] Smith & Stirling. (2008). *Social-ecological resilience and socio-technical transitions: critical issues for sustainability governance*. STEPS Centre.
[87] Miller. (1993). *Obituary: Eric Trist*. The Independent.
[88] Trist. (1981). *The evolution of socio-technical systems*. Ontario Ministry of Labour. Occasional paper.
[89] Lawhon & Murphy. (2011). *Socio-technical regimes and sustainability transitions : Insights from political ecology*.
[90] Arthur. (1989). *Competing technologies, increasing returns, and lock-in by historical events*. The Economic Journal.

dependencies develop over time, through the co-evolution of economic, environmental, and social processes, creating techno-institutional lock-in.[91] However, increasing returns and path-dependency can lock-in sub-optimal technologies.[92]

Socio-technical transitions

This area of complexity science provides a framework for understanding how shifts in large and complex socio-technical systems occur. Socio-technical transitions are major technological changes in the way societal functions are fulfilled. They not only involve changes in technology, but also changes in user practices, regulations, industrial networks, infrastructure, and symbolic meaning within societies (emergence).[93] Evolving from the study of technology innovation and diffusion, evolutionary economics, and the sociology of large technical systems, socio-technical transitions occur when an entrenched, mainstream regime experiences synergistic pressures from multiple levels.[94] Trist's work on the "diffusion of innovative work practices and organizational arrangements"[95] is particularly relevant for understanding socio-technical transitions.

3.3. Energy and Complexity

Energy systems are recognized as complex socio-technical systems. They are not solely energy technologies, but are comprised of a network of technologies, policies, institutions, and social practices that are continuously reproduced over time.[96] They are the product of a co-evolutionary process influenced by interactions between technological innovation, regulatory institutions, resource

---

[91] Könnölä et al. (2005). *Prospective Voluntary Agreements for Escaping Techno-Institutional Lock-In*. Ecological Economics.
[92] Windrum. (2003). *Unlocking a lock-in: towards a model of technological succession*. … evolutionary economics: new empirical methods and ….
[93] F. Geels. (2002). *Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study*.
[94] McCauley & Stephens. (2012). *Green energy clusters and socio-technical transitions: analysis of a sustainable energy cluster for regional economic development in Central Massachusetts, USA*. Sustainability Science.
[95] Trist. (1981). *The evolution of socio-technical systems*. Ontario Ministry of Labour. Occasional paper. P.7.
[96] Jiusto. (2009). *Energy transformations and geographic research*. Blackwell Publishing Ltd. A companion to environmental geography.

availability, and cultural values. Energy systems are tightly coupled, and deeply embedded within social systems. The interaction between social and technical systems not only makes them complex, but also makes them difficult to reform. Transitions in energy systems require not only the emergence of new technologies but also changes in other systems. Furthermore, energy is an enabler of complexity. Energy allows societies to build complex institutions, complex technologies, and complex social systems. Complexity is used to solve problems. Over time, complexity increases in socio-technical systems in order to solve more problems. However, complexity often generates problems that are, in turn, solved with more complexity. As a result, increasing complexity also increases the throughput of energy as well as the costs to maintain the complexity.[97]

Tainter's Paradox

Joseph Tainter's work presents a paradox when investigating the relationship between energy and complexity. In his book, *The Collapse of Complex Societies,* Tainter argues that complexity initially provides a net benefit to society, however, over time societies become increasingly complex as they build layer upon layer of complexity in order to solve the problems they face. As complexity increases, so does the cost to maintain and add more complexity. Accordingly, as the marginal cost of complexity increases, the marginal benefit diminishes overtime relative to social, environmental, and energy costs. As a result, they experience diminishing marginal social return from complexity in terms of well-being for the society. Eventually the society reaches an inflection point where all the available energy is being used simply to maintain its complexity, and beyond that point the society experiences negative returns. If problems can no longer be solved by increasing complexity, the society enters a phase of 'decomplexification' or collapse.[98]

[97] Joseph A. Tainter. (1988). *The Collapse of Complex Societies*. Cambridge University Press. P. 91.
[98] Thomas Homer-Dixon. (2011). *Complexity Science*. Oxford Leadership Journal.

4. Institutional Lock-in

Energy systems are not simply comprised of specific technologies but of a network of technologies, policies, institutions, and social practices that are continuously reproduced over time.[99] Existing energy institutions are robustly embedded within supportive infrastructure and regulations, and enjoy greater institutional support and political legitimacy. They have sunk investment in infrastructure and are understandably guarded of their vested interests.[100] With a supply-side focus, the industry typically understands the energy 'problem' as one where ever-growing demand is to be met by an ever expanding supply of fossil fuels, and massive nuclear and hydropower projects.[101] This is compounded by the fact that the public lacks a clear understanding of the alternatives and does not yet realize that anything is wrong.[102] Referred to as techno-institutional lock-in, these factors create a stabilizing affect that acts as a barrier to reform.[103] In light of this reality, many analysts expect continued growth in carbon based energy, reflecting the institutional inertia of conventional energy systems.[104] These lock-in effects can be found in the relationship between regulations, technology selection, and the scalar effects of energy systems. This means that a transition to sustainable energy will not happen easily.[105]

From a smart grid development perspective, techno-institutional lock-in may be manifesting itself through the centralized control architecture of smart meter information. The Convergence of ICT with the electricity system is an effort to create an intelligent grid. However, the centralized utility vision for grid intelligence simply means 'computerizing' the grid, rather than making it smart.[106] Furthermore, it

[99] Jiusto. (2009). *Energy transformations and geographic research*. Blackwell Publishing Ltd. A companion to environmental geography.
[100] Smith & Stirling. (2008). *Social-ecological resilience and socio-technical transitions: critical issues for sustainability governance*. STEPS Centre.
[101] Jiusto. (2009). *Energy transformations and geographic research*. Blackwell Publishing Ltd. A companion to environmental geography.
[102] Stuller. (2010). *An Electric Revolution: Reforming Monopolies, Reinventing the Grid and Giving Power to the People*. Galvin Electricity Initiative.
[103] Foxon. (2002). *Technological and institutional "lock-in" as a barrier to sustainable innovation*. Imperial College Centre for Energy Policy and ....
[104] Jiusto. (2009). *Energy transformations and geographic research*. Blackwell Publishing Ltd. A companion to environmental geography.
[105] F. W. Geels. (2010). *Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective*. Elsevier B.V. Research Policy.
[106] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.

appears the smart grid is being implemented in a way that not only helps manage an increasingly decentralized and complex system, but also to bolster the utility business model. Faced with existential threats, system brittleness, increasing costs, changing customer demands (reducing GHGs), and emerging technologies, utilities are trying to maintain monopolistic control over the information generated on the smart grid, ostensibly for privacy and security reasons, but possibly also ensure their continued existence.

Furthermore, research has shown that the regulatory and institutional environment presents one of the most important drivers and barriers for the development of the smart grid, over and above any specific technology employed.[107] Smart grid standards and regulations for privacy and interoperability are presently being developed. How these develop can create either a barrier or an opportunity for innovation, and determine whether the smart grid is *evolutionary* or *revolutionary*.

From an evolutionary perspective, proponents of the status quo have argued that the smart grid is just a natural evolution for the regulated utility business model. Indeed there are technological innovations that have penetrated the industry in recent years providing utility engineers and managers with previously unavailable views into the electricity system. However, they argue that technology has been evolving in the electricity industry since the beginning. This includes such innovations as the rotary converter in 1893, nuclear generation in 1956, solid-state relays, SCADA and more recently phasor measurement units. With the exception of the rotary converter, these innovations did not change the fundamental nature of the business. The smart grid is just the culmination of many recent innovations that have been developing for some time.[108]

[107] Dedrick & Zheng. (2011). *Smart Grid Adoption: A Strategic Institutional Perspective*. industrystudies.pitt.edu.
[108] Knight et al. (2010). *How Does Smart Grid Impact the Natural Monopoly Paradigm of Electricity Supply? Part I Knight-Brownell*.

4.1. Regulatory Lock-in

The defining characteristic of the electricity industry is that it is operated as centrally planned regulated monopoly. Over a century ago, the electricity utility industry proposed that it should have itself regulated by government with the ability to fix rates and define standards of service. [109] This was based on the notion that the electricity business should be seen as a "natural monopoly" whereby the most efficient way to deliver electricity was by serving all customers with a single infrastructure for the generation, transmission, and distribution of electricity, and through the pursuit of economies of scale.[110]

From an evolutionary perspective, this regulatory model was designed to provide a stable business environment that minimizes risks by imposing barriers to competition and promoting incremental change. Implicit in the monopoly theory is the absence of competition, and the goal of cost-recovery. Market boundaries are enforced by imposing legal barriers to competition that shelter utilities from the dynamic processes of creative destruction and disruptive innovation. The value proposition to consumers (voters) is fixed rates, however this narrowly defines consumer benefits as low, stable rates. In the economic context of the 21st century, this static model contrasts starkly with other sectors, including today's telecommunications industry. Where other sectors create value through technological change, economic growth, innovation, and product differentiation, the utility business model was specifically designed to stifle innovation and value creation by regulatory fiat. [111]

For many years to come, progress in building the smart grid will depend on actors whose conservatism has historically retarded innovation. Utilities strive only to supply stable electricity to meet demand, and regulators strive to avoid risks to ratepayers. Under cost recovery regulations, there is little

[109] McDonald. (1958). *Samuel Insull and the Movement for State Utility Regulatory Commissions*. Business History Review.
[110] Dedrick & Zheng. (2011). *Smart Grid Adoption: A Strategic Institutional Perspective*. industrystudies.pitt.edu.
[111] Kiesling. (2011). *My Grid-Interop talk: Regulation's role in stifling innovation*. Knowledge Problem.

incentive for taking risks, and a disincentive for investing in assets whose costs cannot be recovered over a long time horizon. [112]

4.2. Technological Lock-in

Even in the absence of regulatory protection, socio-technical systems generate increasing momentum as they mature, creating path-dependencies that make it difficult alter their course. This momentum is aided through "conservative" inventions and incremental changes that work to preserve or reinforce the existing system. Naturally, managers within the system prefer to maintain their control and do not want to see the introduction of radical or disruptive technologies. [113] This dynamic can be seen in the electricity industry with the pursuit of "clean coal" or the renewed focus on nuclear power. These technologies could solve the industry's GHG emissions problem, but they would also work to bolster the century old business model, reinforce the traditional role of utilities and state regulators, and preserve adjacent industries like mining and rail as well. There has been a great deal of political and utility interest in moving in this direction.[114] Furthermore, utilities in the U.S. and Europe are actively trying to limit the introduction of potentially disruptive technologies that are proving to be increasingly competitive to their business model. This can be seen with the recent efforts by utilities to limit net-metering for renewables [115] and resist the introduction on-site electricity storage.[116]

---

[112] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.
[113] Hirsh & Sovacool. (2006). *Technological Systems and Momentum Change: American Electric Utilities, Restructuring, and Distributed Generation Technologies*. The Journal of Technology Studies.
[114] A Lovins & Rocky Mountain Institute. (2011). *Reinventing fire: bold business solutions for the new energy era*. Chelsea Green Pub. P. 180.
[115] Farrell. (2013). *Could Minnesota's "Value of Solar" Make Everyone a Winner?* Institute for Local Self-Reliance. Institute for Local Self-Reliance.
[116] Baker. (2014). *SolarCity accuses utilities of slowing home-battery project*. SFGate.

4.3. Scale Lock-ins

The modus operandi for electricity utilities over the past century was the pursuit of economies of scale. The central nature of the cost recovery model was to reduce costs and increase reliability by promoting demand growth. This model proved to be highly successful. With nearly inelastic demand growth for electricity, utilities could pursue a straightforward strategy: build enough capacity and redundancy to ensure reliability and recover the costs plus a reasonable margin. Consumption grew, reliability increased and rates declined in real dollars. This planning model favoured the construction of big iron; ever-larger centralized generation plants serving distant load centres through bulk transmission corridors. However, as power stations got bigger, they also moved farther from their customers increasing the physical centralization of the electricity system.

This financial model and regulatory structure for utilities succeeded in large part, because of steady and predictable demand growth. This meant that sales of electricity climbed steadily while the unit costs decreased, as did rates for customers.[117] The doctrinaire belief in economies of scale long dominated electricity grid planning and resulted in the capacity of the power generators doubling every 6.5 years, while yielding real economic savings. For almost a century, the centralized utility model proved to be highly successful by delivering increasing reliability with decreasing marginal costs and is still the predominant planning model today.[118] However, scale economies work to reinforce path-decencies by creating high entry barriers that impede competition and innovation from new market entrants.[119]

The pursuit of scale economies can be also be seen with the adoption of renewable energy technologies. The development of renewable energy is increasingly being organized on the same scale as fossil fuel

[117] Fox-Penner. (2010). *The Smart Grid–Enabled Energy Services Utility: How Utilities Can Become Sustainable by Selling Less*. thesolutionsjournal.com.
[118] Diebold et al. (1982). *Brittle Power: Energy Strategy for National Security*. Brick House Publishing. Foreign Affairs. P. 222.
[119] Grünewald et al. (2012). *The socio-technical transition of distributed electricity storage into future networks—System value and stakeholder views*. Energy Policy.

based electricity generation. With the growth of renewable energy largely been driven by government subsidies, utility companies are required to obtain a certain percentage of renewable energy based on renewable portfolio standards. This has prompted utilities to develop large renewable energy facilities with a generation capacity comparable to coal and natural gas plants. Since wind power is relatively less expensive than other renewables, utilities tend to develop wind capacity on a large scale. In order to maximize the power generation, wind farms are trending towards 'industrial' sized turbines (over 400 feet high) arranged in large centralized clusters in remote locations away from their load centres.[120]

However, critics have argued that simply replacing polluting energy technology with greener sources of power will not, by itself, eliminate the unsustainable nature of our conventional systems. The problem with unsustainable energy is not solely the environmental impact of any particular energy technology, but also the "gigantism" of the conventional energy systems. The scale of conventional energy creates unhealthy concentrations of social power and wealth, as well as ecological impacts on the supply side. While on the demand side, they disempower and disconnect energy consumers because of the scale and displacement between generation and consumption.[121] Renewable energy projects built at the same scale as convention energy reproduces the negative characteristics of conventional energy systems in terms of scale, the locus of ownership, and agency.[122] However scale economies also serve to protect the institutional and regulatory order of the centralized utility model.

[120] Ottinger. (2013). *The Winds of Change: Environmental Justice in Energy Transitions*. Science as Culture.
[121] Jiusto. (2009). *Energy transformations and geographic research*. Blackwell Publishing Ltd. A companion to environmental geography.
[122] Ottinger. (2013). *The Winds of Change: Environmental Justice in Energy Transitions*. Science as Culture.

4.4. Smart Grid Lock-ins

The smart grid faces several barriers that could limit its development potential and wide-spread adoption. Not only is there conservatism in the industry, but there is also a lack of consumer demand for smart grid products and the industry finds itself bogged down in a regulatory quagmire with privacy issues for smart grid data, and the slow pace of developing interoperability standards.

Heightened interest in smart grid and excitement in the smart grid industry combined with the initial success of smart meter deployment has led to heightened expectations by industry and customers.[123] However many of the expectations have yet to be met and the smart grid industry finds itself at a crossroads between the initial enthusiasm, and a more pragmatic, cautious path forward.[124] Momentum seems to have slowed with smart grids development. The economic slowdown as well as the end of stimulus money from the U.S. economic recovery act has created uncertainty in the smart grid market. This is making it difficult for investors and utilities to take the leap from pilot stage to the real world for smart grid technologies.

As development of smart grid technologies has slowed, so has investment activity. Of the $1.1 billion in smart grid related investment in 2012, more than 80 percent went to energy efficiency, transportation, and energy storage. This left only $200 million going directly to the smart grid segment for communications, distribution automation, transmission, energy management and software. The reason for the disproportional investment levels in storage and transportation is that these market segments operate outside of the regulated utility industry. Within regulatory boundaries, adoption of nascent technologies is usually constrained by conservative utilities, long budget cycles, and a slow moving

[123] CEA. (2010). *THE SMART GRID: A Pragmatic Approach*. Canadian Electricity Association.
[124] *Ibid*.

regulatory process. Outside of this environment, Silicon Valley has largely outpaced utility incrementalism.[125]

Furthermore, the inherent conservatism within utilities and regulators has discouraged risky smart grid investments. Regulators evaluate smart grid project proposals using the familiar tools of economic recovery. However, innovative projects have unquantifiable benefits and an unproven history compared with traditional practices. Since these are novel technologies or practices, there is no historical data from successful projects yet. As such, utilities are reluctant make risky investments, and regulators have been reluctant to approve new smart grid projects.[126] So far, evidence of any real-world, large-scale distribution automation upgrades or other smart grid innovations is hard to find. Frustrations in the smart grid industry are building as progress continues to slow.[127]

Compounding this is a lack of consumer demand for the smart grid products for demand response, largely due to inadequate incentives for consumers to adopt systems to manage their energy consumption. So far smart grid products do not have consumer appeal. The products have been 'utilitarian' and do not command the emotional connection we have seen with products like smart phones or tablets.[128] Another barrier for uptake in smart grid consumer applications, even for motivated consumers, is that they face high transaction costs simply to get started. They also need access to fine grained usage information. Smart Meters are capable of measuring this, but so far it is not clear if consumers can get access to this. There are ongoing disputes on whether the customer or the

[125] Pollock. (2013). *Venture Capitalists Don't Know How to Invest in the Smart Grid investment activity in 2012* . Greentech Media Inc.
[126] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.
[127] Woods. (2013). *As Momentum Slows, Europe Seeks New Smart Grid Boost*. Navigant Consulting Inc. Navigant Research.
[128] Eisen. (2013). Eisen also said "No one is standing in line at an Apple Store for a smart thermostat". However, as we will see in Section 5.4 that has changed within in the last year.

utility owns that data that a smart meter generates. Without a resolution, many smart grid benefits are hard to come by. [129]

Smart Meters?

Smart meters are intended to be the enabling technology for the smart grid, but so far they are failing to live up to their promise. Smart meters do, however, provide utilities with another foothold on the electricity sector by generating information that they will control.

Research findings in Europe show that smart metering has not lead to the desired savings under the current market design. In the UK where far reaching smart meter rollouts are underway, experience has shown that homeowners may not benefit from variable tariffs at all.[130] Germany rejected a proposal by the E.U., which recommended that it install smart meters on 80 percent of its homes by 2020. Germany's Economy Minister cited an Ernst & Young study showing that the installation cost would be greater than any achievable savings for small homeowners.[131] In Ontario, ombudsman André Marin is taking a close look at Hydro One's time-of-use billing practices due to irregularities from smart meter communications and apparent billing errors. [132] In Australia, an audit found that a $100 million intelligent energy grid trial failed to meet key objectives, and half of the users abandoned the trail before its completion.[133] From a grid management perspective, some have argued that a large-scale smart meter rollout is not required to provide the necessary visibility of the grid, even with high penetration levels of distributed renewables. Only a few metering points are necessary.[134] For example,

[129] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.
[130] Bichler. (2013). *Smart Grids and the Energy Transformation: Mapping Smart Grid Activities in Germany*. Heinrich Böll Stiftung.
[131] Stefan Nicola. (2013). *Germany Rejects EU Smart-Meter Recommendations on Cost Concerns*. Bloomberg L.P. Bloomberg.
[132] Matthew Pearson. (2014). *Ontario ombudsman to probe Hydro One's use of smart meters*. Ottawa Citizen.
[133] Colley. (2014). *Half of users abandon smart meter trial*. NextMedia. itNews.
[134] Bichler. (2013). *Smart Grids and the Energy Transformation: Mapping Smart Grid Activities in Germany*. Heinrich Böll Stiftung.

