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Knowledge Requirements, Gaps and Learning Responses in Smart Grid Adoption: An Exploratory Study in U.S. Electric Utility Industry

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Abstract

The U.S. electric utility industry is facing a number of challenges today, including aging infrastructure, growing customer demand, CO2 emissions, and increased vulnerability to overloads and outages. Utilities are under greater regulatory, societal and consumer pressure to provide a more reliable and efficient power supply and reduce its carbon footprint. In response, utilities are investing in smart grid technologies. Despite various definitions of smart grid, it is characterized by employing a set of sophisticated sensing, processing and communicating digital technologies to enable a more observable, controllable, and automated power supply.

Yet, the adoption of smart grid technologies presents significant knowledge challenges to electric utilities. This study aims to advance the understanding of IT knowledge challenges in smart grid adoption by focusing on three research questions:

1) What knowledge requirements are critical for smart grid adoption?

2) What knowledge gaps are utilities facing with smart grid adoption? How do utilities vary in the level of knowledge gaps?

3) How do utilities overcome knowledge gaps through learning? How do utilities vary in the learning choices?

This study adopts a qualitative approach using data from 20 utility interviews and secondary information to address the above questions. The analysis indicates four broad areas of knowledge requirements, which are smart grid technology and vendor selection, smart grid deployment and integration, big data, and customer management. The data also reveals several knowledge gaps faced by utilities in these four areas, and confirms that utilities vary in the level of knowledge gaps, which depends on a mix of factors including prior experience, IT sophistication, service territory characteristics, size, ownership form, regulatory support and support from external organizations. The data further indicates several learning practices that are commonly adopted by utilities to overcome the knowledge gaps in smart grid adoption. It is also determined that utilities vary in the configuration of these practices, and the scale and format of many practices. The variance in learning responses is jointly determined by level of knowledge gaps, knowledge relatedness, size, risk-averse culture and top management support.

This study has both research and practical implications. Theoretically, it enriches IT adoption, broader IS research and organizational learning literature in several ways. From the practical perspective, it also has valuable implications for utilities, regulators and other regulated industries and economies.

Knowledge Requirements, Gaps and Learning Responses in Smart Grid Adoption: An Exploratory Study in U.S. Electric Utility Industry

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Dissertation
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Table of Contents

List of Tables

List of Figures

1 Introduction

This chapter introduces the statement of the problem, background of the research, research questions, theoretical perspectives, and significance of this study. The main objective of this study is to understand what challenges utilities are facing as well as utilities' responses to these challenges in smart grid adoption. In order to understand the response of utilities, I use organizational learning as a lens to examine the utilities' decisions. Both theoretical and practical implications are discussed.

1.1 Statement of the Problem

Electric utility companies are facing a convergence of challenges such as the need to improve grid reliability and safety and the need to reduce carbon dioxide emissions, as well as the trend towards integrating various renewable resources and electric vehicles into the existing utility infrastructure.

Among the challenges, the need to provide a more reliable power supply is paramount (Department of Energy, 2014). In many states of the United States, the physical infrastructure of the electricity grid that is currently in use was built in the 1950s; it is aging (Harris Williams & Co, 2010). Combining increased customer demand for electricity usage as well as extreme weather events has stressed the current grid to its limit and has made it vulnerable to outages. According to recent statistics, reported outages across the country are on the rise and the monthly average grid outages in 2013 increased six-fold compared to the same period in 2000 (Wirfs-Brock, 2014). Massive blackouts have also become more frequent in recent years, and blackouts following major storms cost the U.S. economy between $35 billion to $55 billion each year (Campbell, 2012). As a result, there is increased public awareness of grid reliability and safety, and utilities are being pushed to improve both.

Utilities are also under societal and regulatory pressure to reduce greenhouse gas emissions, primarily carbon dioxide emissions. Compared to other industries, the electricity sector is the largest source of greenhouse gas emissions, accounting for the 30% of total U.S. greenhouse gas emissions due to heavy use of fossil fuels, coals, and natural gas (Environmental Protection Agency, 2014). To reduce the carbon footprint of utilities the U.S. government has exerted pressure on utility companies to adopt more environmental-friendly practices. For example, the EPACT (Energy Policy Act) and EISA (Energy Independence and Security Act) were enacted in 2005 and 2007 respectively with the goal of promoting the use of clean and renewable energy resources and encouraging investments in grid upgrades. Most state regulators also set up the RPS (Renewable Portfolio Standard) to boost the development of renewable energy.

In parallel with government initiatives to encourage large-scale generation of renewable resources by utilities, there is a growing penetration of customer-sited distributed energy generation and electric vehicles, many of which have been purchased as a result of federal and state subsidies or/and the low prices of clean energy. Activities such as the use of solar photovoltaic panels, in which customers generate electricity for their own use and receive compensation for selling excess energy back to the grid are particularly popular in energy aggressive states like California and several Northeast states (Department of Energy, 2014). Accordingly, utilities face the urge to integrate a variety of intermittent renewable energy sources and electric vehicles while ensuring the quality of the power supply.

Against this background, the smart grid has emerged as a way for utilities to address the aforementioned challenges. This grid was conceptualized as a set of information and communication technologies produced by various vendors that enable monitoring, analyzing, controlling, and communication capabilities to allow more intelligent production, delivery, and use of electricity (Department of Energy, 2014). It incorporates a variety of elements, including digital equipment and devices (e.g. smart meters and sensors), two-way data communication platforms, as well as hardware and software programs, all of which must be integrated with each other and with the electrical infrastructure (Kranz & Picot, 2011). Smart grid innovation enables a set of capabilities that had been missing in the past, for instance, two-way communication between utilities and customers, demand-side management and load control, outage management, asset management, dynamic pricing, and integration of distributed renewable energy resources, and electric vehicles and other dischargeable sources (International Energy Agency, 2011; Kossahl, Kranz, & Kolbe, 2012). As a result, it empowers a more observable, controllable, and automated power supply.

Although the rate of smart grid adoption varies across states in U.S., smart grid has gained wide attention and more utilities are planning and implementing smart grid nowadays (Department of Energy, 2016). Yet, smart grid technologies present significant knowledge challenges for electric utilities. An increasing number of articles have been published in practitioner literature or on various websites discussing the challenges faced by utilities with respect to the deployment and use of smart grid technologies. A major claim is that smart grid entails a heavy penetration of IT (Information Technology) but utilities lags behind in IT investment. Utilities have long-term experience in investing in OTs (Operation Technology), which include a broad category of physical equipment, devices, and processes that operate in real-time to ensure the generation, transmission, and delivery of electricity (Atos, 2012). Some good examples are the adoption of SCADA (Supervisory Control and Data Acquisition) and PLCs (Programmable Logic Controls), which were widely deployed by utilities in the 1980s (ABB, 2012). Accordingly, there is a good amount of legacy knowledge and understanding built around electricity and grid operation, yet utilities have fallen behind in the knowledge and application of IT, in which IT is often restricted to the basic back-office administrative functions; little crossover occurs between IT and OT (Hardcastle, 2013), as one participant noted:

"Utilities had a lot of technologies but IT was not part of that. So when you go inside a substation, and transmission and distribution, up until the early 80s, you wouldn't find any equipment with communications installed, and there is no computing and there is no integration and no IT."

This OT-focused model has served utilities well in the past, but now smart grid entails high interdependence between heterogeneous physical assets and operation processes, hardware infrastructure and software applications, and data as a result of IT and OT integration. For example, SCADA were traditionally isolated from IT infrastructure and used to control a limited number of operational assets. Now there are far broader applications and devices under SCADA's control with IT built in by its architect (Meyers, 2013). More importantly, smart grid witnesses an exponential increase in both quantity and quality of IT applications. New IT solution like MDMS (Meter Data Management System) GIS (Geographic Information System), as well as traditional enterprise IT applications like ERP (Enterprise Resource Planning) and AMS (Asset Management System) that usually serve in the business domain to optimize commercial decision making and business processes, migrate to the operation domain to improve operational efficiency (Meyers, 2013).

Additionally, many physical assets, devices and communication networks are equipped with TCP/IP and other forms of Wi-Fi communications to bridge the silos in grid. Traditionally, there are several isolated physical infrastructure and devices. The communication within each island is either through traditional wired technologies or performed manually, in which a crew of electricians are dispatched to communicate with customers (Mattioli & Moulinos, 2015). Now, with more wireless options from the IT world, multiple types of physical equipment and systems can be connected and glued to operate together (ABB, 2012).

While IT plays a much more important role of optimizing grid operation in utility companies as opposed to the traditional role of "back-office systems" (Atos, 2012), it also increases the complexity and uncertainty of smart grid compared to past technologies, due to the integration and dynamics between different layers and components of technologies (Department of Energy, 2008; Hardcastle, 2013). As a result, smart grid brings fundamental changes to utilities, which requires utilities to develop knowledge that many do not have as it was never necessary before.

Such anecdotal evidence is consistent with the IT adoption literature which argued that knowledge barriers are common in the adoption of new IT innovations (Attewell, 1992; Fichman & Kemerer, 1997), especially when it comes to complex organizational technologies, which "impose a substantial burden on would-be adopters in terms of the knowledge needed to use them effectively" (Fichman & Kemerer, 1997, p. 1346). While basic knowledge regarding product information such as new technologies' characteristics, features, and potential benefits and risks can be acquired during the sales cycle, there can be knowledge deficiencies on the adopters' side in the implementation and use of the new technology regarding how they can be integrated with the organizational practices; for instance, knowledge about the changes and new capabilities demanded by deploying the innovation in the context of their organizational structures and cultures (Markus & Tannis, 2000; Wang & Ramiller, 2009). Yet, lacking necessary knowledge would cause misalignments between the new technology and adopting organization, resulting in either the adopter's delay in implementation or a lack of capability to fully leverage the IT innovations (Fichman & Kemerer 1999).

Inspired by the literature, knowledge gaps can greatly shape the adoption outcomes and should be properly handled. Given the importance of smart grid and the anecdotal evidence that utilities adopting smart grid are facing big challenges, questions like "what are knowledge challenges in smart grid adoption" and "how do utilities overcome such challenges" are critical and should be answered. Unfortunately, few practitioner and academic studies can directly shed light on these questions. Despite findings from practitioner studies, they appear fragmented and inconclusive. Many of these articles focused on specific aspects in smart grid implementation and use, and the results were often inconsistent. Most importantly, although these practical studies proposed a list of strategic advice to smooth the challenges (ABB, 2015; Deign & Salazar, 2013; Savenije, 2014), there is little revealed on how utilities actually meet the knowledge challenges in reality. What's worse, such understanding is also missing in the academic field. Despite the wide attention from engineering and computer science schools that focus on smart grid technologies themselves, for instance, particular application development or algorithm refinement, there is little research on the adoption and use of smart grid technologies in organizational settings (Dedrick et al, 2015; Leeds, 2009).

Considering the increasing adoption of smart grid by utilities and neglect in the academic literature, there is a need to understand what knowledge challenges utilities are facing as well as utilities' responses to these challenges in smart grid adoption. This study has certain boundaries. First, innovation generation and innovation adoption are two distinct concepts in which organizations in the former situation generate new technologies or products whereas organizations in the latter situations acquire technologies developed elsewhere (Damanpour & Wischnevsky, 2006). This study fits the second situation—utilities purchase smart grid technologies from various vendors and implement and use these technologies. Why utilities prefer acquiring smart grid technologies from vendors rather than using internal R&D to develop the technologies is beyond the scope of this study. Second, how utilities make adoption decision regarding what set of smart grid technologies to adopt is also beyond the scope of this study. A recent study has a comprehensive discussion on the factors that could motivate utilities to adopt smart grid technologies (Dedrick, et al, 2015). In this study, I am interested in understanding the knowledge challenges after the adoption decision has been made, or in post-acquisition phase, and how utilities acquire relevant knowledge to fill the knowledge gaps. More specifically, as learning forms the most critical part of knowledge acquisition, I am interested in understanding how utilities learn to overcome the knowledge challenges in smart grid to integrate these new technologies. In order to better elucidate this research, relevant research background is introduced in the following section.

1.2 Relevant Research Background

The Electric Utility Industry

The electric utility industry in the U.S. has historically been characterized as regulated local monopolies. There are over 3,000 utility companies in the U.S.; major players in the industry are investor-owned utilities (IOUs) that produce 75% of generation and serve 69% of all customers in the United States, with the rest served by electric cooperatives, municipal utilities, and a few other players (APPA, 2014). The IOU is a for-profit enterprise owned by stakeholders who may or may not be customers. Their prices and profits are heavily controlled by regulatory bodies, including the Federal Energy Regulatory Commission (FERC) and state Public Utility Commission (PUC). In contrast a municipal and cooperative operates on a non-profit basis and is self-regulated through city governments or city councils (Energy Information Administration, 2000; Rose & Joskow, 1990). Different ownership forms also reflect variance in size: IOUs are usually large companies with adequate resources whereas cooperatives are generally small firms. The municipal-owned utilities vary with the size—in some cases the size of a municipal-owned utility can be as large as a traditional IOU but they can also be small organizations with less than a hundred employees. It should be noted that utilities are not confined to IOUs, municipals, and cooperatives but also include power marketers and federal power agencies (APPA, 2014); however, the first three types dominate the utility industry accounting for over 90% of utilities in the U.S. and are therefore the focus of this study.

Like many regulated industries, electric utility companies operate in a relatively predictable environment with little competition as a result of government regulation--the traditional cost-plus-return regulation resulted in fixed electricity rates among utilities and their profits are protected despite the initial investment amount (RAP, 2011). Hence, utilities are widely recognized as lacking in innovation and are considered risk-averse (Energy Information Administration, 2000).

Smart Grid

Smart grid is a general label for a class of technologies that uses computer-based remote control and automation and is built on the physical infrastructure to enable a more efficient, reliable, and sustainable power supply (Department of Energy, 2014). Based on the location and function of smart grid technologies, they can be grouped into three categories: AMI (Advanced Metering Infrastructure), customer-side technologies, and grid-side technologies (Department of Energy, 2012a). Each system comprises a mix of physical power infrastructure, communication networks, and IT hardware and software, as seen in table 1 (Dedrick et al, 2015; Leeds, 2009). It should be noted that these three groups of technologies are not independent from each other. In fact, they are connected to take full advantage of data and maximize the benefits of smart grid adoption

(Pike Research, 2012; Sierra Energy Group, 2010). However, for the purpose of clearly introducing smart grid, I will introduce the three groups separately.

	AMI	**Customer-side**	**Grid-side**
IT systems & software	Meter data management system (MDMS)	Energy Dashboards and Home Energy Management System (HEMS), Demand Response Management System (DRMS), etc.	Outage Management System (OMS), Geographic Information System (GIS), Fault Detection Isolation and Restoration System (FDIR), Distribution Management System (DMS), Volt–VAR Management systems, etc.
Communication network	WAN (Wide Area Network), LAN (Local Area Network)	HAN (home area networks)	WAN, LAN
Physical Power Infrastructure & hardware	Smart meter, in-home displays, servers, relays, etc.	Smart thermostats and appliances, routers, in-home displays, electric vehicles, etc.	Two-way SCADA, Phasor Measurement Units (PMU), automated re-closures, switches and capacitors, etc.

Table 1 Components of Smart Grid

AMI is a key component in smart grid. It is a fully integrated infrastructure that involves a backbone communication network, smart meters, and backend software systems to support meter data collection and management (Department of Energy, 2014). Before AMI, the communication is limited to the transmission grid covering only high and medium voltage parts of the grid. The AMI fills the missing link in the current networks by extending the communication infrastructure to lower voltage parts of the grid (distribution grid) and even customer sites, and support two-way meter communication between both utilities and consumers (Department of Energy, 2012a). The empowered, integrated communication network also makes AMI an underlying platform that can be leveraged to support a variety of grid technologies and applications to take advantage of near real-time meter data. For instance, AMI has been leveraged to improve operational efficiency and customer service (Department of Energy, 2014). With AMI, utilities can remotely connect or disconnect meters in the office when customers move in or out, without sending crew members to execute such actions in person. This results in a significant reduction in truck rolls (Department of Energy, 2011; Edison Electric Institute, 2011). Additionally, smart meter data increases billing accuracy and is widely leveraged to discover and report any unusual energy consumption patterns, such as electricity leakage and energy thefts (Edison Electric Institute, 2011; National Energy Technology Laboratory, 2008).

Examples of customer-side technologies include home energy management systems, smart thermostats, and direct load control devices through which home appliances are networked to and communicate with smart meters to inform customers about their electricity usage and costs on a real-time basis (Department of Energy, 2012b). Accordingly, customers have access to their daily, weekly, or monthly energy usage data and are empowered to better manage their energy usage (Edison Electric Institute, 2011). Customers who install these smart applications are encouraged to participate in the demand response program by which utilities use a price signal (time-based rates) to incentivize customers to curtail their electricity usage during peak hours (FERC, 2012). For a long time, demand response mainly involved industrial and commercial customers with little residential participation (Leeds, 2009). Now with a two-way AMI platform, there is an expanded range of time-based rate options that can be offered to consumers and smart customer systems that make it easier for consumers to change their behavior. Besides these technologies, customer-end rooftop solar and electric vehicles are a growing trend in some states that have been aggressive in advocating renewable energy (Department of Energy, 2014).

Innovations on the grid-side include applications aimed at improving transmission and distribution system operation and reliability. With traditional enterprise systems like EAM

(Enterprise Asset Management) and OMS penetrating into the operational domain, utilities are able to track the health status of a much broader array of grid assets in near real time and become more responsive to unexpected outages. For instance, based on the trends of equipment performance, utilities can use predictive analytics to forecast any potential problems and take remedial actions to avoid major function failure (Deign & Salazar, 2013). Also, any disturbance in the system will be recorded and sent directly to the back office, allowing system operators to identify and scope the outage quickly (Department of Energy, 2012a). In the situation of an emergency outage, utilities can isolate the problem area while keeping the rest of the grid operating normally (Department of Energy, 2008). In terms of power restoration, the recovery time is also minimized as utilities can have a real-time track on restoration status (Morgan, et al., 2009).

Key Players in Smart Grid Adoption

Smart grid adoption is shaped by a group of shareholders. First, state regulators have a large impact on smart grid deployment as the attitude and regulatory process of a state's PUC greatly influences the progress of a utility in smart grid. In many cases, aggressive state regulatory requirements are an important driver of some leading utilities' advancement in smart grid (Dedrick et al, 2015). Further, regulatory bodies have full authority to review, approve, or reject a utility's deployment request and cost recovery plan (Hertzog, 2012).

Second, utilities themselves play a key role in smart grid, as they are directly responsible for smart grid deployment. Thus, their level of resources and capabilities determine their adoption scale and the eventual outcome.

Third, smart grid adoption is also influenced by customers who are highly involved in some components of smart grid deployment (Lundin, 2012). Although customers are not directly involved in the decision-making process, their level of support and cooperation greatly influences the smoothness of deployment of smart meters and customer-side systems. For instance, a big IOU in California faced a class action lawsuit from its customers when rolling out its smart meters; ultimately its smart meter program was suspended and had to be assessed by an independent, third party evaluation suggested by the California PUC (John, 2009).

In addition to the three groups of stakeholders mentioned above, a number of other players are involved in smart grid deployment, including network providers and IT vendors (Department of Energy, 2008). They are especially influential in pushing new technologies because they provide technical consulting and support services.

1.3 Research Objective and Questions

The main objective of this research is to understand knowledge challenges faced by utilities in smart grid adoption as well as the learning responses of utilities as they work to overcome knowledge barriers. In order to achieve this goal, three research questions are proposed:

1) Knowledge requirements

In this study, one of the main goals is to understand knowledge challenges, or knowledge gaps faced by utilities in smart grid adoption. However, the discussion of knowledge gaps is not meaningful without the discussion of knowledge requirements, as the gap exists between knowledge requirements and existing knowledge. Thus, the first question tries to identify what areas of knowledge are critically related to smart grid adoption.

RQ1: What knowledge requirements are critical for smart grid adoption by utilities?

2) Knowledge gaps

The second set of questions focuses on knowledge gaps by discovering what knowledge utilities are missing but are critically important in smart grid adoption. It is expected that utilities vary in the level of knowledge gaps, as they are subjective to different intrinsic and extrinsic characteristics. It is therefore also interesting to understand how utilities vary in knowledge gaps.

RQ2: What knowledge gaps are utilities facing with smart grid adoption? How do utilities vary in the level of knowledge gaps?

3) Learning responses

The third question is the center of this study as it focuses on the learning used by the various utilities to overcome the knowledge gaps in smart grid adoption. The first part of the question looks at the learning responses adopted by utilities to bridge the knowledge gaps. It is also expected that utilities vary in the choices of these learning response, as they are subjective to different intrinsic and extrinsic characteristics. Hence, the second part of the question examines how utilities vary in their learning choices.

RQ3: How do utilities overcome knowledge barriers through learning? How do utilities vary in their learning choices?

1.4 Significance of the Study

This research is significant in both theory and practice. First, this study addresses the limitations of two dominant paradigms in IT adoption research (Fichman, 2004). On one hand, the bulk of researchers treated the adoption process as a black box and mainly concerned with explaining the general propensity of an organization to adopt and assimilate an IT innovation. Hence, there has been an extensive body of research using variance model to identify antecedent condition that predicts and explains IT adoption (Armstrong & Sambamurthy, 1999; Hsu, Lee & Sraub, 2012;

Ven & Verelst, 2012; Zhu et al, 2006). However, the limitation of such variance model is that it doesn't assume factors affecting IT adoption can interact in complex ways that go beyond simple, linear interaction effects. Yet, this study lends empirical support that there are complex interactions among factors influencing complex IT adoption. On the other hand, another stream of researchers uncovered the black box of IT adoption by examining sequences of events that take place along the adoption process (Robey, Ross, & Boudreau, 2002). Yet, process research provided more description than explanation and little was known about the dynamic underlying the adoption process. This study brings insights to this stream of research by applying the organizational learning perspective in IT adoption process-- it uncovers underlying learning practices as well as the dynamics among these practices in overcoming knowledge gaps in the context of a complex IT adoption. Hopefully, this empirical investigation will make a further step in advancing the process research.

Second, this study adds to the IT adoption literature by enriching the understanding regarding knowledge requirements and gaps along IT adoption. Although the knowledge requirements and gaps identified in this study is subjective to the smart grid context, the findings of this study is consistent with the literature that technical and business knowledge are fundamental in IT adoption (Attewell, 1992; Fichman & Kemerer, 1999; Seddon et al, 2010). Additionally, while previous studies recognized that knowledge gaps always occur in IT adoption (Attewell, 1992; Fichman & Kemerer, 1997), there is little discussion on whether and how adopting organizations vary in knowledge gaps. This study fills this gap by confirming that utilities varied in the knowledge gaps in smart grid adoption and determining that such variance is determined by an interaction of organizational and environmental factors.

Third, this research has the potential to contribute to the broader IS field by developing an integrative framework demonstrating the links among knowledge requirements, knowledge gaps and learning responses in IT adoption efforts. The dynamics among them, in which the contingent and interaction effects of different knowledge, organizational and environmental factors influence the level of knowledge gaps and the choices of learning practices, are particularly interesting. In the next decade, organizations and sectors will face a range of new landscape-changing IT, for instance, big data and the Internet of things as well as artificial intelligence to name but two. Thus, future IS research could seek to further elaborate and empirically test a more general theoretical model around these factors, thereby shedding new light on complex IT adoption processes and the associated organizational learning responses.

This study also has the potential to contribute to organizational learning research by examining learning in a slow-moving, regulated industry faced with disruptive new technologies, which has been rarely explored before (Rashman, Withers, & Hartley, 2009). While findings regarding the configuration of learning practices and factors influencing the learning choices are consistent with the literature, a unique contribution of this study is identifying the dynamics among these factors and how such interaction impact the learning. Moreover, this research not only confirms the previous finding that regulatory environment influences learning through an entrenched risk-averse culture (Brodtrick, 1998), but also provides empirical support that regulatory environment can impact learning by influencing the level of knowledge gaps.

This study also has implications for utility companies, regulators and other regulated economies. The results demonstrate that whereas external impact such as regulatory attitude and uncontrollable factors such as knowledge relatedness, size and service territory characteristics are key factors shaping level of knowledge gaps in smart grid adoption, internal organizational capabilities can also moderate the knowledge gaps. Therefore, utilities should be more active in incorporating IT investment in its R&D efforts to lower knowledge barriers for future technology adoption or upgrades, as this is the trend for future technology. When it comes to learning, this study shows that top management support and level of resources play a crucial rule in learning. The findings illustrate the importance of top management support in knowledge areas with great uncertainty and risks. This calls for managerial attention to create an innovative culture that is beneficial to utilities in the long run. Managers should also factor in their level of resources when making decisions on learning choices- they need to consider how to allocate the human resources and time to improve the effectiveness of learning. Additionally, this study suggests that state regulators should create an environment that encourages innovation and exploration among utilities, so that utilities are more confident in smart grid adoption. The findings of this study are also relevant to other regulated industries or economies that are contemplating or adopting complex information and communication technologies.

1.5 Outline of Dissertation

The remainder of this dissertation is divided into four chapters. Chapter two presents a comprehensive review of the literature that informed this study. A synthesis of findings from knowledge, IT adoption, and organizational learning studies is presented to inform the three research questions. Then, a reflection comparing my study context and those used commonly in the referenced literature is discussed to conclude which findings apply in this study and which do not. Chapter three includes a detailed description of the research methodology undertaken in this study, a qualitative exploration of the phenomenon of interest. It begins with an overview of the adopted methodological approach and an outline of the research design, followed by a detailed description of sampling, data collection, and data analysis procedures. The chapter concludes with a discussion of tactics to assure the validity and generalizability of this study. Chapter four presents the findings related to the research questions of this study. It examines the knowledge requirements and gaps in smart grid adoption, as well as utilities' learning responses to overcome these knowledge gaps. Specifically, chapter four discusses how utilities vary in the level of knowledge gaps and in the learning responses. Chapter five covers the discussions and implications of the findings. Key findings are reviewed, and compared with the literature. In the implications section, both theoretical and practical implications are discussed. Finally, the limitations of this study, as well as recommendations for future work, are provided, followed by a conclusion.

2 Literature Review

Although the academic literature has little discussion that is directly related to knowledge gaps and learning in smart grid adoption by utilities, this chapter examines three sets of studies including knowledge, organizational IT adoption, and organizational learning literature that contribute to this research. First, it reviews knowledge literature to examine how knowledge is defined and constructed. The concept of knowledge itself is important, because it is a key concept in three research questions. Second, it examines how organizational IT adoption studies can shed light on all three research questions. Smart grid adoption is a good example of organizational IT innovation adoption, and it’s worth examining what are the relevant findings regarding knowledge requirements, gaps, and learning in IT adoption in this set of literature. Third, it also reviews the organizational learning literature to further elucidate the third research question. The learning related concepts generally originate from this set of research, and provide guidance to explore the implications on how firms handle and bridge knowledge gaps. Finally, it summarizes how these three sets of literature contribute to this study, and what are the gaps in the literature.

2.1 Organizational Knowledge

This study provides an overview of the conceptualization of organizational knowledge in the knowledge literature as well as common taxonomies of organizational knowledge. The exploration of organizational IT adoption and organizational learning literature is pointless without the discussion of the knowledge itself, because the term “knowledge” is deeply embedded in all three research questions.

2.2.1 The Concept of Knowledge

Knowledge is an important concept in the literature, with great controversy surrounding its definition and nature. (Argote, 2011; Haider, 2003; Nonaka, 1994) (See table 3). Various explanations and understandings of knowledge have been put forward by organizational scholars and accordingly, knowledge has been considered in the literature from several perspectives: 1) data and information; 2) state of mind; 3) an asset, or 4) a capability (Alavi & Leidner, 2001). Due to its multifaceted nature, some scholars even suggested, "it is not productive to attempt to define knowledge" (Snowden, 1997, p,17).

Perspective	Definition	Sample studies
1. Knowledge as data and information	Knowledge is a meaningful set of information that constitutes a justified true belief	Huber, 1991; Nonaka et al, 1996
2. Knowledge as a state of mind	Knowledge is the state of knowing and understanding	Schubert et al. 1998
3. Knowledge as an asset	Knowledge is an asset to be stored and manipulated	Friesl, 2012; Zack, 1998
4. Knowledge as capability	Knowledge is the capability to understand, comprehend, use, reuse, and combine data and information in such a way that better results can be achieved	Davenport and Prusak, 1998; Haider, 2003

Table 2 A Summary of Perspectives on Knowledge (Adapted from Alavi & Leidner, 2001)

In this study, the concept of knowledge is based on the combination of perspectives 1, 2 and 4, in which knowledge not only constitutes data and information but also an understanding of the logics behind the data and information (Grant, 1996; Haider, 2003; Kogut & Zander, 1992; Nonaka, 1994), as well as the capability to develop such understanding. This broader view of knowledge supports both static and dynamic views of knowledge, and is able to capture the multi-layered nature of knowledge where a single view cannot. It is also noted that perspective 3 is embedded in this view because data, information, and some forms of understanding can be stored and used.