Germany is planning to triple the share of renewables to 80 percent of by 2050, but they have yet to see the benefits for a mass rollout of smart meters.[135]

The big push for smart meters comes from the smart home industry. However, without plug-and-play interoperability on the consumer side of the meter, smart metering has little benefit. As a stand-alone technology, smart meters will not enable the demand response business to any significant level. Nor is today's 'old-fashioned' electricity market design able to generate profits with smart meters.[136]

Big Data

Control over smart grid data also works to maintain utility control over the electricity sector, however it also presents the weakness of the centralized control structure.

In the U.S. where smart meter programs have been in place for several years, the advanced metering infrastructure (AMI) is generating enormous amounts of data, up to twice as much of what flows through traditional communications industry. This includes, not only data from smart meters, but also synchrophasors, smart transformers, and any other assets communicating back to the utility. One estimate shows that there will be 10 billion assets on the smart grid that will be connecting and communicating with utilities.[137]

Of course, with Big Data, comes big data management problems. Utilities are awash with data but are uncertain about what to do with it or how to manage it. By 2009 U.S. utilities possessed 194 petabytes of data (iTunes requires 12 petabytes[138]), with terabytes collected every day. The solution is supposed to be Data Analytics. Global spending on utility data analytics is expected to exceed a cumulative total

[135] Stefan Nicola. (2013). *Germany Rejects EU Smart-Meter Recommendations on Cost Concerns*. Bloomberg L.P. Bloomberg.
[136] Bichler. (2013). *Smart Grids and the Energy Transformation: Mapping Smart Grid Activities in Germany*. Heinrich Böll Stiftung.
[137] Tweed. (2012). *Utility Data Flow Could Eclipse Other Industries*. Greentech Media Inc. GTM Research.
[138] Elmer-DeWitt. (2014). *What's 12 petabytes to Apple?* CNN Money.

of $34 billion by 2020.[139] However, so far utilities have yet to realize the potential from the flood of new data that is now flowing on the power grid. A survey conducted by the Electric Power Research Institute (EPRI) found that most utilities do not know what to do with all the data. The other problem is that they do not have an easy way to link the data to what the system state was at any point in time. Except for catching electricity thieves and 'grow-ops', the value of this data collection comes into question.[140]

Another data management issue involves processing challenges. Many utilities have invested in state-of-the-art computers, databases, and networks, and are employing today's best practices in information technology. However, modern IT architecture is designed to access data over networks and this volume of data overwhelms network capacity. For instance, a single calculation might require access to 4 terabytes of data. That significantly slows down response time for a grid that requires real-time management. These data management issues expose the weakness of the centralized information control structures,[141] however monopolistic control over smart grid data gives utilities considerable leverage over the electricity industry.

Interoperability

Interoperability standards present another opportunity for utilities to maintain institutional control over the electricity system. However, implementing these standards is proving to be a significant challenge.

The promise of the smart grid is to deliver greater reliability from interruptions, a more demand-responsive grid, the ability to seamlessly integrate renewable energy, price interaction with intelligent

---

[139] Pike Research. (2012). *Smart Grid Data Analytics*. Navigant Research.
[140] McMahon. (2013). *Utilities Dumbstruck By Big Data From Smarter Grid*. Forbes LLC. Forbes.
[141] *Ibid*.

appliances, and a tremendous range of user options and applications through the smart home. [142] However, this promise cannot materialize without interoperability.[143]

Despite numerous standardization activities, systemic 'plug-and-play' interoperability is not yet available. Furthermore, smart meters cannot yet communicate with consumer appliances and there has been limited uptake of demand management systems by homeowners since smart grid control and interface technologies are either not available or are proprietary.[144]

Presently the marketplace is cluttered with many competing communications protocols including ZigBee, Z-Wave, IEEE 802.15, X10, RF, and others. This is an attempt by competing device manufacturers to lock customers into their proprietary ecosystem, so devices from different manufacturers do not necessarily communicate.[145] However, this significantly limits uptake of smart devices and home energy management systems on the consumer side of the meter, while also limiting the success of demand response programs by utilities.

Globally regulators have been working to develop standards for interoperability, but this is proving to be one of the greatest challenges for the smart grid due to the multitude of technologies, systems, and devices that need to be securely interconnect with the smart grid. [146] Interoperability standards will decide how utilities' systems and smart meters will communicate, how the grid will integrate demand response and distributed generation, how electric vehicles will interact with the grid, and how consumers' home networks will integrate energy management capabilities. [147] The choice about

[142] Kominers. (2012). *Interoperability Case Study: The Smart Grid*. The Berkman Center for Internet & Society at Harvard University. Berkman Center Research Publication.
[143] Gilbert et al. (2011). *Paths to Smart Grid Interoperability*. GridWise Alliance.
[144] Bichler. (2013). *Smart Grids and the Energy Transformation: Mapping Smart Grid Activities in Germany*. Heinrich Böll Stiftung.B
[145] Salkin. (2014). *What the smart home means for utilities*. Utility Dive. Utility Dive.
[146] DeBlasio. (2011). *Interoperability is Key to Smart Grid Success*. Continuum Magazine.
[147] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.

standards will shape the course of innovation, where even the most basic decision can have enormous and unforeseen consequences.

The National Institute for Standards in Technology (NIST) is the central U.S. agency charged with overseeing the adoption of the smart grid and is presently developing a framework for the interoperability of smart grid devices.[148] Since 2007, NIST has been working to develop national standards. However, progress has been slow. Typically standards can take years to develop, but with the enormous scope of the smart grid it is even more arduous because there are thousands of stakeholders. For example, the Ethernet standard for computer networking took a decade to ripen into a standard, and even longer to evolve into the robust standard we use today. This is just one standard, where the smart grid requires hundreds of standards to be developed all at once.[149]

Standards Lock-in

The development of these standards also represent a significant regulatory test that will determine whether they reinforce institutional lock-in or allow for innovation. Standards *are*, in effect, a form of regulation. The test in this case depends on whether interoperability standards are open and accessible, or closed and proprietary. Electricity utilities have a tradition of using proprietary customized systems. Also, utilities have little experience with consumer interoperability since there has never been a need for information systems on the utility side of the meter to interact with devices on the customer side.[150]

The NIST is at work with standards development organizations like the American National Standards Institute (ANSI). Under ANSI's Procedures for the Development and Coordination of American National

---

[148] Kominers. (2012). *Interoperability Case Study: The Smart Grid*. The Berkman Center for Internet & Society at Harvard University. Berkman Center Research Publication.
[149] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review. P. 33.
[150] *Ibid*.

Standards, ANSI seeks to "verify that the principles of openness and due process have been followed" and that "consensus of those directly and materially affected by the standards has been achieved".[151] However, this pluralistic ideal can break down in practice if the process is co-opted by powerful actors that embed content in the standards that favours their interest. There is concern that utilities in partnership with large private sector actors can unite to define the standards in their own interest and exacerbate utility monopoly power in an effort to stymie competition and innovation.[152]

Furthermore, NIST and ANSI have little experience with the electricity grid. They are working closely with the North American Electric Reliability Corporation (NERC), which is responsible for ensuring reliability of the wholesale power system, in accordance with the Federal Power Act.[153] Implicit in this is maintaining the economic viability of regulated utilities.

Interoperability standards are not solely about interaction. They can resolve confusion and promote innovation by giving firms confidence in the marketplace. An open architecture can eliminate market obstacles, and encourage competition from new entrants. If designed properly, standards can protect legacy infrastructure by ensuring compatibility between old and new technology. A standard is considered open if both a Fortune 500 company as well as a teenager in a garage can readily access it and build new products. An open interoperability standard would be like the open platform of the Internet where innovation enables cross-collaboration that draws on new ideas from multiple sources and promotes meritocratic business practices. In this atmosphere, disruptive technologies can produce rapid organizational changes, shifting the locus of power within an industry, and transforming some industries in what seems like overnight.[154]

---

[151] ANSI. (2001). *ANSI Procedures for the Development and Coordination of American National Standards*. American National Standards Institute.
[152] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.
[153] *Ibid*.
[154] *Ibid.*

In contrast to the fast pace of innovation with the Internet, utilities are accustomed to working with long time horizons and plan decades ahead. As such they tend to stick with products that are proven. Furthermore, the regulatory process itself takes time, and leads to slow change. Innovation and learning from mistakes is not the norm for utilities. There will be a strong tendency, and an opportunity, to implement standards that reinforce their monopoly using interoperability standards to do so. [155]

Privacy

Privacy gives utilities a strong case for tightly controlling smart grid information, and another lever of influence over electricity regulation.

Smart meters are now capable of generating reams of data that were not available before. There is voluminous literature on Internet privacy that shows how networking technologies present an ongoing threat to personal privacy. [156] Considering the central role that consumer data plays in the concept of the smart grid, it is not surprising that privacy concerns have arisen forcing utilities and regulators to address them.[157] As smart meters become increasingly sophisticated, they will be able to reveal a lot more about their customers than just energy consumption. They will be able to tell what devices customers own, when they are home and away, and many other characteristics. Smart meter data will be able to provide a virtual peak into people's lives.[158] This is proving to be a regulatory quagmire involving multiple agencies at different levels of government, and no clear rules on how to protect consumer energy data.[159]

---

[155] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.
[156] *Ibid.*
[157] Murphy. (2012). *Privacy and the Smart Grid: How Privacy Protections Were Designed Into Ontario's Central Meter Data Repository*. Gowling Lafleur Henderson LLP. gowlings.
[158] Herold. (2011). *ENSURING SMART GRID SOCIAL ACCEPTANCE BY SECURING DATA PRIVACY*. GRIDTalk.
[159] McNamara. (n.d.). *Data privacy issues may become a regulatory quagmire*. DNVGL.

However, when it comes to the amount of data collected, it raises an obvious question; how much is enough, and how much it too much? This question has pitted the data analytics industry's hopes for access smart grid data against privacy advocates worried that the same data could be abused. This leaves utilities and customers caught in the middle as it prevents the smart grid from achieving its full potential.[160]

Whether intentional or not, privacy may work to ensure that a proprietary network is the standard for the smart grid. This would help to bolster utility control over information by making utilities gatekeepers to user data. Utilities would have discretionary authority over where and how data gets used and by whom. This creates a substantial lever of control over the electricity marketplace.

[160] St. John. (2010). *Smart Grid Data: Too Much For Privacy, Not Enough For Innovation?* Gigaom Inc. GIGAOM.

5. Driving Transitions

New technologies never appear fully formed and in obvious working order. This is particularly true with complex socio-technical systems like the Internet and the smart grid.[161] The electricity grid appears to be at a critical inflection point with the emergence of the smart grid. In one direction the smart grid represents an *evolutionary* transition providing a powerful new tool for grid management within the existing electricity paradigm. In the other direction, grid modernization represents a *revolutionary* transformation that disrupts the existing energy paradigm, and develops the Internet of energy. Furthermore, we know that the regulatory and institutional environment in which the smart grid is emerging can set the course for its long-term development where regulatory decisions made at this nascent stage of development will unavoidably widen some avenues of innovation while foreclosing others.[162]

As shown above, large socio-technical systems develop their own momentum and experience increasing returns to adoption that makes them resilient to change. These systems are marked by long periods of incremental development of the dominant technologies. However, as Schumpeter has argued, these periods are punctuated by short bursts of 'disruptive innovation' where new technological products and processes, as well as the associated social and institutional knowledge, replace the existing regime.[163] We also know that energy regimes have been disrupted in the past and replaced by more efficient and better technology; whale oil was supplanted by kerosene and wood was replaced by coal, not because we ran out of whales or trees, but because rising costs spurred innovation.[164]

[161] Smith & Stirling. (2008). *Social-ecological resilience and socio-technical transitions: critical issues for sustainability governance*. STEPS Centre.
[162] Quinn & Reed. (2010). *Envisioning the Smart Grid: Network Architecture, Information Control, and the Public Policy Balancing Act*. U. Colo. L. Rev.
[163] Windrum. (2003). *Unlocking a lock-in: towards a model of technological succession*. … evolutionary economics: new empirical methods and ….
[164] AB Lovins. (2004). *Winning the Oil Endgame: Innovation for Profits Jobs, and Security*. Rocky Mountain Institute.

There are several factors that are positioned to overwhelm the stabilizing forces of the traditional utility model. *Firstly* the centralized utility model is experiencing institutional brittleness. As it has increased in scale and complexity, it is experiencing decreasing returns and increasing vulnerability. Utilities have reached the tipping point where the centralized top-down operating model will not meet the needs of the next generation grid.[165] In this respect, it appears that a transition is already underway with the move from centralized to a more decentralized system topography.

Secondly, the economics are changing for the centralized model. Where they once experienced increasing rates of returns, they are now experiencing the opposite in the face of increasing complexity. It this respect, the smart grid as it is envisioned by utilities, appears to be an attempt to maintain institutional control over the grid. However, the centralized utility model is now facing diseconomies of scale with increasing costs, and falling profits, while at the same time the alternatives are proving to be more competitive.

Thirdly, the emergence of competing technologies, and new technological configurations enabled by the smart grid, is eroding the centralized model's primary value proposition: *reliability*.

Fourthly, while the development of the smart grid is bogged down in a regulatory quagmire, innovation is doing an end-run around the interoperability standards in the smart home sector. Moreover, these innovations are happening at the 'edge' of the grid outside the regulatory control of utilities using the open platform of the Internet. Despite the fact that this is occurring on the customer side of the meter, the aggregate effect on the utility side could be significant, both positively and negatively for utilities. Furthermore, these innovations appear to be laying the foundation for an *Internet of Energy*.

[165] Dresselhuys. (2014). *Is a disaggregated future really all that far away?* Smart Grid News. Smart Grid News.com.

5.1. Techno-Institutional Brittleness

It is increasingly recognized that the conventional centralized utility model is inadequate for meeting the goals of producing reliable, sustainable, and cost effective electricity. The system is proving to be increasingly vulnerable to a range of interacting factors including system complexity, increasing costs, ageing infrastructure, cascading failures, falling demand, decreasing economic returns, fuel price volatility, and others.[166] In complexity terms, the utility model is becoming *brittle;* it is inflexible and incapable of adapting to changing conditions. Brittleness has arisen in the electricity grid largely due to the pursuit of economies of scale over the past century, its increasing complexity as a socio-technical system, and its centralized command and control structure. Yet despite the increasing complexity, the electricity grid is still conceived of and managed from a simple system perspective. These confounding factors work to make the system increasingly prone to sudden and massive failures from an institutional and technological perspective. However, this opens avenues for innovation as the centralized model shows that it is incapable of meeting future needs.

Institutional Brittleness

With the relentless pursuit of economies of scale, utilities experienced increasing returns (positive feedback) where electricity rates decreased, demand increased, and reliability improved. By 1955 there were significant scale economies available to utilities. Large generation projects helped reduce the per-unit cost of electricity substantially, up to 60% in extreme cases. However, by the 1970s, bulk electricity generation had reached the scale where it was operating in the flat area of the cost curve. Beyond this point, diseconomies of scale, decreasing returns, and technological and financial risk began swamp scale

[166] O'Brien & Hope. (2010). *Localism and energy: Negotiating approaches to embedding resilience in energy systems*. Elsevier. Energy Policy.

economies. As a consequence, the rates charged for electric power had started to rise at an unprecedented rate.[167]

With electricity generation becoming increasingly large and further displaced from its loads, electricity systems were faced with a host of confounding problems included construction delays, cost overruns, increasingly complex and more frequent grid failures, and the need for larger back-up capacity. Longer transmission lines to deliver the electricity to their customers also resulted in greater transmission losses and higher risks for power disruption.[168] Furthermore, the economies of scale model also has a tendency to develop path dependencies. Rigidities in technology, institutions, policy, and market dimensions make it inflexible to changing conditions and external shocks.[169] These factors resulted in higher financing and insurance costs due to the increasing financial risks.

Described as 'hard-path' energy planning, the construction of large centralized generation and transmission infrastructure also requires large capital investments and very long planning time horizons. For instance, the construction and operation of a nuclear generating facility can have a life-cycle ranging from 40 to 85 years. Ontario's Darlington Nuclear Generation Station provides a good example. In 1970 approvals were given to acquire land in Darlington Township. In 1977 provincial and federal approvals were granted. In 1978 site preparation commenced and in 1981 a construction license was granted. Darlington was fully in-service in 1993. Now after 20 years of service, it is time for a major overhaul of Darlington with refurbishment plans that are expected to span form 2013 to 2024. This will push the operation of Darlington to 2055.[170] From inception to the end of service, the Darlington project spans 85 years. It is important to note that this time-frame does not consider decommissioning. So far there is little world-wide experience in decommissioning, dismantling, and disposing of radioactive waste so

---

[167] Christensen & Greene. (1976). *Economies of scale in US electric power generation*. The Journal of Political Economy.
[168] Diebold et al. (1982). *Brittle Power: Energy Strategy for National Security*. Brick House Publishing. Foreign Affairs.
[169] Jurowetzki. (2013). *The Evolution of the Danish Smart Grid Sector: Industrial Composition and Interaction Patterns*.
[170] OPG. (2011). *Darlington Nuclear Generating Station Refurbishment and Continued Operation Environmental Assessment*. Ontario Power Generation.

the total life-span is highly uncertain. However one estimate suggests it could put the life-span of a nuclear power plant at 150 years from construction to decommissioning.[171] These long time horizons make energy planning increasingly difficult and expose utilities and ratepayers to financial risk.

Furthermore, the centralized model has historically relied on a steady increase in demand, but within recent years, this demand growth has been slowing presenting another challenge to the utility business model. While in absolute terms the demand for electricity has steadily risen in North America since 1949, however, the rate of demand growth has been steadily slowing[172] and the U.S. IEA says there is significant uncertainty about future electricity demand.[173] In some areas analysts expect a decline in demand in absolute terms over the next decade.[174] Decreasing demand is leading to falling sales of electricity as well as falling profits for utilities at time when they are expected to make significant investments in aging infrastructure.

Increasing costs, long time-horizons, and uncertainty about future demand exposes the institutional brittleness of the centralized utility model. If planners fail to predict future demand then they could have conditions of over-supply or under-supply. Once the construction of a large project has started it is politically and financially very difficult to change course in response to changing conditions or demand. This inflexibility (brittleness) exposes ratepayers and taxpayers to considerable risk. These factors conspire to cause *decreasing returns* for infrastructure investments and cast considerable doubt on the utility business model. However, they also highlight the benefits of distributed generation since it is more flexible and proving to be increasingly competitive, as we will see below.