Knowledge can be possessed either by individuals or organizationally by which information and insights from diverse individual repositories and routines are integrated and institutionalized and are embodied in organizational routines, practices, and beliefs (Nelson & Winter, 1982; Nonaka, 1994). As this study is interested in the organizational adoption of smart grid innovation, organizational knowledge is the focus here. Nonaka and Takeuchi (1995) argued that individual knowledge is the pre-requisite for organizational knowledge, as organizational knowledge cannot be created without input from individuals. However, organizational knowledge is not the simple gathering of individual knowledge—individual knowledge must be shared, integrated, and crystallized through organizational-level communications and interactions to become organizational knowledge (Tsuchiya, 1994; Tsoukas & Vladimirou, 2001). Yet, organizational knowledge shares many characteristics with individual knowledge as previously mentioned. In this study, organizational knowledge is viewed as a multi-dimensional concept that includes information and data, a collective understanding behind the data, and the organizational capability to develop such an understanding.

2.2.2 Concept of Knowledge Requirements and Gaps

A few scholars in the knowledge literature provided a clear definition on both terms 'knowledge requirement' and 'knowledge gap' and how they are related. Zack (1999) mentioned the concept of a knowledge gap in the context of a discussion of firms' knowledge strategy, and claimed that a knowledge gap is the gap between knowledge needed in knowledge strategy execution and the knowledge possessed. Haider (2003) proposed a similar definition, in which a knowledge gap was viewed as "all types of organizational knowledge which a company currently lacks but identifies to be critically important for its survival and growth and, hence, need to be filled." In a recent study, Qiu and his colleagues Wang and Nian (2014) discussed knowledge gaps in new product development and referred to it as an “intersection between the knowledge required and the knowledge actually possessed by a firm during product development” (p.2).

Although both concepts have been studied in different contexts, the definitions share one major similarity—knowledge requirements are an important aspect in understanding the concept of knowledge gaps and it is problematic to discuss knowledge gaps without touching on the concept of knowledge requirements. According to the aforementioned studies (Haider, 2003; Qiu, Wang, & Nian, 2014), knowledge requirements refer to a set of knowledge and skills needed by an organization, whereas knowledge gaps are the organizational knowledge an organization lacks but identifies to be critically important. While knowledge gaps always correspond to knowledge requirements, having knowledge requirements does not always cause knowledge gaps, due to various levels of possessed organizational knowledge.

This study also agrees that knowledge gap is the difference between knowledge requirements and existing knowledge. Such assumption is reflected in the structure of the research questions.

2.2 Organizational IT Adoption

Next, this study examined organizational IT adoption studies. This dissertation looks at knowledge challenges and learning in smart grid adoption, so examining the adoption process itself is important. Particularly, I am interested in finding how IT adoption is defined and conceptualized? What are the common knowledge requirements and gaps in IT innovation adoption? What are the learning perspectives in the innovation adoption literature?

2.2.1 The Conceptualization of IT Adoption

Studies in organizational IT adoption can be traced back to the early 1990s when the potential of IT to improve operational efficiency and business performance began to be widely acknowledged. IT has been loosely defined to include any digital information and communication technologies and their applications "whose underlying technological base is comprised of computer or communication hardware and software" (Cooper & Zmud, 1990; Swanson, 1994). Thus, a variety of technologies have been examined from an organization adoption perspective; from early simple technical innovations such as microcomputer (Bretschneider & Wittme, 1993) and electronic data interchange (Chwelos, Benbasat, & Dexter, 2001) to more complex IT systems like ERP that are used today (Liang, Saraf, & Hu, 2007; Markus & Tanis, 2000). Consistent with the change in technology, the conceptualization of adoption has undergone a tremendous shift. In early studies, IT adoption has been viewed as the decision to physically purchase the innovation, and the measures include using the timing of adoption (Rogers, 1995), the number and frequency of adoption (Bretschneider & Wittme, 1993; Zmud, 1982), or binary variable like "adopt or not" or "intent to adopt or not" (Chau & Tam, 1997; Pennings & Harianto, 1992). Yet, there was criticism that adoption in these studies was conceptualized as a one-time event and many of these measures captured only the purchasing moments but failed to take into account the post-decision behavior (Fichman, 2001). Such assumptions may work well in early studies when early IT innovations are rather simple and do not involve much organizational change, but they certainly do not fit into those complex IT innovations that require organizational adjustments.

Some scholars recognized that while the decision to access and purchase the innovation is important, the post-decision process regarding how to implement and use the technical innovation are also critical (Chatterjee, 2002; Fichman, 2000). More and more scholars agreed that organizational IT adoption is a long-term process in which new technical systems must not only be acquired, but must also need to be seamlessly fit into the organizational structure and efficiently used by organizational members.

As pointed out in Fichman and Kemerer's (1999) study, there is often an "assimilation gap" in IT adoption where technical innovations can be widely acquired but sparsely deployed and used. The adoption of ERP provides empirical support here. With the potential of greatly improving operational efficiency and organizational performance, ERP is one of the most popular IT solutions since the 1990s and was widely embraced by most large and medium organizations worldwide. However, despite its high adoption rate, there are many reports of ERP failure to achieve expected benefits or has led companies to financial difficulties and had to be abandoned in the post-adoption stage (Liang, Saraf, & Hu, 2007). Evidenced by these real cases, after a new IT innovation is adopted, especially organizational-level complex IT systems, misalignment often occurs between the new technology and entrenched business routines and organizations may experience a long cycle of adjustment before the innovation is widely accepted by organizational members and becomes a routine feature of the organization (Armstrong & Sambamurthy, 1999; Fichman & Kemerer, 1997; Fichman, 2000).

Therefore, scholars called for more attention on the post-decision phase. There are several efforts to capture this phase. Different scholars use different terms such as 'post-implementation' (Santhanam et al, 2007), assimilation' (Armtrong, 1999; Chatterjee, Grewal, & Sambamurthy, 2002) and 'routinization' (Damanpour & Schneider, 2006; Zhu, Kraemer, & Xu, 2006) to represent such phase in which the new IT systems are fully embraced by organizational members and integrated with old business processes and the firms are able to use the capabilities of IT innovations to support business strategy and enhance business performance. Several scholars also considered the actual implementation or deployment belongs to the post-decision phase, especially when it comes to complex IT systems that can take months to implement (Markus & Tanis, 2000; Parr & Shanks, 2000). Despite the variations in terms, these are valuable empirical support of the importance of the post-decision phase in organizational IT adoption.

Despite the variations in the conceptualization of post-decision phase, an important message from the organizational IT adoption literature is that complete adoption is not a one-time event but a long-term cycle. Building on this assumption, this study also views smart grid adoption as a process. Its dimensions include the decision to make the new technology acquisition, but also involves the post-decision phase in which the new innovations are implemented, used and internalized.

2.2.2 Knowledge Requirements and Gaps in Organizational IT Adoption

The organizational IT adoption literature has studied a variety of IT innovations, such as EDI (Electronic Data Interchange), ERP, e-business, web technologies, EPI (Electronic Procurement Innovation), and open source software (Armstrong & Sambamurthy, 1999; Esteves et al, 2003; Rai, Brown & Tang, 2009; Santhanam, Seligman & Kang, 2007; Usman & Ahmad, 2012). A review of the literature indicates that different technologies and study contexts can entail different knowledge requirements and gaps, and this section summarizes common knowledge that are critical across IT adoption. Despite the variance in technologies, both technical and business knowledge are found critical in surviving the general IT adoption. It should be noted that the content and boundaries of these two areas of knowledge could vary depending on the types of IT innovations.

Technical knowledge requirements and gaps

Technical knowledge encompasses the knowledge regarding the value of the various technology features, the potential and limitations of an organization's existing IT infrastructure, and the understanding of architecture of different elements to set up, manage and monitor the hardware and software systems (Armstrong & Sambamurthy, 1999; Esteves et al, 2003). The installation of some IT innovations such as social media and open source software is quite easy involving just click and download, and doesn't require much technical know-how. However, when it comes to more complex IT innovations that involve more elements, the installation is more time-consuming and knowledge-intensive. For instance, technologies like ERP start with a standard-based package and must be modified to adapt to the business process and user environment, and organizations need to have sufficient technical knowledge to adjust the system during the installation (Hong & Kim, 2002). After the hardware and software is installed, organizations also need to possess relevant technical know-how such as database management, network management, client-server architectures, and cyber security to assure the smooth functioning and management of systems (Benbasat, Dexter, & Mantha, 1980; Fichman & Kemerer, 1997; Fichman & Kemerer, 1999; Zhu, Kraemer & Xu, 2006).

Implementation related technical knowledge gaps are discussed in a few studies that examine complex IT innovations, such as the adoption of ERP. In one study, Robey, Ross & Boudreau (2002) observed that system configuration is a critical challenge in enterprise systems adoption, as the functional capabilities are embedded and configured within the enterprise system package and they need to be configured and modified to align with the organizational needs. Other studies found that companies often face knowledge deficiency in system integration when adopting ERP. They had great difficulty unifying the systems and data between their legacy systems and an

ERP package of various operating systems, database management systems software and telecommunications systems (Markus & Tan, 2000; Seddon et al, 2010).

Business knowledge requirements and gaps

Business knowledge relates to the business understanding of new IT innovation. In one study, Santhanam, Seligman & Kang (2007) used the term "managerial IT knowledge" to refer to the key business assumptions required to be made for deploying the technology, and the impact of the IT applications on the current organizational structure and systems. It also includes operational knowledge such as implementation methodology to support the integration of new IT innovation and legacy organizational systems. Especially when it comes to complex, large-scale IT innovations, new technology adoption can cause radical organizational changes where existing business processes need to be to adapted or new business practices need to be added to allow new systems to operate effectively and efficiently (Robey, Ross, & Boudreau, 2002).

The gap in new business process assimilation has been frequently mentioned as a key challenge in IT adoption, as organizations often lack the knowledge to make a seamless integration between the new processes entailed by new IT innovation and the entrenched organizational routines and practices (Edmondson et al, 2001; Fichman & Kemerer, 1997; Markus, 2004; Robey, Ross, & Boudreau, 2002; Robey, Anderson, & Raymond, 2013).

2.2.3 Learning in Organizational IT Adoption

In order to overcome the knowledge gaps imposed by IT adoption, organizations need to learn to acquire knowledge. Yet, there hasn't been much attention on learning in IT adoption, particularly on the post-decision learning when new IT innovations are acquired and introduced into the adopting organization. Only a few studies have adopted a learning-related perspective in IT adoption. Some scholars used the variance model to investigate the influence of organizational learning on the extent of adoption of IT innovation (Roberts et al., 2012). In these studies, learning is commonly measured by proxy construct absorptive capacity, which is defined in terms of knowledge and knowledge diversity (Roberts et al., 2012). They found that companies with greater scale of learning activities, more extensive existing knowledge related to the focal innovation, and a greater extent of the diversity of knowledge are more likely to overcome knowledge gaps and assimilate and sustain new IT adoption (Fichman & Kemerer, 1997; Reardon & Davidson, 2007). However, such variance models lack details on the actual learning practices underneath these learning variables as well as how the learning take place to overcome the knowledge barriers, which are the focal points in this study.

Recognizing the limitations of using variance models, a couple of other studies adopted a rather qualitative approach. In one study, Woiceshyn (2000) viewed technology adoption by oil firms in terms of learning process that includes observation, interpretation, integration, and acting. In another study, Robey et al (2002) examined learning practices that have been used to overcome the knowledge barriers in ERP adoption. Later on, Santhanam and his colleagues (2007) focused on the knowledge transfer between organizational users and IT professionals to identify the knowledge paths in organizational learning. While these studies give more details on the processes and dynamics underlying learning, their focuses are different. Furthermore, the limited number of studies here also decreases the generalization of their findings to related phenomena.

In sum, little attention has been paid to learning in IT adoption literature, and existing findings appear fragmented and inconclusive. Hence, the contribution from this set of literature to understand the learning in post-decision adoption of IT innovations is limited.

2.3 Organizational Learning

Given the limitations in the IT adoption literature in providing insights on learning in new technology adoption as well as the fact that the concept of learning is originated from organizational learning literature, this study further explored organization learning literature to seek additional guidance on how knowledge challenges could be overcome through learning. As one of the research interests in this study is to uncover how learning is accomplished to address knowledge gaps and how utilities differ in learning choices, the review of the organizational learning literature would emphasize the key practices that form the foundation of learning. Particularly, I am interested in understanding how learning is conceptualized? What are the key learning practices? What are frameworks grouping learning strategies/orientations through the configuration lens of learning practices? What factors could explain the choice among these learning strategies? What factors could facilitate or impede organizational learning?

2.3.1 The Concept of Learning

Organizational learning is a vast topic with several definitions. Despite the lack of consensus, many scholars view organizational learning as a change in the organizational knowledge (Argote, Miron & Spektor, 2011) and consider it to be a generic cycle through which knowledge flows; it involves many sub-processes and underlying activities.

Huber (1991) viewed organizational learning as consisting of four processes, including knowledge acquisition, information distribution, information interpretation, and accessing information from organizational memory. Building on Huber's work, many scholars proposed similar frameworks with slight adjustments in terms. Kim (1998) draws on its first three sub-processes and defined organizational learning whereby it entails knowledge creation, knowledge distribution, and knowledge interpretation and integration. Carroll (1998) added the cognitive perspective into the learning process and conceptualized organizational learning as comprised of four sub-processes: observing (noticing, attending, heeding, tracking), reflecting (analyzing, interpreting, diagnosing), creating (imagining, designing, planning, deciding), and acting (implementing, doing, testing). Later, Kane and Alvi (2007) and Argote, Miron and Spektor (2011) argued that organizational learning is a dynamic process of knowledge creation, transfer, and retention.

Despite the differences between these frameworks, organizational learning is generally viewed as consisting of knowledge acquisition, knowledge share and transfer, and knowledge storage. The knowledge must be acquired, either internally or externally, then shared and interpreted within the organization and at last stored as part of the organizational memory. It should be noted that in many case, knowledge acquisition and knowledge share & transfer are highly interdependent and intertwined, reflecting the recursive, interactive, and dynamic nature of the learning (Crossan & Berdrow, 2003).

2.3.2 Practices underlying Organizational Learning Process

As discussed earlier, this study places a great emphasis on underlying practices. However, it should be noted that this dissertation only focuses on practices underlying the knowledge acquisition and knowledge sharing and transfer processes, as they are directly related to my third research question that how utilities overcome knowledge gaps by acquiring new knowledge. Hence, practices underlying knowledge storage won’t be discussed, as they are beyond the scope of this dissertation. Figure 1 below summarizes main activities and practices that have been discussed in the organizational learning literature, followed by detailed discussions on each of them.

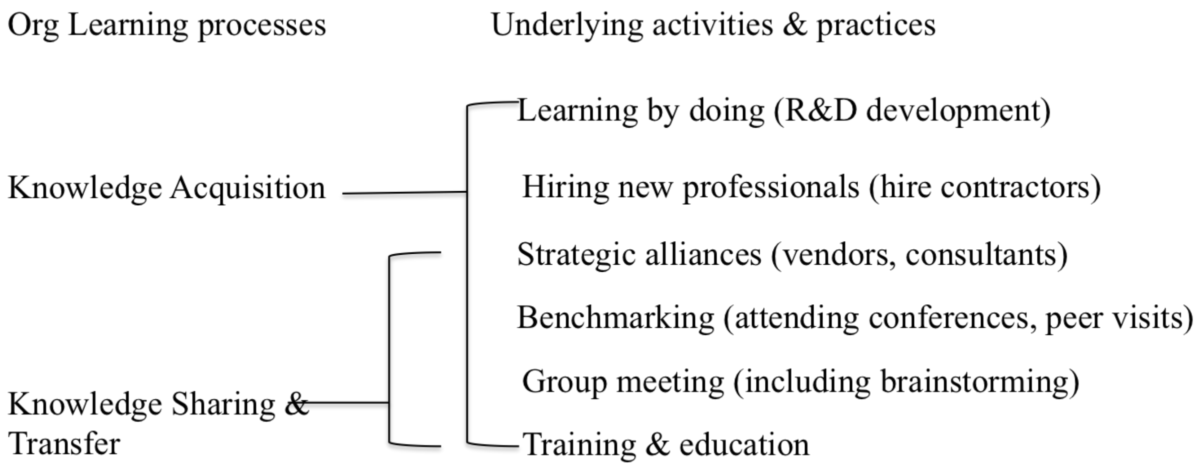

Figure 1 Common Learning Practices

Practices underlying knowledge acquisition

Learning processes take place through various activities, thus it is important to examine the learning activities underlying the learning processes (see Figure 1). Knowledge acquisition, by which companies learn and acquire new knowledge, has been a fundamental part of the literature on organizational learning. Huber (1991) argued that knowledge can be acquired in five ways: 1) congenial learning in which organizations inherit knowledge from history 2) learning from direct experience, whether intentional or unintentional, such as learning by doing where organizational members accumulate specialized skills and expertise by trial-and-error experimentation; 3) vicarious learning by which organizations acquire second-hand experience from interaction with consultants, technology vendors and suppliers, professional meetings and industry conferences, networks of professionals, etc. 4) grafting where learning is realized by transferring knowledge from new members outside the organization that possess needed knowledge to those within the organization; and 5) search by which organizations can acquire new information through scanning, focused search, and performance monitoring.

Later studies empirically confirmed many of the aforementioned concepts. For instance, the establishment of research and development units or departments and strong internal R&D capabilities is one example of learning by doing (Cardinal & Hatfield, 2000). It played a critical role in advancing scientific and technological innovations, especially in science or IT-based industries. Large firms in these industries usually invest in internal R&D, owning independent research centers where a group of research professionals located together share and legitimize knowledge (Levitt & March, 1988). The knowledge developed internally is usually domain-specific and path-dependent, as the accumulation of expertise and experience creates deeper domain knowledge and favors new knowledge close to the prior organizational knowledge (Cohen & Levinthal, 1990). Numerous studies have confirmed the positive relationship between internal R&D activities and organizational innovation performance (e.g. Cohen & Levinthal, 1990; Clercq & Dimov, 2008), emphasizing the importance of internal research capabilities.

Forming a strategic alliance to collaborate with other parties is an example of learning from indirect experience. Strategic alliances have been argued to be an important method for supporting inter-firm knowledge acquisition. It is a cooperative relationship between two or more parties to achieve a mutually beneficial objective while remaining independent entities (Baden-Fuller & Grant, 2004). It embraces a diversity of forms such as joint ventures, licensing agreements, research and development partnerships, R&D outsourcing agreements, customer and supplier partnerships, and technical collaborations and exchanges (Grimpe & Kaiser, 2010; Inkpen, 1998; Mowery, Olxey & Silverman, 1996). Through formal interaction, these inter-firm relationships create an opportunity for alliance organizations to gain access to partners' skills and capabilities and internalize new knowledge (Baden-Fuller & Grant, 2004; Inkpen, 1998). Especially in turbulent environments where firms lack the necessary knowledge to remain competitive, they often choose to look outside for knowledge that is complementary or co-specialized (Lavie, 2006).

If the strategic alliance represents a formal form of vicarious learning, benchmarking activities like attending industry conferences and workshops where senior executives from various companies meet together for technical discussions and exchange (Moran & Weimer, 2004), engaging in casual, personal meetings (Wenger, McDermott, & Snyder, 2002) are a complement to the formal modes of learning. Learning under these informal situations can be unintentional as acquiring knowledge becomes natural when members inside or across organizations are well connected. These boundary-spanning individuals are flexible in their interactions with each other and bring new knowledge from outside, which can be events, practices, or even industry trends.

Hiring external professionals has empirically been found to provide a way for firms to access and acquire knowledge developed at other firms without officially collaborating with them. In one study, Song et al. (2003) carefully examined learning-by-hiring as an approach to facilitate knowledge transfer across firms. They found that learning-by-hiring is likely to happen when the hiring is less path-dependent and the skills and expertise from the hired person are far from the knowledge base of the hiring firm. Their findings suggest that, compared to formal mechanisms such as joint ventures and R&D contracting, hiring is more flexible. However, it usually meets specific task needs. When the knowledge demand is extensive, hiring is often not the primary choice to fulfill the knowledge requirement (Argote & Ingram, 2000).

Additionally, empirical studies have justified the effectiveness of search in acquiring new knowledge. Organizational search can take the form of wide-ranging scanning to look for knowledge in distant areas or local search to acquire related knowledge (Huber, 1991; Jansen, Bosch, & Volberda, 2006; Katila &Ahuja, 2002). The activities also range from informal practices like reading industry journals and white papers (Friesl, 2012), and attending conferences and workshops (Moran & Weimer, 2004), to more formal practices like periodically environment scanning (Friesl, 2012).

Practices underlying knowledge sharing and transfer

Knowledge sharing and transfer is a process by which knowledge can be distributed within or across organizational boundaries (Huber, 1991) though the latter is more prevalent (Argote, Miron & Spektor, 2011). This process is always accompanied by knowledge interpretation because knowledge must be interpreted to be shard (Woiceshyn, 2000). Much knowledge transfer occurs during activities associated with external knowledge acquisition such as collaborating with vendors and consultants or attending conferences and peer visiting, because both processes involve communication, interaction, and collaboration among organizational members (Kane & Alvi, 2007). In many cases, knowledge transfer is not regulated by formal rules but is a result of people voluntarily interacting with each other because they share a concern or are passionate about a topic (Wenger et al, 2002). People from different organizations can be driven by a shared interest to engage in a process of collective learning and to share individual experience and create knew knowledge.

Knowledge sharing usually occurs between organizational units (Argote, Miron & Spektor, 2011). Formal practices include routine group discussions and brainstorming where existing information is pooled and new ideas are generated through the interaction (Berends et al, 2006). These interactions provide a good opportunity for organizational members to map knowledge and solve problems. Employee training and education is another good example of knowledge sharing that aims to distribute knowledge at the organizational level. It usually occurs when there is a sudden demand for knowledge, for instance, after the adoption of new routines/practices or technologies. The role of employee training and education in the IT-related contexts is well documented; many studies confirmed its effectiveness in facilitating new IT implementation (Markus & Tanis, 2000; Robey et al, 2002; Ross & Vitale, 2000; Somers & Nelson, 2004). Empirical studies have observed that lacking employee training would result in negative outcomes such as project delays or adoption failures (Boudreau & Robey, 2005; Lapointe & Rivard, 2005).

2.3.3 Frameworks of Learning Strategies

There have been a few frameworks that comparing learning strategies. This section below provides a detailed discussion on them.

Internal and external learning

This categorization argues that knowledge acquisition comes in two broad areas: internal and external learning (Bierly & Chakrabarti, 1996; Choi, Poon, & Davis, 2008; Kessler, Bierly, & Gopalakrishnan, 2000; Zack, 1998). Internal learning "occurs when organization members generate and distribute new knowledge within the boundary of the firm" whereas external learning "occurs when boundary spanners bring knowledge from outside sources via acquisition or imitation" (Bierly & Chakrabarti, 1996, p. 124).

Firms with internal learning orientation allocate and direct resources to develop needed knowledge and skills in-house to solve technology problems. A sample practice of internal learning is learning by doing, where organizational members accumulate specialized skills and expertise by trial-and-error experimentation (Levitt & March, 1988). During the process, organizations gradually adopt routines, practices, or strategies that lead to successful outcomes and document them in files, operating procedures, culture, or less visual organizational structures and relationships. Other practices include communication between organizational members such as group meetings, collective discussion, debriefing sessions, or a performance evaluation process through which implicit and tacit knowledge is crystalized, articulated, coded, and transferred into explicit knowledge (Zollo & Winter, 2002). In these practices, knowledge is obtained through experience with tasks and tools and other organizational members (Argote & Kane, 2003; Nonaka, 1994).

On the other hand, knowledge acquisition might also occur through external learning where new knowledge is scanned, absorbed, and internalized. The knowledge-based view suggests that knowledge is an important source of competitive advantage (Grant, 1996; Kogut & Zander, 1992) and few companies can independently posses and maintain a wide range of skills and expertise in an ever-changing environment (Almeida et al, 2011). Thus, acquiring knowledge from outside becomes an indispensible part of learning for firms to survive in the market. Some sample practices include consulting and advice from experts (Inkpen, 1998; Yli-Renkoi, Autio & Sapienza, 2001) and hiring outside experts (Song et al, 2003).

Other categorizations

Another categorization is the exploitation vs. explorative learning classification that contrasts adaptive and risk-averse learning leveraging existing technologies and knowledge to the more risk-seeking, entrepreneurial learning of new opportunities and knowledge (March, 1991). Exploitation learning relies on practices such as selection, refinement, reuse, execution and implementation whereas exploration involves search, discovery, experimentation and development. Although March (1991) called for a delicate balance between the two for firm survival and prosperity, he found that firms generally trade one for another and in many cases firms are trapped in the learning myopia to optimize exploitative learning over explorative learning to avoid costs, uncertainties and risks. To some extent, the exploitation vs. explorative distinction contains the internal vs. external dimension comparing the source of knowledge, but it is a bigger concept that takes into account other dimensions as well, such as role of targets (adaptive and risk-averse vs. unpredictability and innovation), innovation radicalness (radical vs. incremental), aspiration levels in regulating resources to search (close search vs. distant search) and outcomes of new knowledge (path-dependent vs. diversity) (Kane & Alavi, 2007).

Other efforts including differentiating fast and slow learning, in which the former radically expand or modify the firm's existing knowledge and the latter gradually make the change (Bierly & Chakrabarti, 1996). Compared to other distinctions, the internal vs. external learning categorization can shed the most light on this study. This categorization reflects the learning choices behind knowledge acquisition, which is considered as a key sub-process in organizational learning in this study. It also best serves the research purpose of this study and provides insights on a main research question: how do utilities learn to overcome the knowledge gaps in smart grid adoption. However, whether this categorization can capture the full variances of learning practices in this study will be revealed in the results of this research. Hence, this study will focus on practices themselves to explore any patterns in terms of learning strategies in smart grid adoption—including those that go beyond the internal/external distinction.

2.3.4 Factors Explaining the Variance in Organizational Learning

To better enlighten the second part of the third research question, which is how utilities vary in their learning choices, this section first reviews factors that influence the choice among learning strategies. Because internal vs. external categorization is the most commonly mentioned framework, this section focuses on the factors influencing the preference between these two learning orientations. Then it also summarizes key factors that facilitate or impede the organizational learning to shed additional light on the variance in learning.

Factors influencing the choice between internal vs. external learning

Although internal and external learning are mutually interdependent and complementary, firms in many situations end up with trading off between internal and external learning, especially when they are subject to a few knowledge and organizational related factors (Bierly & Chakrabarti, 1996; Kessler et al, 2000). The first factor concerns the characteristic of knowledge itself. When it comes to specific types of knowledge, organizations tend to make a stronger emphasis in one direction or the other. Cohen and Levinthal (1990) and Bierly and Chakrabarti (1996) stressed that firm specific, core knowledge are more likely to be internally developed as opposed to external hiring or contracting.

Second, organizational age can have an impact on strategy choice. Gopalakrishnan and Bierly's (2006) study found that older firms tend to favor more on internal R&D. In comparison, younger firms tend to rely on external linkages with scientific communities to build their technological strength. They didn't find any significant support for the influence of size on learning choices between internal vs. external; however, they did found that it's more beneficial for larger firms to focus on their internal investment as it advances their absorptive capacity, which in turn helps them absorb external knowledge. Their findings regarding the influence of age is indirectly confirmed in another study. Oliver (2001) found that firms depend on learning from others during their early stage of corporate development, but focus on internal R&D once they mature.

Finally, prior experience is a key predictor. Argote and Miron-Spektor (2011) argued that a deeper and more diversified experience often equip firms with a much stronger in-house knowledge base and capabilities, which often favors internal learning. With the rich knowledge and expertise available within the organization, firms accumulate strong internal technical competencies and tend to rely on themselves to fulfill the learning needs. In contrast, firms usually rely on external learning, at least in the short run, if they are weak in the existing knowledge.

Factors facilitating or impeding the organizational learning

The review of the organizational learning literature indicates three arrays of factors that could influence learning (Rashman et al, 2009). The first set of factors is related to the context in which firms operate, including societal, institutional and policy contexts. It is found that environmental uncertainty or change in the industry conditions would trigger the motivation and efforts to learn. For instance, Inkpen and Dinur (1998) observed that firms with fierce industry competition are more active in learning, having more frequent knowledge transfer through joint ventures.