[171] M Schneider et al. (2012). *Nuclear Power in a Post-Fukushima World*. Worldwatch Institute.
[172] A Lovins & Rocky Mountain Institute. (2011). *Reinventing fire: bold business solutions for the new energy era*. Chelsea Green Pub. P. 174.
[173] U.S. Energy Information Administration. (2013). *Annual Energy Outlook 2013: with projections to 2040*. P. 61.
[174] OCAA. (2009). *Powerful Options: A review of Ontarios's options for replacing aging nuclear plants*. Ontario Clean Air Alliance Research Inc.

A recent PricewaterhouseCoupers (PwC) survey of utility executives indicates that those in the utility business are feeling the strain from their institutional brittleness. The survey of executives from 53 power utilities across 35 countries shows that many in the industry believe that power utilities are facing a major disruption with immense near-term challenges. Power companies are pulling the plug on conventional generation and the utility commodity business will face continued strong headwinds. 94% of utility executives surveyed predict a complete transformation of the power utility business model to the point of being unrecognizable by 2030.[175]

Utilities have always built infrastructure as long-term investments. The utility sector used to enjoy high investment credit ratings that enabled it to develop capital-intensive assets and rely on predictable long-term cost recovery based on increasing demand.[176] But hardware that seemed like a good investment in the 1990s is suddenly being exposed as untimely and unnecessary. Demand has flattened and customers are increasingly generating their own power.[177] The centralized, vertically integrated giants that emerged from the central planning paradigm, now see their historical business model challenged by several factors. Increased competition due to market liberalization, an influx of private capital into activities that had traditionally been reserved for the public sector, regulation of one part of the business model coupled with competitive pressures in other parts, stagnant demand, aging infrastructure, high fuel costs, and competitive pressure from renewable energy, have created a perfect storm for utility shareholders and executives. Utilities now face uncertain times. With developments in renewable energy, they are like the landline phone companies facing down the iPhone. Distributed energy is already eating into the revenues and marginalizing conventional generation. Ultimately this

[175] PwC PricewaterhouseCoopers. (2013). *Energy transformation: The impact on the power sector business model*.
[176] *Ibid*.
[177] Farrell. (2013). *Utility Shocked to Find It's Already Dead*. ILSR: Institute for Local Self-Reliance.

could shrink the role of the power utility company to operators of back-up infrastructure.[178] These market conditions have presented significant challenges to the centralized utility business model.[179]

Technological Brittleness

The tightly coupled nature of the electricity grid along with the increasing scale of the system also exposes another vulnerability of the centralized model. Complexity tells us that as systems increase in scale they become increasingly unstable and begin to exhibit threshold behaviours and cascading failures. These are the usual mechanisms that cause widespread blackouts in the electricity system. There have been several examples of major blackouts in recent decades: in 1977, nine million people lost power for 5 to 25 hours;[180] in 1996, 7.5 million customers lost power in Northwestern America; in 2003, fifty million people lost power across eight states and two provinces.[181] Globally, there are similar examples: the 2009 blackout in Brazil and Paraguay affected sixty million customers; and in 2012, 600 million people lost power in India across 28 states, taking down three out of fives of its grids.[182]

Blackouts provide excellent examples of brittleness in complex systems. Often these blackouts are the result of a small disturbance that is amplified through *feedbacks*, triggering a *non-linear response* that is radiated outwards through *cascading failures.* For instance, the 2003 blackout was the result of tree branch touching a power line. Furthermore, it is expected that the frequency and severity of power disruptions will continue to grow along with the complexity of the system, and increasingly because of extreme weather due to climate change.[183]

---

[178] PwC PricewaterhouseCoopers. (2013). *Energy transformation: The impact on the power sector business model*.
[179] White et al. (2013). *The future of energy utilities: How utilities can survive the "perfect Storm."* Arthur D Little.
[180] Diebold et al. (1982). *Brittle Power: Energy Strategy for National Security*. Brick House Publishing. Foreign Affairs. P. 51.
[181] Dobson et al. (2007). *Complex systems analysis of series of blackouts: cascading failure, critical points, and self-organization.* Chaos (Woodbury, N.Y.).
[182] Matthewman & Byrd. (2014). *Blackouts: a sociology of electrical power failure*. Social Space (Przestrzeń Społeczna ….
[183] *Ibid*.

According to Amory Lovins, brittleness arises because of mismatched technology. The scale, complexity, centralization, and control structure of electricity systems makes them inherently vulnerable to large-scale failures (a vulnerability which government policies have systematically increased).[184] The extreme centralization of the electricity system and the grossly mismatched scale between generation and consumption is the root of the "brittleness" in the electricity system. This is becoming increasingly apparent, particularly when less centralized energy technologies can avoid this vulnerability, and also do so more economically and with a smaller impact on the environment.[185]

5.2. Changing Economics

A '*burning platform*' is a business lexicon used to describe the point where the costs of staying with the existing system (burning oil platform) are becoming greater than moving to a new system (jumping).[186] In systems thinking, this is referred to as a *tipping point*. This is when a self-organizing system has no more buffering capacity to absorb a disturbance and the system is pushed beyond its threshold and suddenly transitions to a new state of equilibrium.[187]

Momentum appears to be shifting, not only from fossil-fueled generation to renewables, but also from centralized to distributed energy systems. The centralized model is now facing decreasing rates of returns, increasing costs, falling profits, and increasing failures. However, distributed renewable energy is proving to be more cost competitive and profitable, and more resilient. Furthermore, economies of scale are achieved at significantly lower levels with renewable technologies, which also favours smaller and more widely dispersed development. The important leap made with a transition from centralized to

---

[184] Diebold et al. (1982). *Brittle Power: Energy Strategy for National Security*. Brick House Publishing. Foreign Affairs. P. 1.
[185] *Ibid.*
[186] "The Burning Platform." (2012) Problem-Solving-Techniques.com.
[187] Waltner-Toews et al. (2008). *An Introduction to Systems Thinking*. Columbia University Press. The Ecosystem Approach: Complexity, Uncertainty, and Managing for Sustainability.

distributed is that the means of producing electricity has changed from slow moving gigantic projects, to scalable, agile, mass-produced, manufactured products. This has several important outcomes: it helps to level the playing field and enables more players to enter the energy market place; it increases competition and innovation; it improving energy system flexibility and resilience; it reduces financial risks; and enables different ownership structures like cooperatives.

Distributed Energy

> ***"The centralized, infrastructure-centric status quo is the problem with or without high levels of renewable energy"***
> ***Pentland, 2012***

Distributed energy presents a compelling alternative to the centralized energy regimes that have been dominant for almost a century. Described as the "soft energy path",[188] this vision of the of the electricity system would see the electricity industry completely restructured and the underlying utility grid infrastructure completely reengineered based on distributed generation and decentralized transmission and delivery. [189] This emerging paradigm of energy production is geographically dispersed and connects to the existing distribution grid infrastructure. Distributed energy is considered to be more economical,[190] and more flexible and scalable then centralized power generation.[191] Since it can be located closer to load-centres, distributed generation could save nearly 30% of total electricity costs by reducing transmission losses and displacing expensive transmission infrastructure.[192] These facts are fundamentally changing the way planners and engineering conceive of energy production and distribution. [193]

---

[188] AB Lovins. (1976). *Energy Strategy: The Road Not Taken?* Foreign Aff.
[189] Dedrick & Zheng. (2011). *Smart Grid Adoption: A Strategic Institutional Perspective*. industrystudies.pitt.edu.
[190] AB Lovins et al. (2003). *Small is profitable: The Hidden economic benefits of making electrical resources the right size*. Rocky Mountain Institute.
[191] Weis et al. (2010). *Renewable is Doable: Ontario's Green Energy Plan 2.0*. The Pembina Institute.
[192] IEA. (2002). *Distributed generation in liberalised electricity markets*. OECD Publishin.P. 128.
[193] Farrell. (2011). *Democratizing the Electricity System: A Vision for the 21 st Century Grid*. New Rules Project. Institute for Local Self Reliance Pub.: Washington DC, ….

Despite being smaller in scale, distributed energy generation from solar PV and small-scale wind power are uniquely positioned to disrupt the traditional centralized paradigm. In a growing number of cases around the world, distributed renewable generation technologies are proving to be more cost-effective than centralized installations since they can be located close to load centres, requiring less transmission infrastructure. Even though distributed renewable installations presently represent a small fraction of total worldwide electricity generation capacity, it is expected that this will expand rapidly over the next decade.[194] This transition has been enabled by a clutch of clean distributed energy technologies ranging from small wind turbines, to building integrated solar photovoltaic, to micro-CHP fuel cells and micro-turbines that present an environmentally and economically compelling alternative to the status-quo.[195]

However, it is important to note that the clean energy camp is divided with competing views about a sustainable power grid. On one side, developers of utility-scale solar and wind power are scrambling to corner the market by reinforcing the centralized model that excludes competition from small-scale participants.[196] This is one of the problems of feed-in tariffs for wind and solar that has created a gold rush for developers of industrial-scale wind and solar. However, just like the traditional centralized model, these sources produce electricity remotely and transmit it to load centres. Even thought these sources are more distributed then nuclear generation, since the sun and wind are dispersed widely, utility-scale solar and wind power are not true representations of distributed energy.[197]

On the other side, environmentalists, entrepreneurs, and smart growth supporters believe that a better route to sustainable energy is by empowering consumsers to invest in high efficiency, low emission clean distributed technology located close to the point of consumption.[198] From a smart grid perspective, distributed generation should be viewed a way of meeting some level of local demand and

---

[194] Martin. (2012). *Annual Renewable Distributed Energy Generation Installations Will Nearly Triple by 2017*. Navigant Research.
[195] Pentland. (2012). *Renewable Energy's Escalating Political Crisis*. Forbes.
[196] *Ibid*.
[197] Hawkins. (2011). *The Smart Grid and Distributed Generation: A Glimpse of a Distant Future*. Master Resource: A Free-Market Energy Blog.
[198] Pentland. (2012). *Renewable Energy's Escalating Political Crisis*. Forbes.

not solely to feed into the bulk electricity grid. True distributed generation involves small-scale generation sources such as rooftop solar and micro wind turbines as well as many other non-utility scale generation means.[199] Furthermore, distributed generation may have as much to do with the distribution of ownership as it does with its spatial configuration.

In the book *Small is Profitable: The hidden economic benefits of making electrical resources the right size*, Lovins advocates for soft energy paths instead of centralized vision for energy. In it he describes 207 benefits that are derived from decentralized or distributed electrical resources. These benefits typically raise the economic impact of distributed energy by approximately tenfold through improved system planning, utility construction and operation, and service quality, and by avoiding societal costs. He argues that the economies of scale that were initially gained by the centralized power station overlooked larger system wide diseconomies of scale in the grid, the way the system is operated, and the architecture of the entire system. The centralized vision that bigger is better ended up raising the costs and financial risks that it was intended to reduce.[200]

> ***"Central thermal stations have become like Victorian steam locomotives: magnificent technological achievements that served us well until something better came along"***
>
> ***Amory Lovins, 2009***

Historic Crossover

In light of these facts, it is increasingly recognized that the centralized model is growing more and more costly to maintain. In contrast, the costs of the alternatives have experienced a steady decline. Energy efficiency, solar, demand-side management and the smart grid are widely recognized within the utility industry as a threat to their electricity commodity markets.[201] Until recently, growth in renewable

---

[199] Hawkins. (2011). *The Smart Grid and Distributed Generation: A Glimpse of a Distant Future*. Master Resource: A Free-Market Energy Blog.
[200] AB Lovins et al. (2003). *Small is profitable: The Hidden economic benefits of making electrical resources the right size*. Rocky Mountain Institute.
[201] PwC PricewaterhouseCoopers. (2013). *Energy transformation: The impact on the power sector business model*. P. 10.

generation was largely driven by subsidies, but this growth has also contributed to their falling costs. Some cost barriers remain, but at some point, the rising costs of the conventional system will *crossover* the declining costs of the alternatives, even without subsidies. Crossover would overcome these barriers and set the stage for a widespread global industry transformation that is truly market-driven.

It seems that this crossover may have occurred. UBS Investment Research published a paper declaring the "unsubsidized solar era begins" and now utilities' customers are becoming their competition.[202] This was further reinforced by several reports issued within the past year from prominent organizations around the world. Royal Dutch Shell, Deutsche Bank, NDP, and SolarBuzz have each issued reports stating that solar is becoming an increasingly competitive energy source and is coming into grid parity.[203] A Citigroup research study also found that residential solar has already reached parity in regions with high solar insolation, and utility-scale renewables should be competitive with gas-fired power in the short to medium term, with the exact crossover point varying from region to region.[204]

While the costs of renewables are falling, energy from conventional sources are rising. Over the past decade the cost of nuclear generation has seen a significant increase, particularly after the Fukushima disaster. In early 2000, the nuclear industry was promising a "nuclear renaissance" with the costs for Generation III nuclear generators estimated at around $1,000/kW. This made it competitive with the cheapest source of power, natural gas, which was being sold at a low price compared to current prices. However, a decade on, it became clear that claims for these new reactors were hopelessly inaccurate and by 2012 the cost estimates were revised to $7,000/kW.[205]

[202] PwC PricewaterhouseCoopers. (2013). *Energy transformation: The impact on the power sector business model*. P.10
[203] Meehan. (2013). *New Conergy Solar Installations Reach Grid Parity — in New Mexico*. Renewable Energy World.com.
[204] PwC PricewaterhouseCoopers. (2013). *Energy transformation: The impact on the power sector business model*. P. 10.
[205] Mycle Schneider & Froggatt. (2013). *World Nuclear Industry Status Report 2013*.

One explanation for the massive cost increase was the initial estimates were on a cost-plus basis, where any risk or cost overruns would be paid by the government or ratepayers. In Ontario, the plan to build two new reactors at the Darlington site was cancelled when Atomic Energy of Canada Ltd. was asked to submit a fixed cost bid and it came it at $26 billion for 1,200 megawatts of generation. That works out to $10,800 per kW, almost a fourfold increase over the original estimate of $2,900 per kW.[206] Europe has seen nuclear prices soar as well. In 2002 cost estimates were between $2 billion and $4 billion per unit. By 2008 this rose to $9 billion per unit.[207]

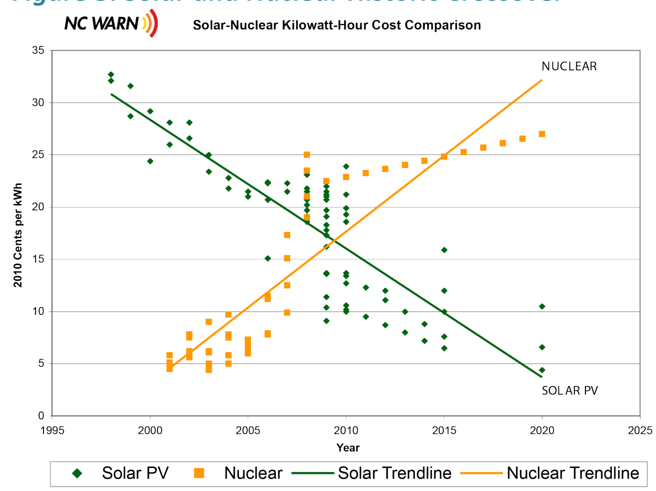
In contrast, the cost curves for solar and wind power have been in steady decline. Since 2008 the installed price for solar PV has fallen by 80% (99% since 1977), and land based wind power has fallen by 29%.[208] This shift to mass-produced energy technology is driving the price of solar relentlessly downwards just as it did with consumer electronics like smartphones or PCs. This is largely due to increasing productivity in China, which has ramped up solar production in recent years to meet its 35 GW PV target for 2015. A single Chinese PV factory can produce several GW of PVs each year.[209] In less than a decade, the solar PV industry has transformed from a cottage industry to a $100 billion business. Driven by subsidies, market innovations, and new market entrants, PV prices have fallen precipitously, and as of 2013, over 100 GW of Solar PV have been installed globally.[210] Analysts have calculated the economic potential of PV growth could be over a terawatt (1,000 GW) by 2020. A more conservative estimate between 400 to 600 GW might be appropriate considering potential barriers due to regulatory changes and access to finance.[211]

---

[206] Hamilton. (2009). *$26B cost killed nuclear bid*. The Toronto Star.
[207] UCS USA. (2013). *The Cost of Nuclear Power: Numbers That Don't Add Up*. Union of Concerned Scientist.
[208] Shahan. (2013). *Solar PV Module Prices Have Fallen 80% Since 2008, Wind Turbines 29%*. Clean Technica. Clean Technica.
[209] Amory Lovins. (2014). *Amory Lovins: Three Major Energy Trends to Watch*. Rocky Mountain Institute.
[210] Montgomery. (2013). *100 GW of Solar PV Now Installed in the World Today*. Renewable Energy World.com.
[211] Aanesen et al. (2012). *Solar power: Darkest before dawn*. McKinsey on Sustainability ….

The crossover point has already been met in North Carolina with nuclear generation. Here state law requires that electricity development follow a 'least-cost' path where less expensive resources are to be added first. It is recognized that energy efficiency, wind power, and combined heat and power (CHP) are already cheaper than new nuclear generation, but recent analysis shows that the levelized cost for solar reached a 'crossover point' in 2010 in North Carolina. It was recognized that Solar PV had reached the *tipping point* where unsubsidized PV generation became cost competitive with conventional sources.[212] See Figure 3.

Figure 3: Solar and Nuclear Historic Crossover



Source: Blackburn[213]

Furthermore, analysts at General Electric anticipate that solar will be cheaper than electricity generated by fossil fuels within five years.[214] However, recently the investment banking giant Citigroup proclaimed that the "age of renewables" in the United States is here. Based on the levelized cost of energy, solar, wind and other renewable energy sources are proving to be more attractive and price competitive than natural gas peaking plants and nuclear baseload plants. Citigroup predicts that solar, wind, and biomass will continue to take market share away from coal and nuclear in the future.[215]

A recent ruling by an administrative law judge for the Minnesota Public Utilities Commission seems to reinforce these predictions. The judge was weighing the costs and benefits between competing energy investments to fill a 100 MW gap in Minnesota. There were several proposals, but the two most competitive options was a choice between a large gas-fired plant and a series of distributed solar

[212] Aanesen et al. (2012). *Solar power: Darkest before dawn*. McKinsey on Sustainability ….
[213] Blackburn & Cunningham. (2010). *Solar and Nuclear Costs — The Historic Crossover*. NC WARN: ….
[214] Wingfield. (2011). *GE Sees Solar Cheaper Than Fossil Power in Five Years*. Bloomberg.
[215] Parkinson. (2014). *Citigroup Says the "Age of Renewables" Has Begun*. Greentech Media Inc.

projects built around the state. Judge Eric Lipman issued a decision this past December and ruled that distributed solar was more cost-effective than natural gas for meeting Minnesota's peak power needs. Lipman gave several reasons: future electricity demand is uncertain and seems to be falling; carbon capture and storage regulations should apply to new fossil plants, including gas plants; distributed solar would save $33 million required to upgrade transmission lines for the centralized gas-fired plant; and lastly considering all these issues, it is better to make incremental, 'scalable' investments in solar rather than a lump sum investment in centralized and inflexible generation.[216]

This decision is proven even more fiscally prudent considering the recent price volatility for natural gas. The unusually cold winter caused by the 'polar vortex' exposes the economic vulnerability with fossil-fuel electricity generation.[217] With renewables, the fuel is always free.

Local Ownership

Local ownership works to increase local and political support distributed energy compared to centralized power generation where we have seen opposition to power plants and transmission lines.

The distributed nature of renewable energy means they tend to favour much smaller economies of scale when compared to traditional large-scale centralized generation.[218] This opens opportunities for greater participation in the energy business and makes it possible for small to midsize enterprises, individuals, and community groups to participate in energy generation. In Denmark, the shift from centralized coal-fired power plants to distributed wind and cogeneration plants over 32 years was made possible in part because 86% of this distributed generation was owned by farmers and their communities. Similarly, in

---

[216] Milford. (2014). *Natural Gas Loses to Solar on Costs, A First*. Huffington Post.
[217] Farrell. (2014). *Natural Gas isn't a Bridge Fuel, it's a Gateway Drug*. Institute for Local Self-Reliance.
[218] AB Lovins et al. (2003). *Small is profitable: The Hidden economic benefits of making electrical resources the right size*. Rocky Mountain Institute.

Germany, half of the renewable capacity is owned by citizens, cooperatives, and communities. [219] Contrary to the unhealthy concentrations of social power and wealth found in centralized systems, distributed energy greatly increases the number of individuals with a direct stake in the success of renewable energy projects, and helps to distribute wealth throughout local communities. Local ownership increases agency over energy production and has the effect of increasing acceptance and public support for renewable energy.

Although distributed ownership of renewables in North America may lag behind Europe, new financial models in the U.S. are providing access to the capital needed to get renewable projects off the ground. Crowd-funding, real estate investment trusts, commercial PACE bonds, and the explosive growth of third-party installers/owners like SolarCity are starting to revolutionize U.S. solar project financing. [220] Furthermore, homebuilders are also helping to increase solar penetration, and reduce costs, by installing them during new home construction. Rooftop solar is becoming a fashionable 'upgrade' for new home purchases, much like granite countertops. Solar will soon be a standard option in California and the price will be rolled up in the mortgage. Solar systems installed during home construction reduce system costs by 20% compared to retrofitting. Where solar was a novelty, it has already transitioned to the "granite countertop phase" and will eventually be a mainstream option, according to Tom Werner of SunPower.[221]

5.3. Emerging Technologies

A variety of new technologies and new technological configurations have recently emerged that present disruptive challenge to the centralized utility business model. These include solar photovoltaics (PV),

---

[219] Amory Lovins. (2014). *Amory Lovins: Three Major Energy Trends to Watch*. Rocky Mountain Institute.
[220] *Ibid.*
[221] Doom. (2013). *Solar Panel Is Next Granite Countertop for Homebuilders*. Bloomberg L.P. Bloomberg.D

battery storage, fuel cells, geothermal energy systems, wind, micro turbines, and electric vehicle (EV) enhanced storage. Although some of these technologies are not new, the changing economic landscape has made them more directly competitive. Furthermore, the integration of the smart grid has enabled novel configurations of technologies like solar power and on-site storage, or smart charger enabled vehicle-to-grid storage. The configuration of distributed generation in combination with distributed storage is conspiring to erode the centralized model's primary value proposition: *reliability.*

Storage

There is a fundamental truth about the electricity grid; that electricity must be supplied at the precise moment and quantity that is demanded by consumers.[222] Failure to match supply with demand can lead to frequency and voltage fluctuations, disruptions in service, or system collapse.[223] This truism makes managing the grid a complex endeavor since demand is not constant. Compounding this problem is the increasing deployment of intermittent sources of electricity generation like wind and solar.[224] This fact imposes limits to the amount of renewable generation that can be managed on the grid without causing reliability issues.[225] In light of this reality, electricity storage is becoming increasingly recognized as an essential component of the future electricity grid. Storage will play a critical role in managing the fluctuation of demand and the intermittency of supply from renewable sources of electricity.[226] Storage may also play a key role in disrupting the centralized utility model too.

Starting a century ago, one of the primary objectives for power utilities was to increase reliability. With the technology of the day, the centralized model was the best way to improve reliability. At the time, power generation was much costlier and less reliable than the grid. In order to achieve an acceptable

[222] Manz et al. (2011). *Value propositions for utility-scale energy storage*. Power Systems Conference and ….
[223] Pejovic. (2011). *White Paper Hydro Energy Storage*. Centre for Urban Energy, Ryerson University.
[224] O'Malley. (2012). *Overcoming hurdles to make energy storage a reality*. MaRS.
[225] *Ibid.*
[226] NRCan. (2012). *Utility Scale Electricity Storage Demonstration Using New and Re-purposed Lithium Ion Automotive Batteries*. Natural Resources Canada.

level of reliability, generation assets were connected through transmission networks to create redundancy. This also contributed to the increasing scale of power plants since they needed enough capacity to compensate for the failure of another large power plant.[227] From an operations standpoint, the electricity grid was designed and operated as a "load-following" system. This meant that loads were variable, but predictable, and generation needed to be "dispatchable", meaning that it could be easily adjusted to follow the varying loads using frequency as a key indicator of overall system reliability.[228]

However, today things are different. Generation typically costs less than transmission, and 98% of power failures originating from the grid. With scale economies, the grid became increasingly dispersed as increasingly larger power plants moved further away from their loads, thus increasing the risk of failures from transmission.[229] Furthermore, the capital-intensive nature of nuclear and other large-scale generation assets means they need to be operated at a steady-state in order to maximize economic return on the investment. Called baseload generation, these assets operate below the minimum demand curve because they are not capable of load-following. Dispatchable assets like gas power "peaker" plants operate to follow the loads above the baseload levels. However, with falling demand, and the integration of intermittent sources, the grid is facing conditions of surplus baseload generation where more electricity is being generated than what is demanded by the grid. Often utilities will need to dump electricity or pay other regions to take their surplus electricity. This further undermines the economic performance of the centralized grid.

In this respect, cheap electricity storage would be a game changer, not only for renewables integration, but also for disrupting the utility business model. As discussed, the decreasing cost for solar PV is already eroding utility revenues. The same is true for storage costs. When cheap distributed solar is

[227] A. B. Lovins. (2009). *Does a Big Economy Need Big Power Plants?* Freakonomics.
[228] GridWise Architecture Council. (2013). *GridWise Transactive Energy Framework: DRAFT Version*. GridWise Architecture Council.
[229] A. B. Lovins. (2009). *Does a Big Economy Need Big Power Plants?* Freakonomics.

integrated with increasingly cost effective storage, this further erodes the need for centralized utilities and their complex load-following system. Reliability is already built into the system nodally without a centralized control structure. Furthermore, this is making the grid optional. Customers can cut the cord from their utility without sacrificing reliability, and it is increasingly at prices that are cheaper than the utility retail system.[230]

Electric Vehicles

Leading the charge for reduced battery costs is the electric vehicle market. In an effort to curb GHG emissions in transportation and improve energy independence, some argue that electric vehicles are poised to disrupt the transportation system. However, the real benefit from mass EV deployment would be the synergies created when integrating two energy networks, transportation and electricity. Historically transportation and electricity energy-infrastructure have been planned and operated separately. Electrifying transportation would enable planning and optimization that takes into account both electricity and transport sectors as one integrated system. While EVs will increase demand on the electricity grid, they will also help manage it when integrated through the smart grid. EVs would become a significant source of storage that would enable greater penetration of intermittent sources like solar and wind while reducing the costs of both.[231] A distributed network of EV batteries integrated in the smart grid will provide grid regulation services to help manage frequency and load fluctuations as well as improve reliability.[232]

Globally transportation represents one of the largest contributors to energy demand, urban air pollution, and greenhouse gas (GHG) emissions. In Canada, this sector accounts for almost 35% of total

---

[230] Bronski et al. (2014). *The Economics of Grid Defection: When and Where Distributed Solar Generation Plus Storage Competes with Traditional Utility Service, Executive Summary*. Rocky Mountain Institute.
[231] Hajimiragha et al. (2010). *Optimal transition to plug-in hybrid electric vehicles in Ontario, Canada, considering the electricity-grid limitations*. Industrial Electronics ….
[232] Sood et al. (2009). *Developing a communication infrastructure for the smart grid*. IEEE. Electrical Power & Energy Conference..

energy demand and is the second highest source of GHG emissions.[233] Despite these benefits, adoption has been slow so far primarily due to cost, performance, and range of EVs that is largely dictated by the cost and capacity of EV batteries.

However, battery storage technology is following the same trajectory as solar panels; reduced costs and improved efficiency. Over the past decade lithium-ion (Li-ion) batteries have seen consistent increases in performance while the cost per unit storage capacity has declined dramatically. Analysts expect this trend to continue over the next decade where stored energy costs could drop from $560 per kWh (2011) to $165 per kWh by 2025. Reduced costs and increased performance will enable broader adoption of EVs and make them cost competitive with internal combustion vehicles by 2025 based on total cost of ownership.[234]

Utility in a Box

Recently Tesla Motors has made a move where analysts expect to see significant cost and efficiency improvements in battery technology. Recognized as a world leader for premium electric vehicles, the company plans to build what they are calling a "Gigafactory" to produce batteries, which could bring mainstream pricing for Tesla's cars, which, at over $100,000, is still a niche product. Tesla is in discussion with Panasonic to partner with for developing its $5 billion Gigafactory that would employ 6,500 people. This would lead to significant unit price reductions through scale economies, just like Henry Ford did 100 years ago.[235] However, analysts are predicting Tesla's Gigafactory will have a much greater impact on Utilities. Adam Jonas from Morgan Stanley indicated that if Tesla can become the world's low-cost producer in energy storage, there is a significant potential for "Tesla to disrupt adjacent

---

[233] Hajimiragha et al. (2010). *Optimal transition to plug-in hybrid electric vehicles in Ontario, Canada, considering the electricity-grid limitations*. Industrial Electronics ….
[234] Manyika et al. (2013). *Disruptive technologies: Advances that will transform life, business, and the global economy*. McKinsey Global ….
[235] Lyons. (2014). *Tesla's Giga Battery Factory Threatens the Auto, Utility and Building Controls Markets*. Greentech Media Inc.

industries".[236] Affordable battery storage is the "holy grail" for the distributed energy movement according to Travis Miller, an analyst with Morningstar Inc. High-capacity battery technology would open the door to a significant increase in options for customers to supply their own power. The scale of Tesla's battery production, even for use in its own cars, makes the company a 'key player' for grid storage.[237]

Tesla seems to be aware of the market opportunity for solar-plus-storage and has launched a partnership with SolarCity, to supply on-site energy and storage services. SolarCity is a market leader for home energy services and has installed nearly one third of all U.S. residential PV in 2013.[238] Described as the 'utility in a box' this emerging technological configuration represents a fundamentally different challenge for utilities. Whereas many other distributed technologies, including solar PV, still require some degree of grid dependence, solar-plus-batteries enable customers to cut the cord all together.[239]

For analysts and utilities, it seems the writing is on the wall. As the cost curve for solar-plus-storage improves, they could directly threaten the centralized utility model.[240] When it reaches grid parity, as it has in some places, this could trigger mass defections from the grid. As customers defect, this creates a viscous cycle where the balance of the cost for the centralized utility is shared amongst few customers. The resulting rate increase will likely prompt more customers to defect leaving utilities to pay for stranded assets with a declining customer base, ultimately challenging the economic viability of the

[236] Quoted in Chediak. (2014). *Tesla Battery Jolts Shares Higher While Disrupting Power*. Bloomberg.
[237] Chediak. (2014). *Tesla Battery Jolts Shares Higher While Disrupting Power*. Bloomberg.
[238] Munsell. (2014). *SolarCity's Market Share Jumps to 32% in US Residential PV*. Greentech Media Inc.
[239] Peter Bronski et al. (2014). *The Economics of Grid Defection: When and Where Distributed Solar Generation Plus Storage Competes with Traditional Utility Service*. Rocky Mountain Institute.
[240] Kind. (2013). *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business*. Edison Electric Institute.

centralized grid.[241] This disruptive potential is leading many to forecast the impending "death spiral" for utilities,[242] and according to Morgan Stanley, the tipping point is near.[243]

Furthermore, trust in energy utilities has reached an all-time low across Europe where utilities are charging customers progressively more, and often delivering less, as intermittent renewables undermine grid stability.[244] There is discontent in North America as well with big-box retail and telecom giants planning to 'divorce' their utilities and go off grid.[245] Solar is currently supplying 2% of U.S. electricity needs, but it is expected to grow to 16% by 2020. To protect revenues, some utilities are raising electricity costs for solar panel owners who have responded by considering grid defection. Walmart, Costco, Kohl's IKEA, Macy's and Verizon have all installed a significant amount of renewable energy. Walmart has installed 65,000kW of solar, which is enough to power 10,000 homes or approximately the equivalent to taking two fossil fuel plants off-line. Their plan is to be 100% renewable by 2020.[246]

Solar-plus-storage is not only putting pressure on utilities, they are also positioned to radically transform the established business model for utilities, and undermine one of the central value propositions for centralized utilities: reliability. The changing economics and this emerging technological configuration is demonstrating that distributed energy is no longer a niche technology or a cottage industry, but has become an "existential threat" to utilities.[247]

---

[241] Lehr. (2013). *Three Regulatory Models That Could Help Utilities Embrace the Future*. Greentech Media Inc.
[242] Lacey. (2014). *This Is What the Utility Death Spiral Looks Like*. Greentech Media Inc.
[243] Parkinson. (2014). *Tipping Point Nears for Abandoning the Utility and Going Off-Grid*. Greentech Media Inc.
[244] Berst. (2012). *Utility business model is dying fast, claims European consultant*. Smart Grid News.com.
[245] Berst. (2013). *First Walmart, then Verizon - and now a how - to guide for divorcing your utility*. Smart Grid News. Smart Grid News.
[246] Finnigan. (2013). *Net metering wars: An environmentalist's view (better news than you might think)*. Smart Grid News.
[247] Mauldin. (2013). *Postcards from the Edge: Is the Utility Industry in Big Trouble?* Transmission & Distribution World Magazine.

5.4. Internet of Energy

The Internet is widely regarded to be a disruptive technology. It is driving profound changes in technology, demographics, and the global economy, and is giving rise to powerful new modes of production based on community, collaboration, and self-organization.[248] It has empowered people by enabling them to organize themselves, create common value together, and generate and distribute their own media. Through new collaborative practices ranging from open innovation, co-design, co-creation, crowd-sourcing, peer-to-peer distribution, the Internet is creating a new social system of commons-oriented peer production, that is fostering a new collaborative economy.[249] As a result, the mass-production, centralized industrial-age model that has persisted for over a century is being disrupted by what has been described as "distributed capitalism".[250]

What happens when the information age meets one of the last great vestiges from the industrial age?

Firstly, it exposes the tension between the utilities centralized paradigm and the Internet's distributed intelligence. With the electricity sector under pressure to modernize, there is a culture clash between the utility sector's extremely slow reaction time and the extremely rapid and disruptive innovation that occurs with the Internet. The fear of losing out has provoked a strong defensive stance on the part of utilities.[251]

Secondly, new innovations in ICT are seeing the creation of intelligent objects through the development of the Internet of Things (IoT). With advances in circuits and software the IoT is embedding intelligence in energy consuming and producing devices. These devices are networked on the Internet giving them

[248] Tapscott & Williams. (2009b). *Wikinomics: How Mass Collaboration Changes Everything*. Portfolio.
[249] Bauwens et al. (2012). *Synthetic Overview of the Collaborative Economy*. P2P Foundation.
[250] Zuboff. (2010). *Creating value in the age of distributed capitalism*. McKinsey Quarterly.
[251] Bichler. (2013). *Smart Grids and the Energy Transformation: Mapping Smart Grid Activities in Germany*. Heinrich Böll Stiftung.

situational awareness, autonomous decision-making abilities and the aggregated capacity similar to a power plant. In effect, these innovations are creating the *Internet of Energy*.

Centralized vs. Distributed

With the utility-centric approach, smart grid functions are based on a centralized control architecture. Presently utilities are using proprietary networks for gathering information from dumb devices (smart meters) and processing it centrally, similar to mainframe computing in the past. [252] However, as shown, they are facing challenges with data management, privacy, and interoperability. This reflects the 'brittleness' of the centralized approach to the smart grid.

Within the power sector, the smart grid simply means the 'computerization' of the existing structure so that utilities can have greater visibility and control over generation and distribution assets as well as consumption through demand response programs.[253] For instance, critics have argued that the preponderance of smart meters are at best "glorified electronic versions of the century old electromechanical ones except that they can be read remotely and more often."[254] Most of them still use proprietary, communications networks and closed software systems that do not integrate or interoperate. [255] The power sector (rightly) fears that the ICT approach might lead to unforeseeable changes and unwelcome competition. The preferred route for utilities is evolutionary development over radical changes.[256] Yet, upheaval dominates our time. History has shown that the Internet's open standards and decentralized design won over the competing proprietary systems for innovation, resilience and growth.[257]

[252] Gershenfeld & Vasseur. (2014). *As Objects Go Online: The Promise (and Pitfalls) of the Internet of Things*. Foreign Affairs.
[253] Bichler. (2013). *Smart Grids and the Energy Transformation: Mapping Smart Grid Activities in Germany*. Heinrich Böll Stiftung.
[254] Steve Collier comments in: O'Brian. (2014). *The Internet of Things*. SEO'Brien.
[255] Steve Collier comments in: O'Brian. (2014). *The Internet of Things*. SEO'Brien.
[256] Bichler. (2013). *Smart Grids and the Energy Transformation: Mapping Smart Grid Activities in Germany*. Heinrich Böll Stiftung.
[257] Gershenfeld & Vasseur. (2014). *As Objects Go Online: The Promise (and Pitfalls) of the Internet of Things*. Foreign Affairs.

In contrast, within the ICT industry, 'smartness' refers to a strategic dimension of connectivity, convergence, and distributed intelligence. [258] What makes the Internet so successful is its distributed architecture. With the Internet, information and intelligence resides at the edges rather than on a central mainframe. This enhances its scalability, performance, and resilience.[259] Applications like Google, or EBay can be created and placed on top of the existing architecture, where with mainframe computing, the entire system would need to be upgraded to install Google. Centralized control architecture erects barriers to innovation, but extending the open platform to the ends of a network enables innovation at its edges. [260] The convergence of ICT with the grid will transform the electricity system to be entirely different from anything we see today. [261]

From a complexity perspective, the centralized approach to managing the smart grid has limited scalability and lacks resilience. Furthermore this approach seems to be creating a 'complexity trap'; the addition of the smart grid appears to be delivering a diminishing marginal return for the investment in complexity. The electricity grid has grown inexorably complex and has created numerous problems in terms of environmental impact, brittleness, and cost. The smart grid is indented to be a solution to these problems, however, it is adding yet another layer of complexity upon an overly complex system. As a result it is has created more problems that need to be solved with even more complex solutions.

[258] Bichler. (2013). *Smart Grids and the Energy Transformation: Mapping Smart Grid Activities in Germany*. Heinrich Böll Stiftung.
[259] HP. (n.d.). *Interconnecting the Intelligent EDGE*. Hewlett-Packard Development Company, L.P.
[260] Gershenfeld & Vasseur. (2014). *As Objects Go Online: The Promise (and Pitfalls) of the Internet of Things*. Foreign Affairs.
[261] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.