The second set of factors concerns the characteristics within the organization, encompassing organizational culture, resources, learning motivation and power. An organizational culture that favors innovation and risk-taking supports organizational learning (Storck & Hill, 2000). Such cultures usually have well-developed mechanisms and channels to promote internal and external knowledge transfer, and encourage questioning the entrenched assumptions (Weick 1996). In contrast, a risk averse and rigid culture could constrain learning. Brodtrick (1998) argued that the regulatory nature of many public sector firms means that they share such cultures and are less active in learning. The resources also matters, because they can influence the extent of efforts to learn. The human and financial resources allocated to any learning activity or practice could promote or impede the learning (Crossan et al, 1999; Woiceshyn, 2000). Similarly, motivation is also critical, because it affects the intensity and efficaciousness of learning efforts (Szulanski, 1996). Firms that are good at emphasizing rewards or removing failure risks often enjoy a virtuous cycle of learning (Woiceshyn, 2000). Additionally, power is also found to have an impact on the promotion or suppression of learning. Organizational members with power can positively or adversely influence learning by manipulating the learning motivations and resource allocation (Geiger *et al*., 2005).

The third set of factors relates to the relationship characteristics. Firms that have strong and diverse ties with other organizations have more advantage in learning, because they have greater access to knowledge and are better equipped to share knowledge (Reagans & McEvily, 2003). The form of relationship is also critical. Informal social networks facilitate learning through greater knowledge transfer than formalized and routine channels (Reagans & McEvily, 2003).

2.4 Discussion

As the review illustrates, all three sets of literature have each provided valuable insights into this study, yet such implications cannot fully address the three research questions proposed in this dissertation-- the complexity of smart grid as well as the unique nature of the utility industry may reveal interesting findings that are not captured in the literature. This section will summarize the contributions and the gaps in previous findings.

First, the key concept of organizational knowledge in this dissertation is rooted in and emerges from the knowledge literature, in which a few key perspectives on knowledge emerge and form a much broader view of knowledge. The concept of knowledge itself is critical, because it is a key term in all three research questions. However, this set of literature doesn't provide direct implications regarding knowledge requirements and gaps, as well as learning.

Second, the IT adoption literature has great implications on the first research question. It indicates that organizational IT adoption is not a one-time event but a long-term cycle in which new technologies need to be introduced, internalized and assimilated. The findings also suggest that both technical and business knowledge are critical in surviving the general IT adoption, which is an important message to this research. However, the complexity of smart grid might entail greater knowledge requirements. On one hand, smart grid can be conceptualized as complex IT systems, which are often characterized by a large number and variety of system components, interaction and interdependency among these components, organizational-wide efforts, and a high potential for difficulty of users understanding the IT system (Sousa & Goodhue, 2003). Thus, findings regarding the general knowledge requirements from prior studies might still apply in this research. On the other hand, smart grid is even more challenging compared to many well-studied complex organizational technologies. While technology like ERP also encompass a variety of IT hardware, software, and network configurations to integrate different enterprise systems and business processes, it does not interact directly with operations technology (OT). Yet smart grid requires a high degree of coordination between physical devices and processes, and IT hardware and software systems. Thus, it is expected that there would be more critical knowledge areas in smart grid adoption. Additionally, smart grid adoption entails close interaction between utilities and customers. Hence, knowledge areas like customer education might also be critical in this study.

In comparison, the IT adoption literature has limited implications to the second and third research questions. The findings regarding the knowledge gaps are inconsistent, because they can vary depending on the type of IT innovations and the study context. For instance, system integration may not be perceived as challenging to companies in other IT-intensive industries with IT adoption, but can be a huge concern to utilities. Also, relatively little is known about what factors can help explain such variance. Thus, it is important to explore the knowledge gaps in smart grid adoption and how utilities vary in the gaps. What's more, little attention has been paid to learning in IT adoption literature, and existing findings based on a few studies appear fragmented and inconclusive

Third, the organizational learning literature provides a solid foundation to the third research question; yet, the utility industry as well as the new technology adoption context might entail findings that can't be captured in previous studies. The process-based view of learning and a thorough list of learning practices help to form the analytic basis of learning in this study. However, this study is situated in a context that is different in important ways from the ones in which existing research on organizational learning has been situated. In prior research, firms are market-oriented and profit-maximizing firms and learning is studied in the contexts of fulfilling strategic goals such as increased innovation and enhanced organizational performance. In comparison, utilities are regulated monopolies, which are characterized by a lack of innovation and technology that is slow to change. More importantly, the purpose of learning is different. Rather than chasing the long-term strategic goal of internally developing new technologies and products, learning in this study is considered to meet the urgent needs of new technology adoption. Hence, whether there are additional learning practices in this context is unknown. Additionally, whether the widely adopted internal vs. external categorization can capture the full variance in learning is not clear yet-- different industry characteristics and learning purpose in this study could lead to different selection over learning practices that feature different categorization. Therefore, this study needs to figure out the configuration of these practices by utilities facing smart grid adoption and showing similarities and variances in their learning choices.

Moreover, although the literature indicates a list of factors that could help explain the variance in learning responses, this study will identify which ones apply in this context and if new factors are identified. For instance, would organizational related factors such as culture, level of resources, influence from powerful organizational members and the extent of diversity and depth in networking ties matter in this study? Particularly, there is no empirical support on the impact of regulatory environment on organizational learning but the literature did indicate that its indirect influence through an entrenched risk-averse culture could impede learning. Given the fact that utilities operate in a highly regulated industry, it would be interesting to validate such claims and explore whether regulatory environment can have a direct influence on utility learning.

3 Research Methodology

This chapter includes a detailed description of the research methodology undertaken in this study. It begins with an overview of the methodological approach adopted and an outline of the research design, followed by a detailed description of sampling, data collection, and data analysis procedures in both pilot study and main study. The chapter ends with a discussion of tactics to assure the validity of this study.

3.1 Qualitative approach

Due to the number of deficiencies in the existing literature that are discussed in the reflection section in chapter two, a qualitative approach is adopted to understand the adoption of a new, complex set of information technologies in a rarely discussed context. Compared to quantitative methods that are primarily used to test pre-specified concepts and hypothesis, the qualitative approach is useful in uncovering context-specific factors and especially appropriate to address the “what” and “how” questions behind the phenomenon of interest (Creswell 1998; Yin 1994). In this study, the main research objective is to investigate the knowledge requirements and knowledge gaps imposed by smart grid adoption as well as utilities’ learning responses in overcoming the knowledge barriers. It also intends to discover if and to what extent utilities vary in the level of knowledge gaps and learning responses. Those questions require a deep investigation of the phenomenon of interest; a qualitative, exploratory design is well suited to serve the aim of this research. The process-based view of organizational learning also supports the qualitative design—a field study with rich understanding of the phenomenon is necessary to understanding the learning activities in the smart grid adoption as well as the variances in the learning process.

3.2 The Pilot Study

This research is a two-stage field study: a pilot study and a main study. The pilot study was part of a larger project[1] on smart grid adoption by electric utility companies. Between May 2012 and September 2014, a team of smart grid researchers conducted a series of semi-structured interviews with utility companies to gather detailed information from the electric utility sector. The main purpose of the interview was to identify motivation for and obstacles to smart grid adoption, and the interview questions were not specially designed for this study. During the iteration between data collection and data analysis, it was noticed that some utilities have mentioned the challenge of knowledge gaps in smart grid. It was also found that they differed in how they overcome the knowledge gaps, ranging from varying internal strategies by learning-by-doing to a more mixed strategy involving both internal learning and hiring consultants. Intrigued by the perception of knowledge gap as well as the diversity in utilities' actions to overcome the gaps, I believed this is an area worthy further investigation. So I took the opportunity in the last four interviews to include more open-ended questions uncovering major knowledge challenges in smart grid adoption and how utilities obtained the knowledge to overcome the gaps.

Forty interviews from 31 utilities across 26 U.S. states were conducted, including investor-owned, cooperative, and municipal forms, covering a variety of policy and regulatory contexts. Among the 40 interviews, eight contained three or four questions related to knowledge challenges and learning, with sample questions: "what are your main knowledge challenges in smart grid adoption?" and "With this knowledge demand, do you have to hire new people to meet the needs or do you have the skills in house or can you train people in house to do that?" I

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[1] This material is based upon work supported by the National Science Foundation under Grant No SES-1231192.

also tried to find industry papers and utility reports related to these eight utilities to supplement the information from interviews.

The analysis centered on the eight interviews that have interview questions related to this study, as well as complementary secondary information. Consistent with the qualitative study tradition (Creswell, 2003; Glaser & Strauss, 1967), I took an inductive approach that involved both open coding and axial coding to analyze the data. The other thirty-two interviews helped to enhance the general understanding of smart grid, but no systematic analysis has been performed.

The pilot study helped me notice the knowledge challenges in smart grid adoption. On one hand, the data from the pilot study suggested several knowledge requirements that were critical to smart grid adoption but were often associated with knowledge gaps by utilities, such as smart grid integration, data analytics and customer outreach. On the other hand, the information from secondary data suggested that areas like technology evaluation and new business assimilation are also challenging in smart grid. So these initial data were combined to generate a more comprehensive list of knowledge areas that are important in smart grid adoption. To this end, pilot study generated initial data, and the analysis of this data as well as key findings from literature review enabled the construction of the interview protocol for the main study.

3.3 The Main Study

3.3.1 Sampling

In the main study, a combination of sampling strategies was employed: purposive sampling and stratified sampling. Purposive sampling involves a careful selection of a small number of cases to meet the researcher's interest. Different from random sampling, purposive sampling focuses on and accesses a particular subset of the population that is aligned with the research purpose.

For this research, the sample was limited to U.S.-based electric utilities that have adopted smart grid technologies.

In addition, stratified sampling strategy was employed to allow for comparison. It is often used for comparison and to capture the major variations in the phenomenon (Patton, 2002). In this research context, part of this research objective was to examine how utilities vary in the knowledge gaps as well as their learning responses in overcoming these gaps, so stratified sampling was used to allow for and include the variations to explore factor(s) that might affect the variance. The stratification is operated based on ownership form, size, and extent of adoption.

The rationale of choosing an ownership form is based on the findings from a recent qualitative study (Dedrick et al, 2015) that ownership form is an important factor in influencing smart grid adoption decisions, in which IOUs can be delayed in smart grid adoption due to a lengthy regulatory approval process or stakeholder pressure to show adequate return on investment, whereas municipals and cooperatives do not face such pressures. It is also interesting to determine whether the difference in ownership form will help to explain the variance in knowledge gaps or learning responses after the adoption decision is made.

Size is a factor often associated with IT adoption in a number of prior studies (Damanpour & Schneider, 2006; Fichman, 2000; Lee & Xia, 2006). It has been measured in different ways, yet the most popular measure is number of employees (Zhu & Kraemer, 2005). This measure was therefore also used as a dimension of stratification in this study.

With regard to status of adoption, the IT adoption studies suggested that adoption is a long-term process and it is often used as an outcome in the literature measured by different categorization of stages. Despite the variations in the conceptualization of stages, they all point out that firms can be in different phases of adoption: some are in the earlier phase of adoption such as adoption and implementation and some are in a more advanced phase of adoption like assimilation and integration. It was employed as the third dimension in this study because it is expected that it also would contribute to create diversity in the sample. In this research, I looked for industry papers, news and utility smart grid reports to determine the extent of adoption. Descriptions like "pilot" always indicated an early phase of adoption, while "in deployment" and "finished a full deployment" suggested an intermediate and more advanced stage of adoption.

As a result, utilities in the sample varied in ownership type, size, and the extent of smart grid adoption, which table 4 and table 5 shows. Table 4 demonstrates the distribution of the sample and table 5 gives a detailed profile of each utility. It can be seen that, IOUs in general are larger utilities and half of them are in the advanced stage of smart grid adoption. In comparison, a few city municipals and all cooperatives are small size utilities with a few hundred or even less then 100 employees, and more than half of them haven't finished the deployment yet. However, it should be noted that are size difference among IOUs: about half of the IOUs are smaller in size in its own category, however, they are still considered large compared to some municipals and all cooperatives.

Utility Types	**Size**	**Adoption status**		
		Pilot	Between	Advanced
IOU	1000-5000 employees	1	2	2
	>5000 employees	1		2
Municipal	<1000 employees		2	1
	1000 -5000 employees		1	2
Cooperative	<200 employees	1	3	2

Table 3 Distributions of Utilities

Utility	**Size (no. of employees)**	**Adoption status**		
		AMI	**Distribution grids**	**Customer technologies**

IOU1	Around 6000	Finished a comprehensive pilot and began a full deployment		
IOU2	Around 2300	Full deployment	Near finished	Web portal to all customers; piloting time-of-use and in-home display
IOU3	Around 3000	Finished the pilot and still in preparation of full deployment		
IOU4	Around 2000	In deployment	In deployment	Piloting web portals, time-of-use and in-home display
IOU5	Around 2000	Full deployment	In deployment	Web portal to all customers; piloting time-of-use and in-home display
IOU6	Around 8500	Full deployment	Full deployment	Web portal to all customers; scaling up various customer programs
IOU7	Around 20000	Full deployment	Full deployment	Web portal to all customers; scaling up various customer programs
IOU8	Around 3000	Full deployment	Full deployment	Web portal to all customers; piloting time-of-use and in-home display
Municipal1	Around 1000	In deployment	In deployment	Piloting web portals
Municipal2	Around 5000	Near finished	In deployment	Web portal to all customers; scaling up time-of-use and in-home display
Municipal3	Less than 100	Full deployment	Full deployment	Web portal to all customers
Municipal4	Around 1000	Full deployment	Full deployment	Web portal to all customers; piloting time-of-use and in-home display
Municipal5	Less than 50	In deployment	In deployment	Piloting web portals
Municipal6	Around 2000	Full deployment	Full deployment	Web portal to all customers; piloting time-of-use and in-home display
Coop1	Around 150	Full deployment	In deployment	Web portal to all customers
Coop2	Less than 50	Full deployment	Near finished	Web portal to all customers; Piloting various customer programs
Coop3	Less than 50	Full deployment	In deployment	Web portal to all customers
Coop4	Less than 100	Full deployment	In deployment	Web portal to all customers; Piloting time-of-use and in-

				home display
Coop5	Less than 50	Still piloting		
Coop6	Less than 50	Full deployment	Near finished	Web portal to all customers

Table 4 Profile of Utilities

3.3.2 Participant Recruitment

There is not a strict rule of thumb when it comes to the sample size in qualitative research. There are different guidelines with regard to what constitutes a sufficient sample size, however, the number ranges from 20 to 50 (Creswell, 1998; Morse, 1994). More generally, an adequate sample is considered to be achieved when saturation occurs, i.e., when no new insights are being revealed. The actual sample size depends on certain qualitative methodological approaches and research aims (Mason, 2010). Yet, for interview studies, some scholars indicate that 20 is the bottom line and 25 is sufficient for smaller projects (Charmaz, 2006; Green & Thorogood, 2009). Hence, this study is designed to get a target number of 25 participants. However, after 20 interviews with 20 participants, saturation was achieved and the sampling discontinued. Therefore, this study finally recruited 20 participants.