Internet of Things

> *"A dizzying array of new energy technologies are reaching or nearing the marketplace… In the background is the most powerful energy technology of all, the microprocessor."*
>
> *Source: Mazza*[262]

Advances in microprocessors and the ubiquitous presence of the Internet through wireless networks is giving rise to the Internet of Things (IoT). With the IoT, intelligence can be embedded within everyday objects in our environment and networked through wireless and wired connections. Once devices are embedded with these small computers, they are given unique addressing schemes (IP address), and can send and receive information via the Internet. These devices will be able to share information, cooperate, and act as part of communities in a complex dynamic ecosystem. The IoT distributes decision-making to intelligent nodes instead of centralized control. It is not a single technology, but a concept where most new things are embedded with intelligence and sensors to give objects situational awareness and decision-making capability.[263] They will be able to collaborate not only amongst themselves, but also with on-line services that will enhance their functionality.[264]

The domain of the Internet of Things is a cross-section between networked embedded systems, ubiquitous computing, and wireless sensor networks. Cooperating objects consist of embedded computing devices equipped with communication as well as sensing and actuating capabilities. They are able cooperate and organize themselves autonomously into networks to achieve common tasks. The ability to interact with other heterogeneous devices and their environment is innate.[265] From a systems perspective, cooperating objects work together because some of these objects share common

[262] Mazza. (2003). *The Smart Energy Network: Electricity's Third Great Revolution*. Climate Solutions.org.
[263] Vermesan & Friess. (2013). *Internet of Things: Converging Technologies for Smart Environments and Integrated Ecosystems*. River Publishers.
[264] Karnouskos. (2010). *The cooperative internet of things enabled smart grid*. Proceedings of the 14th IEEE international ….
[265] *Ibid*.

goals. These objects become parts of teams where cooperative behaviour may be shown at higher levels, but not clearly identifiable at the object level.[266]

With the IoT, billions of connections of devices build networks on top of networks. This creates unprecedented opportunities by harnessing the exponential power networks, commonly referred to as 'network effects'. According to Cisco, the core construct of the IoT is the 'connections economy' where the greatest value will be created by those who can best exploit the benefits of network effects.[267] The IoT has already reached many sectors to form innovations like Smart Cities, Smart Cars and mobility, Smart Homes, and Smart Industries, to form an interconnected IoT ecosystem.[268]

With IP penetration down to the discrete device level, devices will not only provide their information for monitoring to controlling entities, but will be capable of dynamically discovering nearby devices to collaborate with. Peer-to-peer interactions will emerge with advanced capabilities to interact with networked-based services hosted in enterprise systems, or simply somewhere on the Internet. Devices will be able to enhance their own functionality in dynamic ways through emerging services that were not envisioned when the device was designed. Price signals will also be used to affect device behaviour as a key functionality.[269]

While utilities and regulators struggle to deal with interoperability standards, privacy issues, and data management in order for smart meters to interact with home energy management systems, innovative companies are doing an end-run around the utilities by employing the Internet of Things in the emerging smart home market. Where the Internet of Things is the extension of the web paradigm to the connection, monitoring, and control of everyday objects, the *Internet of Energy* (IoE) brings this

---

[266] Karnouskos. (2010). *The cooperative internet of things enabled smart grid*. Proceedings of the 14th IEEE international ….
[267] Evans. (2012). *The Internet of Everything*. CISCO Internet Business Solutions Group.
[268] Vermesan & Friess. (2013). *Internet of Things: Converging Technologies for Smart Environments and Integrated Ecosystems*. River Publishers.
[269] Karnouskos. (2010). *The cooperative internet of things enabled smart grid*. Proceedings of the 14th IEEE international ….

functionality to the energy system.[270] This is creating a complex dynamic ecosystem comprised of networked embedded devices throughout the smart home that are able to measure and share information, and cooperate with each other.[271] Furthermore, the central defining feature of the Internet of Energy is that it is occurring at the 'edge' of the grid, outside of the regulatory control of power utilities, and through the open platform of the Internet.

The Grid Edge

As is true in business, disruption typically occurs at the edge of an industry or business sector. Edges are powerful sources of innovation and experimentation when traditional business models are failing to meet needs or exploit potential.[272] For the electricity industry this edge is the boundary of regulated electricity sector: the smart meter.[273] At this frontier, the Internet of Things is converging with third-party service providers to coordinate distributed energy resources like home energy management and metering devices, renewable generation, smart appliances, and energy storage technology through the Internet of Energy. Since this convergence occurs behind-the-meter, the IoE will interact with the regulated grid, but will not centrally coordinated by the regulator.

The convergence of ICT with the electricity system is a natural progression in the Internet of Things.[274] With the Internet of Energy, energy consuming and producing devices are embedding with intelligence and connected on the Internet. These devices will be interconnected providing fine-grained information allowing energy optimization. This creates a sophisticated dynamic ecosystem where intelligent devices can negotiate to achieve the best energy outcome. They will also provide their functionality as a service

[270] Bui et al. (2012). *The Internet of Energy: A Web-Enabled Smart Grid System*. Network, IEEE.
[271] Karnouskos. (2010). *The cooperative internet of things enabled smart grid*. Proceedings of the 14th IEEE international ….
[272] Hagel & Seely. (2007). *Embrace the Edge or Perish*. Bloomberg Business Week.
[273] Klemun. (2013). *Grid Edge: Utility Modernization in the Age of Distributed Generation*. Greentech Media Inc. GTM Research.
[274] Vermesan & Friess. (2013). *Internet of Things: Converging Technologies for Smart Environments and Integrated Ecosystems*. River Publishers.

to achieve common goals such as energy efficiency, load balancing and grid regulation. [275] Furthermore, we are seeing the emergence 'virtual power plants' where networked devices as well as distributed energy resources are aggregated and controlled as if they were a single power plant.[276]

The IoE has enormous potential for managing energy systems. For instance, buildings account for three-quarters of all electricity use in the United States, and of that, one-third is wasted. Lights are left on when there is enough natural light available or when the room is unoccupied. Fans move air in the wrong direction or cooling and heating systems operate simultaneously. This enormous amount of waste occurs because the behaviour of thermostats, light bulbs, and switches is set by the static design of the building systems.[277] The central premise of the IoE is that efficiencies can be achieved by networking these devices and enabling intelligent autonomous control. This sector is expected to be the largest growth segment as they generate internal synergies: home energy management systems that integrate solar PV, energy storage and demand response will experience increasing returns on their system investments.[278]

What is interesting is that both utilities and non-regulated entities have been competing for this space. However, utilities are bogged down with interoperability standards and privacy issues, while they try to get their smart meters to interface with smart home devices. Meanwhile, third-party entities are more agile and have been able to mobilize faster. In some cases they have an advantage over utilities since they can bundle services like home security, TV, Internet, cable, etc. along with home energy services.

Furthermore, developments in solar-plus-storage significantly increases the energy capacity of the Internet of Energy. Depending on electricity rates, electricity use in the house, and whether the sun is

---

[275] Karnouskos. (2010). *The cooperative internet of things enabled smart grid*. Proceedings of the 14th IEEE international ….
[276] Bayar. (2013). *Virtual Power Plants: A New Model for Renewables Integration*. Renewable Energy World.com.
[277] Gershenfeld & Vasseur. (2014). *As Objects Go Online: The Promise (and Pitfalls) of the Internet of Things*. Foreign Affairs.
[278] Klemun. (2013). *Grid Edge: Utility Modernization in the Age of Distributed Generation*. Greentech Media Inc. GTM Research.

shining, the solar-plus-storage unit can decide whether to store electricity or feed it into the grid. The smart home could ultimately become a decentralized control node for the IoE, where customers can provide the grid with more flexibility in meeting demand. The rise of the smart home exposes the ongoing shift in how consumers interact with the power grid.[279] SolarCity, PowerMatcher, NEST, and ZigBee enabled light bulbs are good examples of innovation occurring at the edge.

SolarCity

Distributed energy resources for both generation and storage are recognized to be a critical part of future electricity systems. With America's biggest solar PV installer and the country's biggest EV producer teaming up to produce a fleet of distributed energy assets, there appears to be considerable progress in this direction.

However, what is most interesting about SolarCity's solar and storage installations is that are all embedded with on-site digital controls and a real-time communications system that networks these distributed resources to SolarCity's cloud-based server infrastructure. Presently their solar-plus-storage systems are marketed and configured for emergency backup. However, the company has installed a general-purpose computer on every unit (distributed intelligence). Also, Tesla's battery technology has deep-cycling capabilities making them perfect for grid applications. With the control infrastructure already in place, SolarCity has the ability to collect data and interact with their system inverters so that PV and battery DC power can be converted into grid-ready AC power. This opens a whole range of possibilities for grid-facing applications, including solving the problems associated with the growth of distributed PV generation, like voltage sags and surges.

[279] Salkin. (2014). *What the smart home means for utilities*. Utility Dive. Utility Dive.

Additionally, the company intends to create synergies with the smart home by linking their systems to demand-side resources like smart thermostats and load controls. The company has been working on the right algorithms to design a system that is flexible and future-upgradable. [280]

NEST

Google's recent move into the Home Energy Management Systems (HEMS) business signals that the Internet of Energy may be going mainstream.[281] Google's $3.2 billion procurement of the NEST programmable thermostat represents one of the company's largest acquisitions since the company bought YouTube in 2006 for $1.6 billion. Along with the thermostat, NEST also makes a smoke-and-carbon-monoxide detector, and both devices can be controlled with a smart phone via Wi-Fi.[282]

While HEMS are not new, what NEST offers is iPhone like esthetic and functionality. In fact, NEST was co-founded by the iPod inventor Tony Fadell and is available to buy on the Apple Store.[284] The $250 gadget has a flashy design and a simple yet powerful interface much like what would be expected from an Apple product. Additionally, it has learning capabilities that learns its owner's daily schedule and adjusts temperatures accordingly. [285] Bringing this capability to energy devices will do what utilities have so far been unable to accomplish for decades. See Figure 4.

Figure 4: NEST Home Energy Management

Source: GreenTech Media[283]

[280] St. John. (2014). *SolarCity and Tesla: A Utility's Worst Nightmare?* Greentech Media Inc.
[281] Terdiman. (2014). *Google's Nest buy could spur growth of "Internet of things."* CNET.
[282] Miners. (2014). *Why Google paid $3.2 billion for Nest's smart thermostats*. PC World.
[283] Davis. (2014). *Will Google and Nest Make Power Companies More Innovative?* Greentech Media Inc.
[284] Levy. (2013). *Nest's Plan to Stop Brownouts Before They Start*. Wired.com. Wired.
[285] *Ibid*.

Nest also delivers smart grid functionality without the smart grid. With limited uptake of for utility driven demand management programs, and the lack of interoperability with most smart meters, the vision of the smart grid has yet to be achieved. Currently, if utilities wanted customers to shed loads on the grid, they instituted unilateral demand response to turn off customers air-conditioning, to the few customers that have registered for the program. NEST has rolled out a series of programs called Nest Energy Services that will enable wide-spread demand-side management.[286] Not only will NEST be able to adjust room temperature according to grid conditions, it will be able to cycle other intelligent energy devices like refrigerators.

This transition from hardware to services is what companies like Apple do best. First they sell devices like iPods, and then they create new platforms for creating value like iTunes. In this respect, Fadell compares power utilities to record labels. Just like Apple has provided services to help customers get music, NEST is building digital services to help customers save money. [287] He also claims that NEST can deliver “all the consumer benefits of the smart grid today, without the smart grid”[288] Ever-smarter connected devices in the smart home are simply better reporting tools than what the smart grid delivers now. NEST offers the capability of transforming increasingly granular consumer energy-use and preference data into better utility strategy and operational intelligence.[289]

Google’s move with NEST is not only an entré into the massive smart thermostat market,[290] but is also seen as a major milestone in the broader Internet of Things. There are other big players striving to dominate the connected home. Samsung recently announced a new smart-home computing platform that will let people control washing machines, televisions, and other devices from the manufacturer with a single app. Microsoft, and Amazon were also expected to take the lead in the smart home

[286] Levy. (2013). *Nest’s Plan to Stop Brownouts Before They Start*. Wired.com. Wired.
[287] Levy. (2013). *Nest’s Plan to Stop Brownouts Before They Start*. Wired.com. Wired.
[288] Quoted in: Davis. (2014). *Will Google and Nest Make Power Companies More Innovative?* Greentech Media Inc.
[289] Davis. (2014). *Will Google and Nest Make Power Companies More Innovative?* Greentech Media Inc.
[290] Lacey. (2014). *The US Smart Thermostat Market Is Potentially Massive With penetration low and*.

category, but, until now, Google had been seen as a laggard. Buying NEST, Google has now leapfrogged the competition.[291] Furthermore, the competition all use proprietary networking platforms, compared to NEST's Wi-Fi based network.[292] With this open platform NEST is recognized as a harbinger for connecting intelligent devices in the IoT ecosystem. Companies that successfully automate, monitor and serve the connected home, not just for heating and cooling, but also security, entertainment, and lighting, will have taken a giant step towards omniscience,[293] and Google intends to be that company.

NEST does not solve any of the privacy issues that utilities are experiencing with their smart meters, however it is not bound by the same regulatory oversight as utilities. In fact, many have speculated that consumer information is NEST's primary value proposition for Google.[294] As an advertising company, Google collects as much data about consumers as possible. NEST operates by extracting data from its environment, including information about lighting, and the daily behaviour of a home's residents. By gaining access to information about how consumers interact within their homes, Google would also gain significant advertising power. For instance, with the IoT, NEST will know how old your refrigerator is, and presumably be able to push advertisements about new fridges. NEST has assured everyone that "we've always taken privacy seriously and this will not change."[295] However, this may not matter since people seem to be willing to exchange privacy for service and convenience.[296]

In contrast to the propriety systems we have seen from utilities, the key to NEST's success is its use of the most ubiquitous communications standard of all: Wi-Fi. Virtually every home with the Internet has wireless networking. Google's services are all cloud-based and eschew proprietary standards. The lack of proprietary protocols to adopt NEST is what gives it the best chance in the home automation race.

[291] "The new GE: Google, everywhere." (2014) The Economist.
[292] Moorhead. (2013). *The Problem With Home Automation's Internet Of Things (IoT)*. Forbes LLC. Forbes.
[293] Davis. (2014). *Will Google and Nest Make Power Companies More Innovative?* Greentech Media Inc.
[294] Misener. (2014). *Google's Nest deal highlights privacy-policy issues: Dan Misener*. CBC News.
[295] Miners. (2014). *Why Google paid $3.2 billion for Nest's smart thermostats*. PC World.
[296] DeMers. (2014). *Consumers Willing to Trade Privacy for a Price?* Huffington Post.

This shows that the future of the Internet of Energy will not be built on a new, proprietary standard, but on existing technologies that can be easily networked.[297] This open platform will enable cloud-based control and new web-based applications that can give consumers a view of their home energy use, and also provide visibility and interoperability to the electricity grid. We know that a prevailing technology sets the standard,[298] so if NEST succeeds like Google is betting, then the open platform of the Internet may become the *de facto* interoperability standard for the smart grid.

ZigBee LED

ZigBee Networked LED

Source: GreenTech Media[1]

As noted, the smart home has been a battleground for competing proprietary technologies; different networks linking different systems that left little room for interoperability. However, LG Electronics may have blinked and given the nod towards the Internet of Energy. A new partnership between Daintree Networks and LED maker LG may also signal an end to proprietary systems. LG announced that they would be selling LED lighting fixtures that run on Daintree's smart light control platform. Instead of using a proprietary system, Daintree uses ZigBee wireless controller. Zigbee is not completely interoperable; it is one of several low-power wireless mesh networking standards, but it is more open then the rest of its competitors.[299] Furthermore, Zigbee is interoperable with NEST.

Virtual Power Plants

The central objective of the Internet of things is the intelligent coordination of objects to achieve common goals. In the Internet of Energy, this cooperative behaviour can be seen with emergence of the

[297] Salkin. (2014). *What the smart home means for utilities*. Utility Dive. Utility Dive.
[298] Eisen. (2013). *Smart Regulation and Federalism for the Smart Grid*. Harvard Environmental Law Review.
[299] St. John. (2014). *The Wireless, Networked LED Goes Standard Do Daintree and*. Greentech Media Inc.

Virtual Power Plant (VPP). The concept of a virtual power plant is an idea that involves an aggregation of distributed energy resources (DERs) that, when networked together, can provide a 'fleet' of resources that are the functional equivalent of a traditional power plant. The system relies upon software and distributed controls to remotely and automatically dispatch and optimize generation, demand-side, or energy storage resources, including plug-in EVs. These resources are integrated into a single, secure web-based connected system.[300]

VPPs have been proposed as a means to capture the economic potential of demand response and also as a cost-effective method to facilitate the integration of intermittent renewable energy. In the VPP system, an energy aggregator gathers a portfolio of smaller generators, or dispatchable loads, and operates them like a unified source of energy that can be sold as a service to grid operators as system reserve.[301] VPPs can offer significant benefits to grid operators and can provide an alternative to expensive and GHG emitting natural gas peaker plants. Cycling off a single HVAC unit does not by itself affect peak demand, but by aggregating thousands of homes together has a measurable affect and can avoid bringing additional generating assets online.

Unlike traditional demand response systems, VPPs are not only able to dispatch loads during peak times, they also can absorb excess grid power, which is a critical feature to avoid the need to curtail surplus generation from renewables.[302] Other benefits include improved network efficiency, cost savings in transmission systems, increased value from existing assets, and reduced emissions from peaking power plants. Most importantly, VPPs also enable more efficient integration of renewable energy resources.[303]

[300] Eisen. (2012). *Distributed Energy Resources, Virtual Power Plants, and the Smart Grid*.
[301] Bayar. (2013). *Virtual Power Plants: A New Model for Renewables Integration*. Renewable Energy World.com.
[302] St. John. (2013). *PowerShift Atlantic: The Virtual Power Plant of the Future?* Greentech Media Inc.
[303] Bayar. (2013). *Virtual Power Plants: A New Model for Renewables Integration*. Renewable Energy World.com.

According to Navigant Research, VPPs are essentially an 'Internet of Energy' that maximizes value for both the end user and power utilities through software innovations.[304]

PowerMatcher

PowerMatcher is an example of a VPP aggregator. They enable 'intelligent clustering' of numerous small electricity consuming and producing devices so that they operate as a single highly flexible generating unit, creating a significant degree of added-value in electricity markets. These technologies will optimize the potential for aggregating individual electricity producing and consuming devices in order to adjust their operation.[305] Using ICT, PowerMatcher integrates distributed generation, demand response, and electricity storage to create a general purpose coordination mechanism for balancing supply and demand in within clusters that have a high share of distributed energy resources.[306] It uses multi-agent systems and a market-based approach to optimize the operation of consuming and producing devices to provide grid regulation services and achieve an over-all match between electricity production and consumption.[307]

Transactive Energy

The utility-centric view of the 'grid edge' is that of a wild frontier with intermittent distributed resources and uncontrollable loads that all need to be subdued by the command and control structure of the smart grid.[308] In contrast, the Internet of Energy vision sees the future electricity system as an internet-enabled marketplace where consumers and producers of energy meet to participate in energy transactions. Considering this future Energy Market, a number of pieces are already in place, including distributed generation and storage, and a network to coordinate these resources (Internet of Things,

---

[304] Asmus. (2011). *Growth of Distributed Energy Resources to Drive Investment in Virtual Power Plant Systems*. Navigant Research.
[305] "PowerMatcher: A quick overview of the technology." (2014) PowerMatcher smartgrid technology.
[306] Kok et al. (2010). *Intelligence in electricity networks for embedding renewables and distributed generation*. Intelligent infrastructures.
[307] *Ibid*.
[308] St. John. (2013). *A How-To Guide for Transactive Energy*. Greentech Media Inc.

VPPs), however, the final piece is the system architecture that will enable these transactions. It appears this architecture is *Transactive Energy (TE).*

Transactive Energy is concept being developed by Pacific Northwest National Laboratory (PNNL), for a market-based control technology that can be implemented in building automation systems (smart homes) in order to make buildings more demand responsive. "Transactive" refers to market-based decision-making that uses value signals to price energy transactions.[309] TE is an agent-based strategy where interactions between various components in a complex energy system would be controlled by negotiating immediate and contingent contracts locally, instead of through centralized command and control. Each device in the system is given the ability (intelligence) to negotiate deals with its peers (producers and consumers of energy) to maximize revenues while minimizing costs.[310] TE essentially opens up a two-way communication link between generation and loads that previously did not exist. Once in contact, load and generation can exchange global information about the state of the grid, as well as local information such as weather data and forecasts, to support local decisions that work to optimize the grid.[311]

In simple terms, TE is a means of managing electricity supply, delivery, and demand by creating economic value through markets, rates, contracts or other value-based mechanisms. Most importantly, this concept is a means of managing distributed energy resources.[312] Transactive networks will be characterized by the free communication of information between parties that enables exchanges and transactions. In a TE network, price signals are embedded throughout the energy system to enable

[309] Berst. (2013). *Why every utility MUST learn the word transactive*. Smart Grid News. Smart Grid News.
[310] Katipamula et al. (2006). *Transactive Controls: Market-Based GridWise TM Controls for Building Systems*. Pacific Northwest National Laboratory. … , Richland, WA.[Online]. ….
[311] Melton. (2014). *Giving fillip to RE integration*. Energy Next.
[312] Berst. (2013). *Why every utility MUST learn the word transactive*. Smart Grid News. Smart Grid News.

energy commerce. This universal language will bridge different devices and institutional boundaries, making possible distributed decision-making that optimizes energy resources. [313]

Similar to the concept of intelligent nodes with the Internet of Things, TE will distribute the intelligence and decision-making of the energy distribution and control system - from a central core to many peripheral nodes throughout the grid.[314] Networked embedded devices will make decisions independently based on value signals without a centralized control structure.[315] This transition from the traditional centralized control architecture to a decentralized information-enabled network has many similarities to the transition from mainframe computers to cloud-based computing.[316] Based on economic, market, and grid conditions, TE (or transactive control) will coordinate generation, allocate resources, and optimize the consumption and flow of electricity[317] to enable the dynamic balance of supply and demand.[318]

The motivation for TE has arisen due to the increasing diversity of resources and components in the electricity system, and the inability of the existing centralized model to accommodate these changes. The electricity system has evolved towards enormous complexity and constraints with the increasing deployment of intermittent generation on the bulk supply side, distributed energy resources throughout the system, and intelligent devices and appliances on the demand side. A new approach is needed for balancing supply with demand, and also to capture the actual costs of running the system. [319] Transactive energy responds to this reality by coordinating energy resources to meet multiple generation, transmission, and distribution objectives. TE provides a way to maintain reliability and security of the electricity system while improving both economic and energy efficiency. It accomplishes

[313] Mazza. (2003). *The Smart Energy Network: Electricity's Third Great Revolution*. Climate Solutions.org.
[314] Bui et al. (2012). *The Internet of Energy: A Web-Enabled Smart Grid System*. Network, IEEE.
[315] Karnouskos. (2010). *The cooperative internet of things enabled smart grid*. Proceedings of the 14th IEEE international ….
[316] Hendricks & James. (2012). *The Networked Energy Web: The Convergence of Energy Efficiency, Smart Grid, and Distributed Power Generation as the Next Frontier of the ICT Revolution*. Center for American Progress.
[317] Kennedy. (2013). *Transactive Energy: The Next Big Deal for the Smart Grid?* The Energy Collective.
[318] GridWise Architecture Council. (2013). *GridWise Transactive Energy Framework: DRAFT Version*. GridWise Architecture Council.
[319] *Ibid*.

this by embracing both the economics and engineering of the power system[320] and by coordinating control systems and balancing markets that enable agents to send and receive value signals.[321]

TE also drives economic efficiency. Presently power prices are not based on market demand or even true cost, but are essentially controlled by regulatory forces that must agree to rate changes, and attempts to recover costs.[322] By leveraging the power of the economic system and markets, TE will optimize and balance the electricity grid by assigning 'value' to energy. This value will capture the *real* costs of generating, delivering, consuming, storing, and conserving energy across the grid. With the real costs visible, consumers will begin to define the electricity system instead of just utilities and regulators. Rather then simply buying kilowatt-hours of electricity as a bulk commodity, consumers will be presented with choice in the energy marketplace – replace aging transmission infrastructure or build micro-grids, generate energy from nuclear or install more distributed energy with storage, get my electricity from fossil-fuel based generation or choose renewable energy. Just like in the marketplace, consumer choice will naturally drive economic efficiency in the electricity system and define the future of the smart grid.

Presently PNNL has a TE demonstration project (Pacific Northwest Demonstration Project), using $178 million in DOE stimulus grants. The project connects eleven utilities and 60,000 metered customers in a framework that spans five states, Idaho, Montana, Oregon, Washington, and Wyoming. The project attempts to provide about 60 to 70 megawatts of responsive resources by providing two-way communication about what power is available, and at what price. The goal is to continue to use transactive energy when the project is complete. [323]

---

[320] GridWise Architecture Council. (2013). *GridWise Transactive Energy Framework: DRAFT Version*. GridWise Architecture Council.
[321] Berst. (2013). *Why every utility MUST learn the word transactive*. Smart Grid News. Smart Grid News.
[322] Mchale. (2013). *Transactive Energy Markets will Drive Distributed Power*. Automated Buildings.
[323] Tweed. (2013). *Can One Project Redefine Power Delivery?* Greentech Media Inc.

With the increasing deployment of distributed generation and storage technologies, as well as the forthcoming smart home, the utility business model organized around cost recovery is facing significant grid management, and economic challenges. With distributed generation, storage and the smart home conserving electricity, utilities will be selling less electricity to fewer customers.   Yet, many distributed generation customers have the expectation that the grid will be there as back-up when their system fails. With rising costs, decreasing electricity sales, and the potential for mass grid defection, it is clear that the centralized model will need to be transformed. Transactive energy offers a solution to the utility 'death spiral' by transitioning the utility business model from cost recovery to value creation. While TE will fundamentally transform the nature of the utility business, it will also preserve the financial security of the grid.

6. Conclusion

According to the Schumpeterian view, socio-technical systems are marked by long periods of incremental development with dominant technologies, but these periods are punctuated by short bursts of ‘disruptive innovation’. It appears that the convergence of ICT with the electricity grid may be the catalyst that disrupts the century-old utility paradigm, and brings about a revolutionary transition in the electricity system.

There are two central questions this research was asking. Will the smart grid be an evolutionary or revolutionary technology, and will it be a catalyst for a sustainable energy transition? On both questions, it appears the answer is yes.

The disruptive capacity of the smart grid appears to be overcoming the institutional inertia of regulated utilities. Despite the stabilizing forces of the traditional utility model, there are several factors positioned to overwhelm the techno-institutional lock-ins. *Firstly*, the electricity system has become increasingly complex, and the introduction of the smart grid with a centralized control architecture is proving to be incapable of managing the increasingly distributed nature of the electricity grid. This exposes the brittleness of the centralized model.

Secondly, the economic landscape is changing due to the increasing costs for conventional energies and decreasing costs for the alternatives. Scale economies are experiencing diminishing returns for centralized utilities, while the costs of the alternatives are experiencing increasing returns. It appears a crossover point has been reached.

Thirdly, solar-plus-energy undermines the fundamental value proposition of the centralized model. With intermittent renewables combined with on-site storage, reliability is built in locally without the need for a centralized utility.

Fourthly, the Internet of Things is converging with energy systems in the smart home. This is creating an Internet of Energy with a distributed control architecture that is outside the regulatory control of utilities. A host of new energy services like virtual power plants and home energy management systems are emerging that are enabled by intelligent devices connected to the Internet. Furthermore, Transactive Energy is creating an energy marketplace where energy consumers and producers (or their devices) can meet to participate in energy transactions. In doing so, TE brings market competition and efficiency to the electricity grid. With intelligent devices, it distributes decision-making throughout the grid. While it fundamentally transforms the electricity business from cost-recovery to value creation, it simultaneously protects the grid infrastructure by providing a means to generate profit for using its services.

Energy transitions occur when new technologies emerge that can offer substantial improvements in the quality and quantity of energy services they provide. There are several developments shown in this research suggesting that the smart grid may be a catalyst for a sustainable energy transition. The changing economics, emerging technologies and the Internet of energy are enabling a transition away from fossil-fuel based electricity generation and towards renewable energy. Solar generation has recently achieved grid parity in many regions and the smart grid is the enabling technology that allows for a high penetration of renewables. Since renewable energy achieves economies of scale much sooner than conventional energy sources, there will be increased competition in the energy sector, primarily based on renewables.

Furthermore, the synergies created by converging the transportation and electricity systems may bring about a broader energy system transition away from fossil-fuel based energy. Electric vehicles will reduce emissions associated with transportation, and also drive down the costs of energy storage. This will further enable distributed energy on the grid by providing a source of distributed storage.

From a complexity perspective, socio-technical transitions require changes, not only in technology, but also in user practices, regulations, industrial networks, and infrastructure. The development of the Internet of Energy appears to achieve all these conditions: renewable energy and storage technologies represent the technological change; the smart home represents changes in user practices; regulations are changing in response to the smart grid; changes in industrial networks can be seen in the utility sector; and the transition from centralized generation to distributed represents changing infrastructure.

Although the future of the electricity system is difficult to predict, it is clear it will vastly different that what we know today. The electricity system is poised to experience the same level of innovation that we have seen with telecommunications after being deregulated in the 1970s. However, it is possible to imagine some outcomes:

- The Internet of Energy will blur the lines between information technology and energy technology
- Utilities will become more like information technology companies that provide grid services
- Every building becomes an energy producer and has on-site energy storage
- The smart home becomes a decentralized control centre for energy system management
- The grid becomes an interactive marketplace where retailers bundle energy services

7. Bibliography

AAA&S. (2011). *Beyond Technology: Strengthining Energy Policy Through Social Science*. American Academy of Arts and Sciences. Retrieved from http://www.amacad.org/pdfs/alternativeEnergy.pdf

Aanesen, K., Heck, S., & Pinner, D. (2012). Solar power: Darkest before dawn. *McKinsey on Sustainability …*, (May), 1–16. Retrieved from http://solarprogram.com.au/assets/SRP_solar.pdf

Ajmone-Marsan, M., Arrowsmith, D., Breymann, W., Fritz, O., Masera, M., Mengolini, A., & Carbone, A. (2012). The emerging energy web. *The European Physical Journal Special Topics*, *214*(1), 547–569. doi:10.1140/epjst/e2012-01705-1

ANSI. (2001). *ANSI Procedures for the Development and Coordination of American National Standards*. American National Standards Institute.

Arthur, W. (1989). Competing technologies, increasing returns, and lock-in by historical events. *The Economic Journal*, *99*(394), 116–131. Retrieved from http://www.jstor.org/stable/10.2307/2234208

Asmus, P. (2011). *Growth of Distributed Energy Resources to Drive Investment in Virtual Power Plant Systems*. *Navigant Research* (p. 7609). Retrieved from http://www.navigantresearch.com/newsroom/growth-of-distributed-energy-resources-to-drive-investment-in-virtual-power-plant-systems

Baker, D. R. (2014). *SolarCity accuses utilities of slowing home-battery project*. SFGate. Retrieved from http://www.sfgate.com/business/article/SolarCity-accuses-utilities-of-slowing-5325791.php

Bauwens, M., Mendoza, N., Iacomella, F., Burke, J., & Pinchen, C. (2012). *Synthetic Overview of the Collaborative Economy*. P2P Foundation. Retrieved from http://p2pfoundation.net/Synthetic_Overview_of_the_Collaborative_Economy

Bayar, T. (2013). *Virtual Power Plants: A New Model for Renewables Integration*. *Renewable Energy World.com* (pp. 1–6). Retrieved from http://www.renewableenergyworld.com/rea/news/article/2013/09/virtual-power-plants-a-new-model-for-renewables-integration

Beltrame, J. (2012, June 13). Canada Dutch Disease? OECD Says Yes. *The Huffington Post*, pp. 2–3. Retrieved from http://www.huffingtonpost.ca/2012/06/13/canada-dutch-disease-oecd-report_n_1593050.html

Berst, J. (2012). Utility business model is dying fast, claims European consultant. *Smart Grid News.com*. Retrieved from: http://www.smartgridnews.com/artman/publish/News_Commentary/Utility-business-model-is-dying-fast-claims-European-consultant-5330.html#.UtBl6f0jhho

Berst, J. (2013). *First Walmart, then Verizon and now a how to guide for divorcing your utility*. *Smart Grid News* (pp. 1–2). Smart Grid News. Retrieved from http://www.smartgridnews.com/artman/publish/news/First-Walmart-then-Verizon-and-now-a-how-to-guide-for-divorcing-your-utility-5731.html#.U0TEoa1dVD0

Berst, J. (2013). *Why every utility MUST learn the word transactive*. *Smart Grid News* (pp. 1–3). Smart Grid News. Retrieved from www.smartgridnews.com/artman/publish/Business_Strategy/Why-every-utility-MUST-learn-the-word-transactive- 5467.html#.UulcKnddXug

Bichler, M. (2013). *Smart Grids and the Energy Transformation: Mapping Smart Grid Activities in Germany*. Heinrich Böll Stiftung. Retrieved from http://www.boell.org/downloads/Bichler_Smart-Grids-Report.pdf

Biello, D. (2013). *How Much Will Tar Sands Oil Add to Global Warming?* Scientific American Inc. Retrieved from http://www.scientificamerican.com/article/tar-sands-and-keystone-xl-pipeline-impact-on-global-warming/?print=true

Blackburn, J., & Cunningham, S. (2010). Solar and Nuclear Costs — The Historic Crossover. *NC WARN: …*, (July 2010). Retrieved from http://sa.indiaenvironmentportal.org.in/files/NCW-SolarReport_final1.pdf

Block, C., Bomarius, F., Bretschneider, P., Burger, N., Drzisga, T., Plail, B., … Weinhardt, C. (2010). *Internet of Energy: ICT for energy markets of the future*. (C. Block & F. Briegel, Eds.). Federation of German Industries (BDI) publication No. 439. Retrieved from http://www.iese.fraunhofer.de/content/dam/iese/en/mediacenter/documents/BDI_initiative_IoE_us-IdE-Broschuere_tcm27-45653.pdf

Bronski, P., Creyts, J., Guccione, L., Madrazo, M., Mandel, J., Rader, B., … Tocco, H. (2014). *The Economics of Grid Defection: When and Where Distributed Solar Generation Plus Storage Competes with Traditional Utility Service, Executive Summary*. Rocky Mountain Institute. Retrieved from http://www.rmi.org/electricity_grid_defection#economics_of_grid_defection

Bui, N., Castellani, A., Casari, P., & Zorzi, M. (2012). The Internet of Energy: A Web-Enabled Smart Grid System. *Network, IEEE*, (August), 39–45. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6246751

Carbon Tax: Canada Will Inevitably See One, Conference Told. (2013, April 18). *The Huffington Post*, p. 3110082. Retrieved from http://www.huffingtonpost.ca/2013/04/18/carbon-tax-canada-conference_n_3110082.html

CEA. (2010). *THE SMART GRID: A Pragmatic Approach*. Canadian Electricity Association. Retrieved from http://www.electricity.ca/media/SmartGrid/SmartGridpaperEN.pdf

CEA. (2013). *The Integrated Electric Grid: Maximizing Benefits in an Evolving Energy Landscape*. Canadian Electricity Association (CEA). Retrieved from http://www.electricity.ca/media/pdfs/CanadaUS/CEA_US Policy Paper_EN.pdf

Chediak, M. (2014, February 16). Tesla Battery Jolts Shares Higher While Disrupting Power. *Bloomberg*. Retrieved from http://www.bloomberg.com/news/2014-02-25/tesla-battery-gigafactory-to-help-transform-power-grid.html

Christensen, L., & Greene, W. (1976). Economies of scale in US electric power generation. *The Journal of Political Economy*, *84*(4), 655–676. Retrieved from https://www.amherst.edu/media/view/104700/original/christenson_and_green_76.pdf

Coad, L., Crawford, T., & Macdonald, A. (2012). *Shedding Light on the Economic Impact of Investing in Electricity Infrastructure: Report February 2012.* Canada: Conference Board of Canada. Retrieved from http://www.conferenceboard.ca/e-library/abstract.aspx?did=4673

Colley, A. (2014). *Half of users abandon smart meter trial*. *itNews* (pp. 1–2). NextMedia. Retrieved from http://www.itnews.com.au/News/370919,half-of-users-abandon-smart-meter-trial.aspx

Collier, S. (2012). *A Good Offense Is the Best Defense*. *The Energy Collective*. Retrieved from http://theenergycollective.com/stevencollier/154896/good-offense-best-defense

Davis, C. (2014). *Will Google and Nest Make Power Companies More Innovative?* (pp. 1–3). Greentech Media Inc.

DeBlasio, R. (2011). Interoperability is Key to Smart Grid Success. *Continuum Magazine*, *1*(1). Retrieved from http://www.nrel.gov/docs/fy11osti/52129.pdf

Dedrick, J., & Zheng, Y. (2011). Smart Grid Adoption: A Strategic Institutional Perspective. *Industrystudies.pitt.edu*, 1–15. Retrieved from http://www.industrystudies.pitt.edu/pittsburgh11/documents/Papers/PDF Papers/2-3 Dedrick.pdf

DeMers, J. (2014, February 7). Consumers Willing to Trade Privacy for a Price? *Huffington Post*, pp. 1–2. Retrieved from http://www.huffingtonpost.com/jayson-demers/consumers-willing-to-trad_b_4740682.html

Denholm, P., & Mehos, M. (2011). *Enabling Greater Penetration of Solar Power via the Use of CSP with Thermal Energy Storage*. *NREL*. Retrieved from http://speloop.com/stuff/contentmgr/files/0/5d893618bf2af9d96e90593c41cfc418/attachment/201111_nrel___enabling_greater_percentage_of_solar_via_csp_with_tes.pdf

Diebold, W., Lovins, A. B., & Lovins, L. H. (1982). *Brittle Power: Energy Strategy for National Security*. *Foreign Affairs* (Vol. 61, p. 224). Brick House Publishing. doi:10.2307/20041378

Dobson, I., Carreras, B. a, Lynch, V. E., & Newman, D. E. (2007). Complex systems analysis of series of blackouts: cascading failure, critical points, and self-organization. *Chaos (Woodbury, N.Y.)*, *17*(2), 026103. doi:10.1063/1.2737822

Doom, J. (2013). *Solar Panel Is Next Granite Countertop for Homebuilders*. *Bloomberg* (pp. 2013–2015). Bloomberg L.P. Retrieved from http://www.bloomberg.com/news/2013-09-10/solar-panel-is-next-granite-countertop-for-homebuilders.html

Dresselhuys, E. (2014). *Is a disaggregated future really all that far away? Smart Grid News.com* (pp. 1–3). Smart Grid News.