I selected participants based on the criteria that they should be both knowledgeable about and play a key role in smart grid adoption. Many of them are mid-level managers with titles like “Smart Grid Director” who are identified as having a leadership role for smart grid adoption, general manager, or director in operations. They may be engineers where the department is directly involved and impacted by smart grid. They usually have a sense of a global view of the organization as compared to low-level employees and engineers but are also more involved in the day-to-day workings of the company; they understand detailed issues as opposed to senior executives. It is noted that in a number of small size utilities, there are participants from senior executives with titles like “Chief Operation Officer.” Due to the small size of their companies, some senior managers also serve as the director of smart gird deployment. Despite the variations in the title, it was established by the researcher that participants are well informed about the research questions in this study. Table 6 summarizes the individual participant profiles.

	IOUs	**Municipals**	**Cooperatives**
Number of participants	8	6	6
Smart grid director/manager	8	4	2
CIO/COO	0	2	4
Female/male	1/7	1/5	1/5
Number of interviews	8	6	6
In person/telephone	2/6	0/6	1/5

Table 5 participant profiles

3.3.3 Data Collection

The main study was conducted from March 2015 to March 2016. During this stage, 20 utilities across 17 states were interviewed, including eight IOUs, six municipals, and six cooperatives.

The data is mainly obtained from two sources: 1) semi-structured interviews with selected utilities; and 2) secondary data from industry reports, academic papers, and news articles. The multiple sources of data enable the researcher to build a comprehensive description of case phenomenon, and more importantly, increase the reliability of research findings (Creswell, 1998).

Interview:

Interviewing is one of the common techniques in qualitative research, as it is often used to collect detailed insights from the research phenomenon by exploring opinions, experiences, and motivations of individual participants (Berg & Lune, 2012). Compared to structured interviewing in which there is little room for variation and unstructured interviewing in which there isn’t any set format and can be time-consuming to take, semi-structured interviewing take the advantage of combining both structure and flexibility: it defines a scope for participants to answer the questions, yet still provides them the flexibility to elicit more information (Creswell, 1998; Weiss, 1995). Hence, semi-structured interviewing is often used when researchers want to develop a keen understanding of the phenomenon, yet within certain structure. It is well-suited for this study, because I want to gain more information on smart grid adoption but with a key focus on knowledge gaps and learning strategies, and finish the interview in a time-efficient way. Therefore, semi-structured interviewing is chosen in this study.

In this study, most interviews were conducted by phone, with two carried out face-to-face in an industry meeting. Compared to traditional face-to-face interview, phone-interview is becoming more popular among qualitative scholars given its lower cost (Chapple, 1999), wider access to geographically distant participants (Sturges & Hanrahan, 2004; Sweet, 2002), and greater access to sensitive content or sites (Novick, 2008). Given the fact that participants are geographically dispersed in 15 states as well as the time and financial constrains on this dissertation project, phone-interview is a preferred technique in this study. The absence of visual cues has been the biggest concern when using phone-interview method (Garbett & McCormack, 2001); yet, many scholars figured out that interviewers could still use voice cues to follow the dynamic (Novick, 2008). Other reported disadvantages such as reduced in-depth discussion (Creswell, 1998) and potential of distraction in interviewee's' environment (McCoyd & Kerson, 2006) is not unique to phone-interviews, as they were also reported in face-to-face interviews (Novick, 2008). Hence, it is believed that using phone interviews would not reduce the quality and quantity of the information that is conveyed from participants.

The final interview protocol (See Appendix 1) includes three major sections: 1) utility's current status in smart grid adoption, 2) questions regarding knowledge requirements, gaps, and learning practices in smart grid adoption in five areas, and 3) the last section asks whether participants encounter other knowledge challenges that are not mentioned in the interview. The five knowledge areas are proposed based on the pilot findings as well as industry papers, and were further revised and finalized during the interview. For each knowledge area, the participant was asked if they thought this type of knowledge was important to them, whether they had the gap in this type of knowledge, and, if so, how they would overcome the gap.

Participants of interest were first contacted via email requesting their participation. The email contained the project description (Appendix 2) and a consent form (Appendix 3). Once the participant signed the consent form, he or she was contacted to confirm the interview date and time, and asked for their consent to record and transcribe the interview. If the request was rejected, notes were taken instead. A week prior to the interview, participants were sent a copy of the interview questions by email, to ensure that participants had sufficient time and information to prepare for the interview. The interviews lasted, on average between 35-40 minutes. At the start of each interview, the participant was given a brief introduction to the study to help establish rapport with the participant. It should be noted that the interview protocols served as a framework to guide the interview, however, the conversation did not strictly follow the questions. If participants mentioned points that were of particular interest or were relevant to this study but were not covered in the protocol, the researcher followed the topic to uncover additional information. At the end of each interview, the participant was thanked and promised a copy of the research findings for examination and correction.

This study was conducted in compliance with Syracuse University, Institutional Research Board guidelines (IRB). The qualitative study design utilized in this study is responsive to the protection of human subject rules that requires the agreement of informant consent for participants to participate, and there is minimal risk to humans as a result of participating in this study. Anonymity of the participants is assured by not using the participant's name or the organization's identity, or any information that could identify the subjects. All data and analysis documentation is also secured and will only be accessed by the researcher.

Documents:

Although interviews serve as a powerful method for capturing rich, detailed information about the phenomenon and context, it is important to include other sources of data to ensure the creditability and validity of the findings. The documents, including 5 utility self-reports of smart grid deployment, 3 case studies of customer outreach, and 10 white papers and industry reports regarding general smart grid challenges and best practices, were used and analyzed in this study to complement the interview data and to provide more grounded interpretation and elaboration of the phenomenon. The documents gathered for this research include industry reports, academic papers, and news articles on knowledge challenges with and learning responses to smart grid adoption. Information from these sources helped to confirm or elaborate on information gathered from the interviews.

Saturation was used as a criterion to decide when the data collection stopped. Saturation occurs when adding new data does not lead to new information regarding the research questions (Glaser & Strauss, 1967). In the middle stage of data collection, the concepts regarding the knowledge requirements and knowledge gaps become similar. No participants added additional knowledge areas they felt were important or that they deemed challenging in smart grid adoption; factors that explain the variance in knowledge began to fall into the same set and new factors stopped emerging. However, it took much longer to observe the data saturation in learning responses because there were revisions to the questions in the learning section. Originally, the questions in the main study were used to elicit learning related information: “Do you have to hire new people to meet the needs or do you have the skills in house and the ability to train people in house to do that?” Later, it became evident that such questions provided little room for exploration in the variety in learning, so the questions were changed to: “How do you address this gap?” and “What activities do you take?” With revised question, richer opinions and insights on learning were more abundant. After 16 interviews, the fixed number of activities as well as the variance in the configuration and performing of these activities became apparent. Four additional interviews were conducted to ensure that themes were repeating and no fresh insights would be brought by the new data. As a result, the sampling discontinued after 20 interviews in the main study were conducted.

3.3.4 Data Analysis

The data collection and analysis process is iterative and reflective, in which codes are developed, revisited and refined several times during and after the fieldwork until the patterns are clear enough to induce findings. However, for the sake of articulating the steps in data analysis in this study, it will be described separately here. It took place in two steps: individual utility case analysis and cross-utility analysis. I perform both steps.

Individual utility case analysis

For each utility, I created an excel file to help present the codes. The secondary data from utility annual reports, case studies and industry white papers are reviewed, and notes are taken on smart grid knowledge challenges and practices to overcome the challenges relating to each utility in the interview sample. These notes, together with the interview transcripts, are coded to facilitate the organization and interpretation of the data.

Consistent with the qualitative study tradition (Creswell & Miller, 2000; Glaser & Strauss, 1967), an inductive approach was taken to guide the coding, which involved open coding and axial coding. Open coding is the first part of the analysis where all the information including interviews transcripts and notes from secondary documents are labeled and segmented into descriptive concepts or categories, or conceptual codes. In this study, the open coding is done line by line from the interview transcripts and notes from secondary data. The coding is based on the organizational IT adoption and organizational learning literature, as well as on the codes that emerge from the data in this study. Findings from these two sets of literature helped me identify some codes in knowledge challenges (e.g. position change) and the learning practices (e.g. hiring and training); however, I remain flexible by expanding new codes (e.g. interoperability issue and lack of advanced modeling) encountered in interview and secondary data. When new codes are found, I go back to previous excel files and recode the data to examine whether this code is also present. There are situations when some texts can be coded in multiple ways, for instance, a quote regarding the interoperability challenge can be coded as “gap in interoperability” and “lack of standards”, and I would keep all the conceptual codes in this stage.

The process of open coding generated a preliminary list of codes focusing on specific knowledge gaps utilities are encountering, the perceived level of challenge with these the gap, the fundamental learning practices utilities are using, and the motivations behind some practices. A sample of these codes is illustrated in Table 7.

Conceptual codes	**Interview transcripts**

Interoperability issue	“What we really found in implementation with use case is it's still all of the technology implementation was very different, and the displays were not compatible with each other. So you'd have one meter brand that was compatible with one display, but that display might not do the things you wanted it to do…”
Lack of advanced modeling	“…And we’re really good at situational using the data, but what I can say is that we all probably need to do better in is taking that next step of more automated analytics as far as the data and the sets that are being collected.”
Position change	“When technology changes, people's positions are just going to change. Those that we do have now that work on our AMI system, there's stuff that is completely different now, because they need to be aware of things like radio signals, they need to be aware of communication, they need to be aware of things to look for when they're out in the field with regard to why meters might not be working, and being able to troubleshoot a lot of that information.”
Training	“Formalized training was still deemed very important to allow our users to prepare for formalized testing efforts and ultimately successful operation of the system. Sessions were conducted in-person and numerous training manuals were available to aid the process. In addition, given the previously established successes with WebEx…”
Hiring consultants	“Here we utilized a lot of contractors as we had three software integration projects, and that was almost all exclusive contractors that we had. They worked with us for a lot of the project as we were doing deployment to help work through issues, problems, things that just weren't there, and that's something we've always done when we've done newer technology projects.”
Organizational culture	“So we tend to be a little bit later to the party, and seeing what types of programs are providing good returns for other companies, but at the same time, we don't want to be lagging too far behind the industry. It’s tough to fight with because everybody's doing that right now, and we'd rather let the people that have five million customers and $200 million to spend on it make their mistakes and learn from them, and make good investments.”

Table 6 Samples of Conceptual Coding

Axial coding explores the relationships between conceptual codes developed in open coding. During this process, similar codes are grouped together to form a bigger theme. For instance, some specific issues referring to the same knowledge area were grouped together. Similarly, the dynamic between knowledge gaps and learning practice is also found, as certain practices are preferred in overcoming certain knowledge gaps. In this stage, repetition of codes was also addressed. When there is a substantial overlap between two conceptual codes, I would merge them or use one code that is much stronger. A sample of axial coding is listed in Table 8.

Theme	Conceptual code
Big data	Lack of advanced modeling
Smart grid deployment	Interoperability issue
	Order of integration
	IT & OT convergence
	Position change
Learning practices	Training
	Hiring consultants

Table 7 Samples of Axial Coding

In each excel file, I created a table (see Appendix 4) to help visualize and summarize the data. The first column listed the major knowledge areas that are critical in smart grid adoption and each row refers to each knowledge area. The other columns, separately, indicated the actual knowledge gaps, perceived level of challenges in each knowledge gaps, learning practices, format and scale of learning practices, and motivations behind learning choices. In each cell, it has either statement or quote from interview or secondary documents.

Cross-utility analysis

In the cross-utility analysis, I first aggregate information on knowledge areas and knowledge gaps from individual utility case. It turns out that four types of knowledge are critical in smart grid adoption: smart grid technology and vendor selection, smart grid deployment and integration, big data, and customer management. Each knowledge area has several reported knowledge gaps-any knowledge gap that is even mentioned by only one utility is also included.

Then, a big table (see Appendix 5) was created to help identify the similarities and variance among utilities in terms of knowledge gaps and learning choices. The rows of this table list all reported knowledge gaps that are grouped under four knowledge areas. The columns of the table correspond to 20 utilities. Each utility contains four columns that indicated how they perceive the level of challenge with regard to each knowledge gap, their choice of learning strategy, the format and scale of the practice, and the motivation behind such choice. With this table, I can more easily compare and determine which types of knowledge gaps are more/less challenging to which group of utilities and what are the common features behind these group of utilities. This table also aids my analysis on the configuration of learning practices, similarities and variance on the format or extent of efforts as well as the motivations behind them.

3.4 Data validity and generalizability

Although the term validity has traditionally been associated with quantitative research, increasingly it is being considered an important criterion in judging the rigor and credibility of qualitative design (Creswell & Miller, 2000). In general research, validity indicates the extent to which research representation of a phenomenon matched the phenomenon itself. In qualitative design, validity pertains to the accuracy and creditability of the findings (Creswell, 1998). The trustworthiness of qualitative research generally is often questioned, because the nature of qualitative data collection and analysis usually entails an extensive amount of subjective interpretation. Hence, it is important to validate the findings in a qualitative study.

To assure validity, several tactics based on Creswell's (2003) recommendations were undertaken. First, I used both interviews and documents to triangulate different data sources to build more grounded and coherent accounts for the research questions. Several methods of triangulation were found: 1) Documents are used as evidence to corroborate or verify findings from interviews.

For example, training and hiring consultants were frequently mentioned in the interviews and are also confirmed in the reports or case studies of companies that had been interviewed. In another case, there are conflicting statements regarding a utility's learning strategies and they were asked about in the interview with the utility's smart grid director. 2) Documents are used to supplement the interview data. One utility in the interview talked about a rather high level of practice in technology selection and evaluation such as using their own testing lab, and there are case studies of the same company providing details on how they operate the evaluation in the lab; for instance, how they score on vendors and what procedures they follow. 3) Documents provide the context for the research participants. The majority of IOUs in the study have public reports on their smart grid deployment with details on the company background information as well as their current deployment status, projects, and plans. Some even update their reports annually. Such information enabled the researcher to develop a deeper understanding of each utility and prioritize certain questions accordingly.

Second, member checking is used in which the draft of the research findings is sent to all the participants for further review or correction. Participants were made clear on the nature of the study so that their comments would be based on a clear understanding of the study. Third, data analysis was conducted with several iterations and reflections to provide a rich, thick description of the phenomenon. Fourth, I have five years of research experience in smart grid adoption by utilities, which helped me develop an in-depth understanding of the utility industry including its history, industry structure, and regulatory environment, as well as integrating the contextual meaning to the interpretation of themes regarding knowledge requirements, knowledge gaps, and learning practices. Finally, feedback from the study advisor, colleagues, and other researchers increased the validity of this research.

Generalizability is another criteria commonly used in research, but its expectations are different as opposed to the one in quantitative research. Different from quantitative work where generalizability is tested through statistical significance, generalizability in qualitative work is "to make logical generalizations to a theoretical understanding of a similar class of phenomena rather than probabilistic generalizations to a population (Popay et al, 1998, pp. 348-349)." While generalizability is traditionally ignored or even rejected by qualitative scholars, as the nature of qualitative design makes examining this criteria challenging (Creswell, 2003), there is a growing interest in using generalizability in qualitative research and many believed that the importance of the qualitative approach would be diminished if the findings were not considered to be generalizable (Horseburgh, 2003). This study maximized the generalizability of the findings by following a well-designed sampling strategy, a structured presentation of data collection and analysis, and a coherent synthesis and reflection on the findings and associated implications. Hence, this study will shed light on other regulated industries or economies learning new technologies or/and companies adopting complex IT technologies.

4 Findings

In this chapter, I present the findings of this study. These findings are discussed in four parts that correspond to the four major knowledge areas critical for smart grid adoption that emerged from the analysis, including smart grid technology and vendor selection, smart grid deployment and integration, big data, and customer management. In each area, I present the knowledge requirements and knowledge gaps, as well as the learning responses addressing these gaps. Finally, I provide the summary of findings that highlight the similarities and difference across utilities in perceiving and overcoming knowledge gaps in smart grid adoption.

4.1 Smart Grid Technology and Vendor Selection

The complexity of smart grid and the speed of new technologies is driving a shift in vendor supplies, from a traditional single vendor with proprietary products to multiple, competing vendors with standard-based products ranging from communication technologies to hardware devices to intelligent software solutions (Schubert, 2012). Hence, it is important for utilities to make well-informed technology selections to minimize the risks associated with new technology deployment.

4.1.1 Knowledge Requirements

This area includes the knowledge necessary to identify different technologies and solution options, and evaluate and select the most appropriate vendor solutions to meet the utility expectations.

4.1.2 Knowledge Gaps in Smart Grid Technology and Vendor Selection

While the utility industry has decades of experience in selecting and testing OT applications and systems (e.g. SCADA and meters/sensors), the heavy involvement of IT components as well as high interdependence among smart grid components poses new challenges to utilities in technology evaluation and selection. The data suggested that there is knowledge deficiency with regard to smart grid standards when selecting and evaluating potential vendor solutions. Smart grid value comes from an interoperable grid where various technologies and systems can be connected and function together to achieve operational efficiency and grid resiliency; hence interoperability is really critical (Department of Energy, 2014). Not surprisingly, standards are key to smart grid interoperability as they make uniform the data exchange format. Yet, many smart grid standards are not mature-- despite the efforts from federal and private industry consortia and special interest groups to refine the interoperability standards in smart grid, many existing standards are not widely agreed upon (National Institute of Standards and Technology, 2014). As mentioned by several participants, for many technologies such as smart meters, there is no unified standard and utilities are expected to choose common standards among diverse vendors, determine which products support them, and ensure standards are consistently interpreted across a global marketplace of energy technologies. Adding to the complexity, many standards are poorly defined, leading to different interpretations and specifications of the same standard. The manager from IOU4 explained:

“*What the issue was, was that when you actually tried to pair a meter with a ZigBee chip in it to a display, you got very different results with all the vendors, even though you had "interoperability" between the two. We had some tremendous challenges, we actually wound up scrapping the entire idea of the in-home display from our project*”

4.1.3 Variances in Knowledge Gaps

The level of knowledge gap is perceived differently by utilities. It is found that utilities with smaller size or relevant experience in smart grid standards development and refinement have much lower or no challenge with regard to smart grid standards. The data further suggests that support from National Rural Electric Cooperative Association (NRECA) and strong push from state regulator can explain such variance, which influence the level of knowledge gap either by lowering knowledge demand or enhancing existing knowledge.

Support from National Rural Electric Cooperative Association (NRECA)

Cooperatives and a few small city municipals (Municipal 3 and Municipal 5) argued that standards are not a challenge they face when selecting smart grid vendors. The main reason is that the national association, NRECA (National Rural Electric Cooperative Association), collaborated with several vendors to develop MultiSpeak standards to ease the interoperability problem among cooperatives. MultiSpeak is a data-exchange standard to ensure pieces of software or hardware "talk" seamlessly over the communication platform (2017, June 27th). MultiSpeak is focused on meeting the needs of cooperatives, but is also an ideal standard for utilities with small IT staffs and less demanding integration requirements. Compared to many products that claimed to build into each other, it offers true interoperability in "off-the-shelf" products available in today's market and has been proof-tested in many installations (Karaim, 2015). Apparently, these utilities face less demanding knowledge requirements and hence have a relatively easy time in selecting vendor solutions. As in the words of the participant from a coop4:

"We require our software partners to implement MultiSpeak. If something is not MultiSpeak compliant, we don't buy it. Because we don't have time to deal with all the integration issues if it's not MultiSpeak compliant already."

However, there are no specialized standards for bigger utilities, including IOUs and a few larger city municipalities. These utilities tried to minimize the interoperability issue by purchasing products that are built to work together or choosing vendors that are standard compliant, yet problems often occur due to the immaturity of standards as previously discussed. As commented on by several participants, buying a suite of products from the same vendor can still involve interoperability issues. Some big vendors have a line of products but they buy other companies to produce the products. These different products are branded under the same hood, but they are not compatible.

Relevant experience

Second, relevant experience plays an important role of lowering this knowledge gap by expanding and enhancing certain utilities' knowledge base, which is further led by regulatory push. A few utilities, including IOU6, IOU7, Municipal2, and Municipal4, have fewer struggles in smart grid standards when selecting among various vendors. They all operate in states leading and driving smart grid policies and development. They are strongly pushed by their state regulators to be actively involved in the establishment and refinement of smart grid standards, since NIST (National Institute of Standards and Technology), who is assigned the "primary responsibility to coordinate development of a framework that includes protocols and model standards for information management to achieve interoperability of Smart Grid devices and systems" under the Energy Independence and Security Act of 2007 (EISA) [EISA Title XIII, Section 1305], first coordinated the development effort in 2010. Two of the main purposes of collaborating with several public/private industry consortia and special interest groups (e.g. SGIP, EPRI, IEC, IEEE, UCAIug, and the GridWise Alliance) were to define interoperable requirements connecting the different software components and technologies comprising the smart grid as well as ensuring reliability, safety, security and privacy are adequately addressed (National Institute of Standards and Technology, 2014). Accordingly, they have better knowledge on smart grid standards itself as well as the status of vendors' products in complying with these standards, and are well informed to make good decisions in choosing standard-compatible products.

4.1.4 Learning Responses

Whatever the level of knowledge gap, the data suggested that utilities generally make learning efforts to acquire related knowledge in smart grid technology selection and evaluation. According to several participants, technology and vendor selection is a key step prior to smart grid implementation and use; hence utilities have to fill the knowledge gap as soon as possible through learning. Searching, learning by doing and hiring consulting services, are common practices adopted by utilities to overcome the knowledge gap listed above in technology and vendor selection.

Searching

Searching is an important learning practice because utilities need to gather information to develop the understanding of smart grid standards and potential vendor solutions. Meeting and interviewing vendors is a direct way to learn different standards and technology options, and utilities have utilized various ways to acquire the information, for instance, organizing consortiums to engage various vendors, technology specialists, and service providers to present products, or assembled a team to visit vendors' sites and complete trial installations to learn more about potential vendors. Other activities include attending seminars and conferences, knowledge sharing with other utilities, and reviewing industry journals and white papers on potential solutions, etc.

Learning by doing

Learning by doing is another critical learning practice, through which utilities acquire necessary knowledge through direct experience of comparing and evaluating smart grid standards and technologies in the lab. Such experiential learning helped utilities to develop knowledge on the extent of interoperability as well as technical capabilities and limitations of potential vendor solutions. The manager from IOU1 mentioned that they had a hard time selecting wireless communication solutions among Zigbee, Wimax and Mesh-network standards. After conducting internal technical assessments in their lab and outdoor field-testing, they determined that Wimax works best in their service territory.

Hiring a consulting service

Some utilities also retained a consulting firm to minimize issues with regard to smart grid standards. The consultants are generally involved in the full cycle of technology selection, including compiling potential vendors, developing an RFP (Request for Proposal), comparing the bids, and evaluating the performance of selected solutions prior to full deployment.

4.1.5 Similarities and Variances in Learning Responses

The configuration of these practices as well as the focus and format of some practices are jointly determined by level of knowledge gaps, knowledge relatedness, and size.

Level of knowledge gaps

Whatever the level of knowledge gaps, searching and learning by doing are the main learning practices adopted by all utilities. Not surprisingly, utilities with smaller or no challenge in smart grid standards, as in the case of all coops, IOU6, IOU7, Municipal2, and Municipal4, involve few or no consultants. For coops, the MultiSpeak standard is sufficient for their smart grid project and they don’t have to worry choosing other standards. The other four utilities have accumulated rich knowledge on standards from past relevant experience, which is sufficient to help overcome the gap in smart grid technology selection and evaluation and there is no need to hire consultants. The participants from these utilities mentioned that they see the ongoing value of developing a good understanding smart grid technology internally, as it would help them smooth the later implementation and use. As the manager from Municipal2 stated:

"There's a learning curve but at the end we've now got, you know, a good handful of people who have excellent knowledge of how to run the system, how to operate the system…we didn't want to try to utilize a contractor or consultant or anything like that, because we didn't want that knowledge to walk out the door. So, we chose to develop the expertise in-house."

Utilities with bigger challenges in smart grid standards are more inclined to recruit consulting services in addition to searching and learning by doing. For instance, several IOUs (IOU1, IOU3, IOU4, IOU5 and IOU8), and city municipals (Municial1 and Municipal6), face big gaps in technology selection and evaluation due to the fact of immature standards and their lack of experience in smart grid standards. Hence, in general, they have hired a few consultants to help smooth the selection process. The manager from IOU1 mentioned that the consultants helped them conduct technical analysis and score the potential vendors on several factors, including network performance, interoperability, technological maturity, technology risk, network performance, and security. According to the manager from IOU3:

"*We don't have any smart grid experts, and it turned out to be much harder than we thought it was going to be, and finding bids and getting that kind of stuff. So we use several consultants and local contractors to supplement their knowledge, and we use them as a resource to educate us, and we kind of carry out with it.*"

Knowledge relatedness

However, it should be noted that among those utilities that recruit consultants in addition to searching and learning by doing, internal employees always take the lead in learning, and consultants generally play a rather minor role. When I analyze the motivations behind such trends, the concept of knowledge relatedness emerges. According to many participants, although they have to learn smart grid standards, it’s not completely different from their existing knowledge realm because utilities have long-term history of technology selection and evaluation. Although the smart grid technology is more complex and demanding, the structured knowledge of selecting, comparing and evaluating still applies and helps to bridge their old experience and new smart grid standards. Many stated that through searching and learning by doing, their internal cross-functional teams are able to develop the RFP, perform technical assessments, and evaluate the bids, and the consultants provide suggestions to address specific issues. As reflected in the words of the manager from IOU8:

“*This is not a completely new area to us—we know the procedure and have the knowledge base to understand and communicate with the external guys. Yes, we bring consultants, but they are managed by our mangers and we still take the lead.*”

Size

It is determined that size can influence the focus and form in searching and learning by doing. Bigger utilities, including IOUs and some larger city municipals, have wider search and more extensive learning by doing whether they have big or small gap in smart grid technology selection and evaluation. They have allocated several engineers and technicians to gather information to learn new standards and potential vendor solutions. The search often involves a wide variety of information channels, including meeting with vendors, attending seminars, attending conferences, reviewing journals, and supporting research consortia.

The abundance of resources also affords them to create a platform to encourage experiential learning: they either built new smart grid labs or enlarged their original labs to conduct technical assessments to smooth the technology selection process. Confirmed by both participants and online news, the capacity of their internal testing environment allows the technical evaluation of a comprehensive range of smart grid technologies (Bradley & Hanley, 2013). The manager from IOU1 mentioned that they had opened a smart grid center prior to their pilot, where various vendor products could be tested. Assessment activities include testing potential vendors in the lab and field to confirm effective communication, standards compliance, and security. Solutions that have performed sufficiently were then selected and used in a pilot program. Another manager from IOU6 added:

"*Then we built Smart Grid test labs because we knew that there would be lots of new equipment and software that we wanted to fully test before we put it into production. The test environment is up and running right now so we are testing a lot of these technologies and solutions and interfaces in our labs."*

In comparison, utilities of small size, including two city municipals (Municipal3 and Municiapl5) and all cooperatives with employees less than 50, followed a narrower but deep search and smaller-scale learning by doing. Due to the constraints on budget and human resources, they often engaged in fewer channels in information gathering, mostly vendor shopping and attending conferences, but had a deep search in potential vendor solutions. A few of them assembled a team to visit vendors' sites and complete trial installations to learn more about potential vendors. One participant added that they even contacted other customers of their interested vendor for more reviews on the product and vendor commitment to the project:

"We've been very successful with that. We select vendors that had been doing this for quite some time. They had a history of integration, actually had standard integration for a number of times. We are very critical with questions…I'm asking the other customers 'did you have any challenges? What would they do differently? And then that just makes your project that much better?' "

Both interview and secondary data indicated that most of them also built dedicated smart grid labs to evaluate and compare smart grid technologies, but in many cases the evaluation is only restricted to smart meters and a few distribution devices. For the rest of smart grid technologies, they often asked vendors to conduct the evaluation and relied on the vendor claims. A common explanation is that they do not have the human resources or time to test a full range of technologies. Yet, several participants also mentioned that MultiSpeak is quite reliable and vendor products that have been interoperability tested in the factory could typically be directly used and integrated at a utility.