ECO. (2013). *Failing Our Future: Review of the Ontario Government's Climate Change Action Plan Results*. Environmental Commissioner of Ontario (ECO). Retrieved from http://www.eco.on.ca/uploads/Reports-GHG/2013/2013GHG.pdf

Eisen, J. (2012). Distributed Energy Resources, Virtual Power Plants, and the Smart Grid. Retrieved from https://www.law.uh.edu/eelpj/publications/7-2/03EisenFinal.pdf

Eisen, J. (2013). Smart Regulation and Federalism for the Smart Grid. *Harvard Environmental Law Review*. Retrieved from https://litigation-essentials.lexisnexis.com/webcd/app?action=DocumentDisplay&crawlid=1&doctype=cite&docid=37+Harv.+Envtl.+L.+Rev.+1&srctype=smi&srcid=3B15&key=90b498082afec6c564dfe9f58122f084

Elmer-DeWitt, P. (2014). What's 12 petabytes to Apple? *CNN Money*. Retrieved March 31, 2014, from: http://tech.fortune.cnn.com/2011/04/07/whats-12-petabytes-to-apple/

Environment Canada. (2013). *Greenhouse Gas Emissions by Economic Sector* (p. 2014). Environment Canada. Retrieved from http://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=F60DB708-1

Environment Canada. (2014). *Canada's Sixth National Report on Climate Change: 2014*. Environment Canada. Retrieved from http://unfccc.int/files/national_reports/non-annex_i_natcom/submitted_natcom/application/pdf/final_nc_br_dec20,_2013[1].pdf

Evans, D. (2012). *The Internet of Everything* (pp. 1–9). CISCO Internet Business Solutions Group.

Farrell, J. (2011). Democratizing the Electricity System: A Vision for the 21 st Century Grid. *Institute for Local Self Reliance Pub.: Washington DC, …*, (June). Retrieved from http://www.ilsr.org/democratizing-electricity-system-vision-21st-century-grid/

Farrell, J. (2013). *Could Minnesota's "Value of Solar" Make Everyone a Winner? Institute for Local Self-Reliance*. Institute for Local Self-Reliance. Retrieved from www.ilsr.org/minnesotas-value-solar-winner/

Farrell, J. (2013). *Utility Shocked to Find It's Already Dead*. ILSR: Institute for Local Self-Reliance.

Farrell, J. (2014). *Natural Gas isn't a Bridge Fuel, it's a Gateway Drug* (pp. 3–6). Institute for Local Self-Reliance. Retrieved from http://www.ilsr.org/natural-gas-bridge-fuel-gateway-drug/

Finnigan, J. (2013). *Net metering wars: An environmentalist's view (better news than you might think)*. *Smart Grid News* (pp. 1–3). Retrieved from http://www.smartgridnews.com/artman/publish/Technologies_DG_Renewables/Net-metering-wars-An-environmentalist-s-view-better-news-than-you-might-think-5968.html/#.UtBc5P0jhhp

Fox-Penner, P. (2010). The Smart Grid–Enabled Energy Services Utility: How Utilities Can Become Sustainable by Selling Less. *Thesolutionsjournal.com*, (5), 1–8. Retrieved from http://thesolutionsjournal.com/node/750

Foxon, T. (2002). Technological and institutional "lock-in" as a barrier to sustainable innovation. *Imperial College Centre for Energy Policy and …*, 1–9. Retrieved from http://www3.imperial.ac.uk/pls/portallive/docs/1/7294726.PDF

GEA. (2012). *Global Energy Assessment: Toward a Sustainable Future*. (J. F. Ahearne, O. Davidson, J. Jäger, E. Jochem, I. Johnson, R. Leemans, … J. Zou, Eds.). Cambridge, UK: Cambridge University Press. Retrieved from http://lup.lub.lu.se/record/3458094

Geels, F. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study, 1–39. Retrieved from http://www.sciencedirect.com/science/article/pii/S0048733302000628

Geels, F. W. (2010). Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. *Research Policy*, *39*(4), 495–510. doi:10.1016/j.respol.2010.01.022

Gershenfeld, N., & Vasseur, J. (2014). As Objects Go Online: The Promise (and Pitfalls) of the Internet of Things. *Foreign Affairs*, *1*(March/April).

Gilbert, E. I., Violette, D. M., & Rogers, B. (2011). *Paths to Smart Grid Interoperability*. GridWise Alliance. Retrieved from https://www.smartgrid.gov/sites/default/files/doc/files/Paths_Smart_Grid_Interoperability_Overview_d_Summary.pdf

GridWise Architecture Council. (2013). *GridWise Transactive Energy Framework: DRAFT Version*. GridWise Architecture Council. Retrieved from http://www.gridwiseac.org/about/transactive_energy.aspx

Groarke, D., Kellison, A. Ben, & Pollock, Z. (2013). *Global smart grid technologies and growth markets 2013-2020*. Greentech Media Inc. Retrieved from http://www.greentechmedia.com/research/report/global-smart-grid-technologies-and-growth-markets-2013-2020

Grünewald, P. H., Cockerill, T. T., Contestabile, M., & Pearson, P. J. G. (2012). The socio-technical transition of distributed electricity storage into future networks—System value and stakeholder views. *Energy Policy*, *50*, 449–457. doi:10.1016/j.enpol.2012.07.041

Hagel, B. J., & Seely, J. (2007, November 28). Embrace the Edge or Perish. *Bloomberg Business Week*, pp. 2–3. Retrieved from http://www.businessweek.com/stories/2007-11-28/embrace-the-edge-or-perishbusinessweek-business-news-stock-market-and-financial-advice

Hajimiragha, A., Member, S., Cañizares, C. A., Fowler, M. W., & Elkamel, A. (2010). Optimal transition to plug-in hybrid electric vehicles in Ontario, Canada, considering the electricity-grid limitations. *Industrial Electronics …*, *57*(2), 690–701. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5129873

Hamilton, T. (2009, July 14). $26B cost killed nuclear bid. *The Toronto Star*, pp. 26–27. Retrieved from http://www.thestar.com/business/2009/07/14/26b_cost_killed_nuclear_bid.html

Hawkins, K. (2011). *The Smart Grid and Distributed Generation: A Glimpse of a Distant Future* (Vol. 2011). Master Resource: A Free-Market Energy Blog. Retrieved from www.masterresource.org/2011/04/the-?-smart-?-grid-?-and-?-dg/

Hendricks, B., & James, A. S. (2012). *The Networked Energy Web: The Convergence of Energy Efficiency, Smart Grid, and Distributed Power Generation as the Next Frontier of the ICT Revolution*. Center for American Progress. Retrieved from http://www.americanprogress.org/wp-content/uploads/2012/08/0709_CleanEnergyWeb1.pdf

Herold, R. (2011, July). ENSURING SMART GRID SOCIAL ACCEPTANCE BY SECURING DATA PRIVACY. *GRIDTalk*. Retrieved from file:///Users/helenbrown/Downloads/GridTalk-1_Protecting_your_investment_07-2011_EN.pdf

Hertel, T. W., Burke, M. B., & Lobell, D. B. (2010). The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, *20*(4), 577–585. doi:10.1016/j.gloenvcha.2010.07.001

Hirsh, R., & Sovacool, B. (2006). Technological Systems and Momentum Change: American Electric Utilities, Restructuring, and Distributed Generation Technologies. *The Journal of Technology Studies*, 72–85. Retrieved from http://scholar.lib.vt.edu/ejournals/JOTS/v32/v32n2/hirsh.html

Homer-Dixon, T. (2011). *Carbon Shift: How Peak Oil and the Climate Crisis Will Change Canada (and our lives)* (pp. 1–17).

Homer-Dixon, T. (2011). Complexity Science. *Oxford Leadership Journal*, *2*(1). Retrieved from http://www.oxfordleadership.com/journal/vol2_issue1/homerdixon.pdf

HP. (n.d.). *Interconnecting the Intelligent EDGE*. Hewlett-Packard Development Company, L.P. Retrieved from http://www.hp.com/rnd/pdfs/Interconnect_Fabric_white_paper.pdf

IEA. (2002). *Distributed generation in liberalised electricity markets*. OECD Publishin. doi:10.1787/9789264175976-en

IEA. (2011). Technology Roadmap: Smart Grids.

IESO. (2009). *Enabling Tomorrow's Electricity System: Report of the Ontario Smart Grid Forum*. Independent Electricity System Operator.

IESO. (2014). The Smart Grid in Ontario. Retrieved from: https://www.ieso.ca/imoweb/siteShared/ontarios_smart_grid.asp?sid=md

Jaccard, M. (2011). PEAK OIL AND MARKET FEEDBACKS: Chicken Little versus Dr. Pangloss. In *Carbon Shift: How Peak Oil and the Climate Crisis Will Change Canada (and our lives)*. Random House Canada.

Jiusto, S. (2009). Energy transformations and geographic research. In N. Castree, D. Demeritt, D. Liverman, & B. Rhoads (Eds.), *A companion to environmental geography* (pp. 533–535). Blackwell Publishing Ltd. Retrieved from http://www.hamyaar.ir/book-download/Blackwell Companions and Guides/Companion to Environmental Geography, A.pdf#page=543

Joseph A. Tainter. (1988). *The Collapse of Complex Societies*. Cambridge, Cambridgeshire: Cambridge University Press. Retrieved from http://ejournals.library.ualberta.ca/index.php/complicity/article/viewArticle/8797

Jurowetzki, R. L. (2013). *The Evolution of the Danish Smart Grid Sector: Industrial Composition and Interaction Patterns*. Retrieved from http://druid8.sit.aau.dk/acc_papers/ky6nabml55jgibctxm6cj6dfsuvu.pdf

Karnouskos, S. (2010). The cooperative internet of things enabled smart grid. *Proceedings of the 14th IEEE International …*, 1–6. Retrieved from http://www.smartgrid.gov/document/cooperative_internet_things_enabled_smart_grid

Katipamula, S., Chassin, D., & Hatley, D. (2006). *Transactive Controls: Market-Based GridWise TM Controls for Building Systems*. *… , Richland, WA.[Online]. …*. Pacific Northwest National Laboratory. Retrieved from www.pnl.gov/main/publications/external/technical_reports/PNNL-15921.pdf

Keith, D., & Homer-Dixon, T. (2009). Dangerous abundance. In *Carbon Shift: How Peak Oil and the Climate Crisis Will Change Canada (and our lives)* (pp. 27–57). Random House Canada. Retrieved from http://keith.seas.harvard.edu/papers/114.Keith.Dangerous.Abundance.e.pdf

Kennedy, J. (2013). *Transactive Energy: The Next Big Deal for the Smart Grid?* (pp. 1–2). The Energy Collective. Retrieved from http://theenergycollective.com/ecsjessica/253846/transactive-energy-next-big-deal-smart-grid

Kiesling, L. (2011). *My Grid-Interop talk: Regulation's role in stifling innovation* (pp. 1–6). Knowledge Problem.

Kind, P. (2013). *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business*. Edison Electric Institute. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Disruptive+Challenges:+Financial+Implications+and+Strategic+Responses+to+a+Changing+Retail+Electric+Business#0

Klare, M. T. (2013). *The Third Carbon Age: Nonrenewable "Unconventional" Oil and Gas*. *Global Research* (pp. 1–8). Centre for Research on Globalization. Retrieved from http://www.globalresearch.ca/the-third-carbon-age/5345458

Klemun, M. (2013). *Grid Edge: Utility Modernization in the Age of Distributed Generation*. *GTM Research*. Greentech Media Inc.

Knight, M., Street, S. B., & Brownell, N. (2010). How Does Smart Grid Impact the Natural Monopoly Paradigm of Electricity Supply? Part I Knight-Brownell, 1–22.

Kok, J., Scheepers, M., & Kamphuis, I. (2010). Intelligence in electricity networks for embedding renewables and distributed generation. *Intelligent Infrastructures*. Retrieved from http://link.springer.com/chapter/10.1007/978-90-481-3598-1_8

Kominers, P. (2012). Interoperability Case Study: The Smart Grid. *Berkman Center Research Publication*, *7641*. Retrieved from http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2031113

Könnölä, T., Unruh, G., & Carrillo-Hermosilla, J. (2005). Prospective Voluntary Agreements for Escaping Techno-Institutional Lock-In. *Ecological Economics*, (July), 137–155. Retrieved from http://www.sciencedirect.com/science/article/pii/S0921800905002041

Lacey, S. (2014). The US Smart Thermostat Market Is Potentially Massive With penetration low and, 1–4.

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

Lagi, M., Bertrand, K. Z., & Bar-yam, Y. (2011). The Food Crises and Political Instability in North Africa and the Middle East, 1–15.

Lamonica, M. (2009). *Cisco: Smart grid will eclipse size of Internet*. *CNET News* (pp. 1–5). Retrieved from news.cnet.com/8301-11128_3-10241102-54.html

Lawhon, M., & Murphy, J. T. (2011). Socio-technical regimes and sustainability transitions : Insights from political ecology, *36*(3), 354–378.

Lehr, R. (2013). *Three Regulatory Models That Could Help Utilities Embrace the Future*. Greentech Media Inc. Retrieved from http://www.greentechmedia.com/articles/read/new-utility-business-models

Levy, S. (2013). *Nest's Plan to Stop Brownouts Before They Start*. *Wired* (pp. 1–6). Wired.com. Retrieved from www.wired.com/business/2013/04/nest-energy-services/

Lichtenstein, B. B. (2000). The Matrix of Complexity: A Multi-Disciplinary Approach for Studying Emergence in Coevolution, 1–34.

Lovins, A. (1976). Energy Strategy: The Road Not Taken? *Foreign Aff.*, *6*(20). Retrieved from http://heinonlinebackup.com/hol-cgi-bin/get_pdf.cgi?handle=hein.journals/fora55&section=8

Lovins, A. (2004). *Winning the Oil Endgame: Innovation for Profits Jobs, and Security*. Rocky Mountain Institute. Retrieved from http://books.google.com/books?hl=en&lr=&id=hb3-ac_Hd3IC&oi=fnd&pg=PP3&dq=Winning+the+Oil+Endgame:+Innovation+for+Profits+Jobs,+and+Security&ots=HhEFeDT6pc&sig=aINthQuJyLu8uWJplrNhCiBnnX0

Lovins, A. (2014). *Amory Lovins: Three Major Energy Trends to Watch* (pp. 1–7). Rocky Mountain Institute.

Lovins, A. B. (2009). *Does a Big Economy Need Big Power Plants? Freakonomics*. Retrieved from /www.freakonomics.com/2009/02/09/does-??a-??big-??economy-??need-??big-??power-??plants-??a-??guest-??post/

Lovins, A., Datta, E. K., Feiler, T., Rábago, K. R., Swisher, J. N., Lehmann, A., & Wicker, K. (2003). *Small is profitable: The Hidden economic benefits of making electrical resources the right size*. Rocky Mountain Institute. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Small+is+Profitable:+The+Hidden+Economic+Benefits+of+Making+Electrical+Resources+the+Right+Size#0

Lovins, A., & Rocky Mountain Institute. (2011). *Reinventing fire: bold business solutions for the new energy era*. White River Junction, VT: Chelsea Green Pub. Retrieved from http://books.google.com/books?hl=en&lr=&id=ZW7EAgAAQBAJ&oi=fnd&pg=PR9&dq=Reinventing+Fire:+Bold+Business+Solutions+for+the+New+Energy+Era&ots=RuNITbqr5q&sig=7cZvpU_yEmGMFVCVDo6l7JoNpqY

Lyons, C. (2014). *Tesla's Giga Battery Factory Threatens the Auto, Utility and Building Controls Markets*. Greentech Media Inc.

Manyika, J., Chui, M., & Bughin, J. (2013). Disruptive technologies: Advances that will transform life, business, and the global economy. *McKinsey Global …*, (May). Retrieved from http://www.chrysalixevc.com/pdfs/mckinsey_may2013.pdf

Manz, D., Keller, J., & Miller, N. (2011). Value propositions for utility-scale energy storage. *Power Systems Conference and …*. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5772524

Martin, R. (2012). *Annual Renewable Distributed Energy Generation Installations Will Nearly Triple by 2017* (pp. 1–2). Navigant Research. Retrieved from http://www.navigantresearch.com/newsroom/annual-renewable-distributed-energy-generation-installations-will-nearly-triple-by-2017

Matthew Pearson. (2014, February 3). Ontario ombudsman to probe Hydro One's use of smart meters. *Ottawa Citizen*, pp. 1–3. Retrieved from http://www.ottawacitizen.com/technology/Ontario+ombudsman+probe+Hydro+smart+meters/9465092/story.html

Matthewman, S., & Byrd, H. (2014). Blackouts: a sociology of electrical power failure. *Social Space (Przestrzeń Społeczna …*, 1–25. Retrieved from http://eprints.lincoln.ac.uk/12908

Mauldin, P. (2013). *Postcards from the Edge: Is the Utility Industry in Big Trouble?* Transmission & Distribution World Magazine. Retrieved from http://tdworld.com/blog/postcards-edge-utility-industry-big-trouble

Mazza, P. (2003). The Smart Energy Network: Electricity's Third Great Revolution. *Climate Solutions.org*, 1–22. Retrieved from http://climatesolutions.org/resources/reports/powering-up-the-smart-grid-a-northwest-initiative-for-job-creation-energy-security-and-clean-affordable-electricity/SmartEnergyNetwork.pdf

McBean, G. (2012). *Telling the Weather Story: Prepared by the Institute for Catastrophic Loss Reduction for the Insurance Bureau of Canada*. Insurance Bureau of Canada. Retrieved from http://www.ibc.ca/en/natural_disasters/documents/mcbean_report.pdf

McCauley, S. M., & Stephens, J. C. (2012). Green energy clusters and socio-technical transitions: analysis of a sustainable energy cluster for regional economic development in Central Massachusetts, USA. *Sustainability Science*, *7*(2), 213–225. doi:10.1007/s11625-012-0164-6

McDonald, F. (1958). Samuel Insull and the Movement for State Utility Regulatory Commissions. *Business History Review*, *32*(3), 241–254. Retrieved from http://journals.cambridge.org/abstract_S0007680500005092

Mchale, A. (2013). *Transactive Energy Markets will Drive Distributed Power*. Automated Buildings. Retrieved from http://www.automatedbuildings.com/news/jul13/articles/memoori/130626032505memoori.html

McMahon, J. (2013). *Utilities Dumbstruck By Big Data From Smarter Grid*. *Forbes*. Forbes LLC. Retrieved from http://www.forbes.com/sites/jeffmcmahon/2013/09/25/utilities-dumbstruck-by-big-data-from-smarter-grid/

McNamara, W. (n.d.). Data privacy issues may become a regulatory quagmire. *DNVGL*. Retrieved March 25, 2014, from: http://www.dnvkema.com/insights/smart-energy/articles/data-privacy-issues-may-become-a-regulatory-quagmire.aspx

Meehan, C. (2013). New Conergy Solar Installations Reach Grid Parity — in New Mexico. *Renewable Energy World.com*. Retrieved from: http://www.renewableenergyworld.com/rea/blog/post/2013/06/new-conergy-solar-installations-reach-grid-parityin-new-mexico

Melton, R. (2014). Giving fillip to RE integration. *Energy Next*, *4*(3), 52–53. Retrieved from http://www.energynext.in/wp-content/uploads/2014/01/EN-JAN-14-.pdf

Milford, L. (2014, January 7). Natural Gas Loses to Solar on Costs, A First. *Huffington Post*, pp. 2–3. Retrieved from http://www.huffingtonpost.com/lewis-milford/natural-gas-loses-to-sola_b_4556162.html

Miller, E. (1993, June 14). Obituary: Eric Trist. *The Independent*, pp. 4–5. Retrieved from http://www.independent.co.uk/news/people/obituary-eric-trist-1491594.html#

Miners, Z. (2014). *Why Google paid $3.2 billion for Nest's smart thermostats*. *PC World*. Retrieved from www.pcworld.com/article/2087520/why-google-paid-32-billion-for-thermostat-startup-nest.html

Misener, D. (2014). *Google's Nest deal highlights privacy-policy issues: Dan Misener* (pp. 1–3). CBC News. Retrieved from http://www.cbc.ca/news/technology/google-s-nest-deal-highlights-privacy-policy-issues-dan-misener-1.2504839

Monika. (2013). Murmuration of Starlings in Netivot, Isreal. *The Fab Web*. Retrieved from: http://thefabweb.com/76463/30-best-animal-pictures-of-the-week-jan-26th-to-feb-1st-2013/attachment/76496/

Montgomery, J. (2013). *100 GW of Solar PV Now Installed in the World Today*. *Renewable Energy World.com*. Retrieved from http://www.renewableenergyworld.com/rea/news/article/2013/02/100-gw-of-solar-pv-now-installed-in-the-world-today

Moorhead, P. (2013). *The Problem With Home Automation's Internet Of Things (IoT)*. *Forbes* (pp. 1–3). Forbes LLC. Retrieved from http://www.forbes.com/sites/patrickmoorhead/2013/09/26/the-problem-with-home-automations-iot/

Munsell, M. (2014). *SolarCity's Market Share Jumps to 32% in US Residential PV*. Greentech Media Inc. Retrieved from http://www.greentechmedia.com/articles/read/solarcitys-us-residential-pv-marketshare-jumps-to-32

Murphy, P. R. (2012, July). Privacy and the Smart Grid: How Privacy Protections Were Designed Into Ontario's Central Meter Data Repository. *gowlings*. Gowling Lafleur Henderson LLP. Retrieved September 21, 2013, from: www.gowlings.com/KnowledgeCentre/article.asp?pubID=2722

Newell, C. (2008). The class as a learning entity (complex adaptive system): An idea from complexity science and educational research. *SFU Educational Review*, *2*(1), 5–17. Retrieved from http://journals.sfu.ca/sfuer/index.php/sfuer/article/view/31

NRCan. (2012). *Utility Scale Electricity Storage Demonstration Using New and Re-purposed Lithium Ion Automotive Batteries* (pp. 3–4). Natural Resources Canada. Retrieved from www.nrcan.gc.ca/energy/science/programs-funding/2046

O'Brian, P. (2014). The Internet of Things. *SEO'Brien*. Retrieved from: http://seobrien.com/internet-of-everything

O'Brien, G., & Hope, A. (2010). Localism and energy: Negotiating approaches to embedding resilience in energy systems. *Energy Policy*, *38*(12), 7550–7558. doi:10.1016/j.enpol.2010.03.033

O'Connor, P. A. (2008). Energy transitions. *Encyclopedia of Earth*, (12). Retrieved from http://www.bu.edu/pardee/files/2010/11/12-PP-Nov2010.pdf?PDF=pardee-paper-012-energy

O'Malley, L. (2012). *Overcoming hurdles to make energy storage a reality*. MaRS. Retrieved from www.marsdd.com/2012/09/27/overcoming-hurdles-to-make-energy-storage-a- reality/

OCAA. (2009). *Powerful Options: A review of Ontarios's options for replacing aging nuclear plants*. Ontario Clean Air Alliance Research Inc. Retrieved from www.cleanairalliance.org

Oldreive, M., Macdonald, C., & Pegolo, E. (2012). Managing Current Complexity: Critical Energy Infrastructure Failures in North America. *Dalhousie Journal of …*, *8*. Retrieved from http://ojs.library.dal.ca/index.php/djim/article/viewArticle/2012vol8Oldreive

Ontario Ministry of Energy. (2011). *Results-based Plan Briefing Book: 2011-2012*. Retrieved from http://www.energy.gov.on.ca/docs/en/ENERGY 2011-12 RBP EN.pdf

OPG. (2011). *Darlington Nuclear Generating Station Refurbishment and Continued Operation Environmental Assessment*. Ontario Power Generation. Retrieved from http://192.75.131.106/power/nuclear/refurbishment/Roundtable Presentation Darlington Refurb EA October 19 2011.pdf

Ormand, C. (2013). *Introduction to Complex Systems: What Constitutes a Complex System?* (pp. 1–5). Science Education Resource Centre. Retrieved from http://serc.carleton.edu/NAGTWorkshops/complexsystems/introduction.html

Ottinger, G. (2013). The Winds of Change: Environmental Justice in Energy Transitions. *Science as Culture*, *22*(2), 222–229. doi:10.1080/09505431.2013.786996

Pardy, B. (2009). Climate Change Charades. *Windsor Review of Legal and Social Issues*, *26*(October 2007), 179–204. Retrieved from http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1375094

Parkinson, G. (2014). *Citigroup Says the "Age of Renewables" Has Begun* (pp. 1–5). Greentech Media Inc. Retrieved from http://www.greentechmedia.com/articles/read/citigroup-says-the-age-of-renewables-has-begun

Parkinson, G. (2014). *Tipping Point Nears for Abandoning the Utility and Going Off-Grid* (pp. 1–5). Greentech Media Inc. Retrieved from http://www.greentechmedia.com/articles/read/Tipping-Point-Nears-for-Abandoning-the-Utility-and-Going-Off-Grid

Pejovic, S. (2011). *White Paper Hydro Energy Storage*. Centre for Urban Energy, Ryerson University. Retrieved from http://www.stanpejovic.com/WP on Hydro Energy Storage S Pejovic.pdf

Pentland, W. (2012). *Renewable Energy's Escalating Political Crisis*. *Forbes*. Retrieved from www.forbes.com/sites/williampentland/2012/06/16/renewable-??energys-??escalating-??political-??crisis/

Peter Bronski, Creyts, J., Guccione, L., Madrazo, M., Mandel, J., Rader, B., … Tocco, H. (2014). *The Economics of Grid Defection: When and Where Distributed Solar Generation Plus Storage Competes with Traditional Utility Service*. Rocky Mountain Institute. Retrieved from http://www.reznickthinkenergy.com/sites/reznickthinkenergy.com/files/CRTE_RMIGridDefection_2014-05.pdf

Pike Research. (2012). *Smart Grid Data Analytics*. *Navigant Research*. Retrieved from http://www.navigantresearch.com/research/smart-grid-data-analytics

Pollock, Z. (2013). *Venture Capitalists Don't Know How to Invest in the Smart Grid investment activity in 2012 .* Greentech Media Inc. Retrieved from http://www.greentechmedia.com/articles/read/Venture-Capitalists-Dont-Know-How-to-Invest-in-the-Smart-Grid

PowerMatcher: A quick overview of the technology. (2014). *PowerMatcher smartgrid technology*. Retrieved from: http://www.powermatcher.net/in-a-nutshell/

PwC PricewaterhouseCoopers. (2013). *Energy transformation: The impact on the power sector business model*. Retrieved from http://www.pwc.com/gx/en/utilities/global-power-and-utilities-survey/download-the-survey.jhtml

Quinn, E., & Reed, A. (2010). Envisioning the Smart Grid: Network Architecture, Information Control, and the Public Policy Balancing Act. *U. Colo. L. Rev.*, (forthcoming). Retrieved from http://heinonlinebackup.com/hol-cgi-bin/get_pdf.cgi?handle=hein.journals/ucollr81&section=22

Renewable Distributed Energy Generation Installations Will Reach Nearly $86 Billion in Market Value by 2017. (2012). *Wall Street Journal* (pp. 0–1). Retrieved from www.marketwatch.com/story/renewable-distributed-energy-generation-installations-will-reach-nearly-86-billion-in-market-value-by-2017-forecasts- pike-research-2012-12-12

Rosenfield, M. G. (2010). The smart grid and key research technical challenges. *2010 Symposium on VLSI Technology*, 3–8. doi:10.1109/VLSIT.2010.5556140

Salkin, G. (2014). *What the smart home means for utilities*. *Utility Dive* (pp. 2–5). Utility Dive. Retrieved from http://www.utilitydive.com/news/what-the-smart-home-means-for-utilities/220417/

Schneider, M., & Froggatt, A. (2013). *World Nuclear Industry Status Report 2013*. Retrieved from http://terras-altas.net.br/MA-2013/desastres ambientais/2012MSC-WorldNuclearReport-EN-V2.pdf

Schneider, M., Froggatt, A., & Thomas, S. (2012). Nuclear Power in a Post-Fukushima World. *Worldwatch Institute*, (April). Retrieved from http://www.worldwatch.org/system/files/pdf/WorldNuclearIndustryStatusReport2011_FINAL.pdf

Schumpeter, J. A. (1939). *Business Cycles: A Theoretical, Historical and Statistical Analysis of the Capitalist Process* (Vol. 1950, pp. 1883–1950). New York: McGraw-Hill. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Business+Cycles:+A+Theoretical,+Historical+and+Statistical+Analysis+of+the+Capitalist+Process#6

Shahan, Z. (2013). *Solar PV Module Prices Have Fallen 80% Since 2008, Wind Turbines 29%*. *Clean Technica* (pp. 5–6). Clean Technica. Retrieved from http://cleantechnica.com/2013/05/06/solar-pv-module-prices-have-fallen-80-since-2008-wind-turbines-29/

Shum, K. L. (2010). Renewable Energy Technology—Is It a Manufactured Technology or an Information Technology? *Sustainability*, *2*(8), 2382–2402. doi:10.3390/su2082382

Smart Grid 2025. (2011). *Institute for the Future*. Retrieved March 20, 2014, from: http://www.iftf.org/our-work/people-technology/games/smart-grid-2025/

Smith, A., & Stirling, A. (2008). *Social-ecological resilience and socio-technical transitions: critical issues for sustainability governance*. STEPS Centre. Retrieved from http://steps-centre.org/anewmanifesto/manifesto_2010/clusters/cluster7/Transitions_Working_Paper.pdf

Sood, V., Fischer, D., Eklund, J. M., & Brown, T. (2009). *Developing a communication infrastructure for the smart grid*. *Electrical Power & Energy Conference* (Vol. 4, pp. 1–7). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5420809

St. John, J. (2010). *Smart Grid Data: Too Much For Privacy, Not Enough For Innovation? GIGAOM* (pp. 2–5). Gigaom Inc. Retrieved from http://gigaom.com/2010/03/22/smart-grid-data-too-much-for-privacy-not-enough-for-innovation/

St. John, J. (2013). *A How-To Guide for Transactive Energy*. Greentech Media Inc. Retrieved from http://www.greentechmedia.com/articles/read/a-how-to-guide-for-transactive-energy

St. John, J. (2013). *PowerShift Atlantic: The Virtual Power Plant of the Future?* (pp. 1–6). Greentech Media Inc. Retrieved from http://www.greentechmedia.com/articles/read/powershift-atlantic-the-virtual-power-plant-of-the-future

St. John, J. (2014). *SolarCity and Tesla: A Utility's Worst Nightmare?* Greentech Media Inc. Retrieved from http://www.greentechmedia.com/articles/read/SolarCitys-Networked-Grid-Ready-Energy-Storage-Fleet

St. John, J. (2014). *The Wireless, Networked LED Goes Standard Do Daintree and*. Greentech Media Inc. Retrieved from http://www.greentechmedia.com/articles/read/the-wireless-networked-led-goes-standard

Stefan Nicola. (2013). *Germany Rejects EU Smart-Meter Recommendations on Cost Concerns*. *Bloomberg* (p. 2020). Bloomberg L.P. Retrieved from http://www.bloomberg.com/news/2013-08-01/germany-rejects-eu-smart-meter-recommendations-on-cost-concerns.html

Stephens, J. C., & Jiusto, S. (2010). Assessing innovation in emerging energy technologies: Socio-technical dynamics of carbon capture and storage (CCS) and enhanced geothermal systems (EGS) in the USA. *Energy Policy*, *38*(4), 2020–2031. doi:10.1016/j.enpol.2009.12.003

Stuller, J. (2010). *An Electric Revolution: Reforming Monopolies, Reinventing the Grid and Giving Power to the People*. Galvin Electricity Initiative. Retrieved from http://www.galvinpower.org/electric-revolution

Tapscott, D., & Williams, A. D. (2009a). *Wikinomics: How Mass Collaboration Changes Everything* (Vol. 50, pp. 563–4, 566). New York: Portfolio.

Tapscott, D., & Williams, A. D. (2009b). *Wikinomics: How Mass Collaboration Changes Everything* (Vol. 50, pp. 563–4, 566). New York: Portfolio.

Terdiman, D. (2014). *Google's Nest buy could spur growth of "Internet of things." CNET* (pp. 1–5). Retrieved from http://www.cnet.com/news/googles-nest-buy-could-spur-growth-of-internet-of-things/

The Burning Platform. (2012). *Problem-Solving-Techniques.com*. Retrieved from: http://www.problem-solving-techniques.com/Burning-Platform.html

The CNA Corporation. (2007). *National Security and the Threat of Climate Change*. Retrieved from http://www.cna.org/reports/climate

The new GE: Google, everywhere. (2014, January). *The Economist*, 1–4. Retrieved from http://www.economist.com/news/business/21594259-string-deals-internet-giant-has-positioned-itself-become-big-inventor-and

Trist, E. (1981). *The evolution of socio-technical systems*. *Occasional paper*. Ontario Ministry of Labour. doi:0-7743-6286-3

Tweed, K. (2012). *Utility Data Flow Could Eclipse Other Industries*. *GTM Research* (pp. 2012–2013). Greentech Media Inc. Retrieved from http://www.greentechmedia.com/articles/read/utility-data-flow-could-eclipse-other-industries/

Tweed, K. (2013). *Can One Project Redefine Power Delivery?* Greentech Media Inc.

U.S. DOE. (2008). *The Smart Grid: An Introduction*. Litos Strategic Communication. Prepared for the U.S. DOE. Retrieved from http://energy.gov/oe/downloads/smart-grid-introduction-0

U.S. Energy Information Administration. (2013). *Annual Energy Outlook 2013: with projections to 2040*. Retrieved from http://www.eia.gov/forecasts/aeo/pdf/0383(2013).pdf

U.S. EPA. (2013). *Sources of Greenhouse Gas Emissions*. U.S. Environmental Protection Agency. Retrieved from http://www.epa.gov/climatechange/ghgemissions/sources/electricity.html#Trends

UCS USA. (2013). *The Cost of Nuclear Power: Numbers That Don't Add Up* (pp. 1–3). Union of Concerned Scientist. Retrieved from http://www.ucsusa.org/nuclear_power/nuclear-power-and-our-energy-choices/nuclear-power-costs/?print=t

Utility Dive. (2014). *The State of the Electric Utility: 2014*. *Utility Dive*. Retrieved from http://www.utilitydive.com/library/2014-state-of-the-electric-utility/

Vermesan, D. O., & Friess, D. P. (2013). *Internet of Things: Converging Technologies for Smart Environments and Integrated Ecosystems*. (O. Vermesan & P. Friess, Eds.). River Publishers. Retrieved from http://www.internet-of-things-research.eu/pdf/Converging_Technologies_for_Smart_Environments_and_Integrated_Ecosystems_IERC_Book_Open_Access_2013.pdf

Waltner-Toews, D., Kay, J., & Lister, N. (2008). An Introduction to Systems Thinking. In *The Ecosystem Approach: Complexity, Uncertainty, and Managing for Sustainability*. Columbia University Press. Retrieved from http://books.google.com/books?hl=en&lr=&id=2FyW-dqlrmYC&oi=fnd&pg=PR9&dq=The+Ecosystem+Approach:+Complexity,+Uncertainty,+and+Managing+for+Sustainability&ots=G9MyvCZZqa&sig=qGdETih4-EDDsTOOdwzE7oDuEDY

Weinrub, A. (2012). *Labor's Stake in Decentralized Energy*. Trade Unions for Energy Democracy. Retrieved from http://energyemergencyenergytransition.org/wp-content/uploads/2012/10/Labors-Stake_10-23-121.pdf

Weis, T., Stensil, S.-P., & Stewart, K. (2010). *Renewable is Doable: Ontario's Green Energy Plan 2.0*. The Pembina Institute. Retrieved from http://www.pembina.org/pub/2059

White, N., Ingham, K., von Bechtolsheim, M., Haischer, M., & Francis, R. (2013). *The future of energy utilities: How utilities can survive the "perfect Storm."* Arthur D Little. Retrieved from http://www.adlittle.com/downloads/tx_adlprism/The_future_of_energy_utilities.pdf

Windrum, P. (2003). Unlocking a lock-in: towards a model of technological succession. *… Evolutionary Economics: New Empirical Methods and …*, (292), 1–38. Retrieved from http://books.google.com/books?hl=en&lr=&id=ESITBpxiBkgC&oi=fnd&pg=PA292&dq=Unlocking+a+lock-in:+towards+a+model+of+technological+succession&ots=BVRhn4jR5i&sig=EmUJ2eqpytJYUrRmfAwCoqhAifo

Wingfield, B. (2011, May 26). GE Sees Solar Cheaper Than Fossil Power in Five Years. *Bloomberg*. Retrieved from http://www.bloomberg.com/news/print/2011-05-26/solar-may-be-cheaper-than-fossil-power-in-five-years-ge-says.html

Woods, E. (2013). *As Momentum Slows, Europe Seeks New Smart Grid Boost*. *Navigant Research* (pp. 1–2). Navigant Consulting Inc. Retrieved from http://www.navigantresearch.com/blog/as-momentum-slows-europe-seeks-new-smart-grid-boost

Zeller, T. (2011, September 26). Jeremy Rifkin: The "Democratization Of Energy" Will Change Everything. *Huffington Post*.

Zuboff, S. (2010). Creating value in the age of distributed capitalism. *McKinsey Quarterly*. Retrieved from http://www.perfcons.com/bibliotheque/veille/strategie143.pdf