4.2 Smart Grid Deployment and Integration

In addition to technology selection, it is also important to ensure that new devices and systems are properly installed, interconnected, and function as expected. The concept of integration is particularly important, as smart grid value comes from an interoperable grid where IT and OT converge and various technologies and subsystems communicate. Yet, both interview and industry reports indicated that smart grid integration is not only restricted to the technical aspect in which systems talk to each other, but also the social aspect of integration in which people, ideas, resources, and business processes are also critical (ABB, 2015; Monnier, 2013). Interestingly, such observation is also aligned with the conceptualization of integration in the literature. In reviews by Waring and Wainwright (2000) and Wainwright and Waring (2004), integration is considered of comprising four dimensions: technical, system, organizational and strategic. While the first two dimensions represent integration between physical assets, systems and data, the latter two represent softer parts of integration involving coordination between functions, attitudes and principles. Cleary, smart grid integration necessitates a combination of these two aspects. As evidenced in the manager from IOU3:

"The real value comes when you integrate the tools into multiple other capabilities, and people from different groups. That (integration) is a challenging stage for all the utilities because all the facilities we installed, the IT systems in our history were chosen for their own merits and didn't necessarily link with other systems. Also importantly, we need to break silo boundaries among people."

4.2.1 Knowledge Requirements

This area includes technical knowledge necessary to install, link, and manage various physical devices, systems, and communication platforms of electrical grids, as well as the business and organizational knowledge to manage soft part of integration including coordinating people, resources, and activities across functions, and adjusting business procedures and processes to enable an efficient operation of the smart grid devices and systems.

4.2.2 Knowledge Gaps in Smart Grid Deployment and Integration

Several participants mentioned that, while much of the technical demands on the installation and maintenance of grid devices and systems required for smart grid adoption has not changed appreciably, the work is more complex and challenging compared to past technology upgrade projects due to the holistic and multi-layer integration in smart grid. As discussed in the section 4.1, while utilities have taken various efforts to ensure standard compliance when selecting vendor devices and systems, standards alone cannot guarantee interoperability. The analysis revealed several knowledge gaps that are associated with different dimension of integration.

For instance, there is knowledge deficiency with regard to the technical aspect of integration, in which integration is seen as “a goal to make complex software and hardware artifacts communicate utilizing appropriate protocols, conventions and technologies” (Wainwright & Waring, 2004, pp.331). According to a number of participants, they face the challenge in networking communication among physical infrastructure, as certain house conditions and service territory topologies such as rural areas featured with hills and mountains can make the communication really difficult. The manager from IOU1 mentioned they have issues with networking among smart meters. Because lots of homes in their pilot area are old and lots of them use wire mesh with plaster, in many cases homes didn’t pass the signal quality between meters and some in-home technologies. Another participant from Coop1 also stated the challenge they ran into when dealing with communicating over hilly areas, as the wireless gets strained with the climbing: *“Some utilities are blessed to have a nice flat, no trees, plains area, that’s easy to be communicated, that other utilities are sitting in the Rocky Mountains that can’t communicate from one ridge to the next because of the topography of the land. So we’re sort of in between them, we’ve got little small hills and it’s a challenge to communicate to all these devices that are out in the field.*”

Another commonly reported challenge is the lack of understanding of different systems’ specifications and assumptions. The manager from IOU2 shared their negative experience in integrating AMI with DMS (Distribution Management System). The DMS is designed to only accept 15-minute interval data but in reality, their AMI has data in different interval settings—some are 15-minute intervals and others are hourly intervals. It gave them quite a headache to accommodate the DMS system. The manger from Municipal6 added that his utility faced the problem of balancing different capacities when integrating the AMI with the outage system—the AMI system has more capability of collecting data but their old customer information system has the fewer capability of receiving and storing the data. The old CIS (customer information system) is built around old principles where only one or two manual reads are expected per month whereas the AMI is designed to collect 26 reads per day. Technically, two systems are integrated but they do not function effectively as expected:

"The data management and the customer information systems are behind, so it's slower for processing data than our capabilities are to collect the data. So we have a challenge in trying to coordinate our systems to where we get full capability throughput. We're still a little behind on the data management and integrations with the customer information system."

A few participants also mentioned the issue regarding the order of integration. Two participants reported the challenge is in AMI deployment. Ideally, the data receiving and management system should be installed first, the network receiving system should come the second, and the meter installation should come last. However, a few utilities reversed the order and suffered from negative consequences. As noted by the participant from IOU4, they installed the meters before they set up the MDMS to receive the data. As a result, they continued to read meters in the old manual way for several years because of the fact that they had invested millions of dollars in the system. They admitted this was a horrible mistake. In another case, IOU5 installed everything all at once. However, they soon recognized that they should have built the IT infrastructure first. In their words:

"So if I had to do it over, I would do it in a different way. We're trying to do everything all at once, but basically you've got to put your IT stuff in place, your systems to manage the data, you have to have your back haul system in place so you can get the data back. And you have all that done and working properly with the billing system and all that, before you put in the first meter."

In addition, there is knowledge deficiency with regard to the soft part of integration, which involves the adjustment of business processes and structure as well as coordination or even integration between people and resources. (Wainwright & Waring, 2004). A widely mentioned challenge from both interview and industry reports is that smart grid deployments involve changes to business processes, workflow, and logistics within and across the business units, which is typical of major new software and systems (Monnier, 2013). In smart grid, the infusion of IT components in traditional operation technologies has automated many processes. For instance, in the metering department, where much of the legacy business processes were designed around reading meters manually once or twice or month, they are now automated and many skill sets have become obsolete. As a result, meter readers are reskilled to become technicians who learn how to use computers and systems to adapt to the new environment. The learning curve is huge, as noted by several participants who claimed that many of their blue-collar workers have never used computers before. Employees in other departments are also affected. In customer departments, customer service personnel had to learn the new billing systems and handle the system bugs that can cause billing errors. As noted in the manager from IOU3:

"*Everything is touched by this technology. It has changed the business in a way that we performed. There is role changes, there is new positions being created. So for example, how we handle diversion and tamper is totally different from the way we did in the past. I mean, really,* *everything we do is been touched by [this new technology], even from the customer service and billing aspect. Process of change and adoption of that change is really critical*."

Another commonly reported challenge lies in IT and OT coordination. There have been long-term silos between IT and OT. Historically, IT is mainly associated with back office information systems to support internal functions such as accounting, billing, revenue collection and customer reporting whereas OT is typically associated with field-based devices or infrastructure that can monitor and manage the grids, such as SCADA, grid switches, and distribution management systems (ATOS, 2012). In the past, IT and OT are managed, maintained, and used by different silos in the organization, with few crossovers occurring. The silo model has served utilities in the past, but now the lines are blurring and smart grid forces closer coordination between IT and OT. As reflected in the annual report of IOU6 and IOU7, a central challenge has been the lack of understanding of other groups' roles, boundaries, and expectations). What used to be a pure OT problem now carries many IT considerations, and both groups are learning to figure out the nature of the problems including each group's work responsibility and the boundary and limitation of each group's knowledge and capability, etc.

4.2.3 Variances in Knowledge Gaps

The level of knowledge gap is perceived differently by utilities. Some utilities perceive a big challenge in certain knowledge gaps while others feel the gap is not disturbing and minor. It is determined that service territory characteristic, ownership forms and IT sophistication influence the level of technical aspect of knowledge gaps whereas size influences the level of social and organizational aspect of knowledge gaps in smart grid deployment and integration.

*Service territory characteristics*

A service territory with mountains and hills or one in a rural area poses greater requirements for communication among smart grid meters and field devices, because communication can easily gets blocked or strained as a result of climbing or traversing long distances. Three utilities with such rough topology including IOU1, Coop1, and Coop3 mentioned that installing the communication platform is particularly challenging. The managers from these utilities mentioned that they all choose PLC (Power Line Carrier) communication technology that is designed to transmit over long distance; but still face communication problems due to extreme topology situations. The participant from Coop3 stated that their meters are widely spread out across the service areas with extreme distance like being 30 miles apart, which pose a big challenge for physical layer communication. It is noted that the majority of utilities with flat service territories have much fewer struggles in communication because their typology entails a more easy communication deployment and lower knowledge requirements. They admitted that they face a learning curve, but that it is not overwhelming, as evidenced the in the words of a manager from Coop4:

"*We're fortunate that we are pretty flat. We use cellular for all of our communication with pole line equipment and it works very well. We don't have many problems in deploying communication platform, it's pretty straight forward.*"

Ownership form

It is found that municipals and coops generally have modest or smaller scale of investment and deployment in smart grid, and face lower requirements on technical integration due to limited number of systems needs to be integrated. Most of them are small-size utilities facing constrained budgets, personnel challenges and lack of return-on-investment guarantee (ABB, 2012). The last reason even affected some bigger municipals, such as Municipal 1 and Municipal

6, which also limited the scope of smart grid deployment to lower the complexity and risk in the technical aspect of smart grid integration. According to them, it would be more practical to keep the necessary investments, such as AMI and distribution automation, as they fear missteps in extensive adoption of smart grid will fail to receive the expected return on investment. Particularly, cooperatives have much fewer struggles on technical integration among systems because they generally purchased vendor products that are MultiSpeak based and the standard itself contained common data models that can ease data integration. Hence they consider smart grid integration to be rather easy. Some used the words "plug-and-play" to describe the ease of integration.

"*So the way we are quite smooth in integration is we limit our number of systems that are integrated, and use multi speak, and require our software partners to implement MultiSpeak as part of our integration. Those two points really helped us to get things done in a relatively quick timeframe without a bunch of custom furnishing.*"

For IOUs, they are in general larger utilities with less financial and human resource constrains, and most importantly the cost-plus regulation mode ensures guaranteed rate of return for approved investment (Energy Information Administration, 2000). Hence, in addition to common investment on AMI and distribution automation, many explored other smart grid technologies such as demand response, HAN (home area network), and renewable generation, and face higher requirements on technical integration.

IT sophistication

Utilities with a good IT platform do not perceive the technical aspect of integration as overwhelming. A few participants mentioned that they have an advanced IT infrastructure that can well support the technical integration, in which an enterprise service bus is often built to facilitate the exchange of information across various applications. It serves as an integration platform to easily connect various applications and software systems without the weaknesses of point-to-point integration. It communicates between traditional OT applications (e.g. SCADA, DMS, OMS), and enterprise applications (e.g. MDMS, ERP), and greatly reduces the variability, customization, and fragility in the traditional point-to-point integration. It is observed in a few utilities that have rich prior technology experiment experience including IOU6, IOU7, Municipal2, and Municipal4. They have extensive experience in exploring communication technologies prior to smart grid, and through the process they realized the importance of building an advanced IT platform. Hence, even with extensive deployment, as in the case of IOU6 and IOU7, such enterprise bus greatly reduces the issues of lack of system assumptions and made the integration easy:

"*What we've done in the very beginning of our project, we put in an enterprise service bus, so basically everything can talk to everything else as long as it's connected with us. We don't do point to point anymore, because the more systems you put on in point to point, it just gets way too complicated and they break too easy, so we don't do that anymore. We have an enterprise service list, so it's like plug and play.*"

Size

It is noted that small utilities in general have lower challenges compared to bigger utilities when it comes to softer part of integration including assimilating new business and enabling cross-function coordination. Such patterns have been observed in all cooperatives and a few small city municipals (Municipal 3 and Municipal 5) with less than 50 employees. They usually have a tighter organizational structure with fewer departments--for instance, the engineering department is often merged with the operations group and also sometimes contains the metering staff. As a result, people usually serve multiple roles—it is common for a technician in the metering department to also monitor operation systems. The business change associated with smart grid is much smaller than the one in big utilities—many of their employees already serve multiple roles and smart grid changes the focus a little bit. In their perspective, the smart grid transition is straightforward—it is more like system upgrades and a few position changes associated with it. The IT and OT collaboration is also easier due to their flexibility. As discussed earlier, in quite a few cases, the IT department already serves some OT functions. The small size makes meeting and information sharing fairly easy. As noted by several participants from small utilities, collaboration is part of their daily job and they share information and discussion issues all the time, which would be impossible in big utilities.

For bigger utilities, the level of change is massive. Compared to smaller utilities, more departments and employees are directly impacted by smart grid, thus they face more business process changes, more position changes, and more acceptance from internal employees. To them, the challenge is not reskilling a few meter readers, but raising the level of expertise for the whole department. As noted in several participants, it is common for a group of meter readers to have served utilities for decades and to have never touched a computer before, and thus getting buy-in from these long-time employees who may not have been exposed to IT before takes time. The collaboration between IT and OT also entails much bigger organizational change due to the bureaucracy and silos.

4.2.4 Learning Responses

Despite the level of knowledge gap, the data suggested that utilities generally actively make learning efforts to acquire related knowledge in smart grid technology deployment and integration. According to several participants, integration is key to ensure smart grid success and is highly intertwined with technology deployment; hence utilities have to fill the above knowledge gaps as soon as possible to finish project on time. Learning from vendors, consulting, training, learning by doing and learning by investing are the main practices adopted by utilities to overcome both technical gaps and business gaps in smart grid deployment and integration.

Learning from vendors

Compared to consultants, vendors serve as the primary knowledge source because they are directly involved in the system implementation/device installation and configuration, applications integration and necessary software modifications, and provide training sessions to employees. In many cases, utilities approach the vendors and work with their product experts and technical staffs to fix problems associated with system specifications and data integrations. In one case, the utility failed to communicate two grid systems due to different standards interpretation. They approached one of the vendors to reset the parameter and change the attribute from optional to mandatory to make the integration work.

Consulting

Consultants facilitate utilities' learning by giving expert guidance and supplementing necessary knowledge in overcoming knowledge gaps in smart grid integration. In many cases, they are a complement to the vendor's knowledge. Several utilities hired a third party integrator in the beginning of the project to help perform utility business assessment to identify and prioritize current status and changes required to achieve strategic initiatives, and help develop a technology strategy and roadmap to support on-going investments.

Training

Training has been adopted by all utilities to smooth the struggles in role changes and IT and OT collaboration, and is mostly provided by vendors. With training, employees in the organization can understand the capabilities of new technologies and how they can help and affect their daily work. They can also help them prepare for successful operation of the system. Training usually takes the form of formalized in-person or on-line sessions in which trainers from vendors or internal employees introduce contents like project status, challenges faced, specific technical topics, interoperability issues or lessons learned. Such formal sessions are accompanied by numerous training manuals with more detailed explanations.

Learning by doing

Learning by doing is also widely adopted to understand new processes and address coordination issues across business units. Employees can learn knowledge regarding the potential and limitation of new technologies or system as well as the new procedures through direct experience. For instance, in customer department, customer service personnel had to learn new MDMS and billing systems, and new processes around customer communication and engagement. Additionally, smart grid project management requires collaboration among various departments, such as weekly or biweekly meetings between managers and department heads and between IT and OT teams, and there is a natural knowledge exchange of roles and responsibilities in project meetings. Several participants mentioned they documented the role assignment and working order whenever they have issues in the project meeting, and it helped to set up reference models for future cross-functional collaboration.

Internal knowledge sharing

In addition to learning by doing, several utilities also make dedicated efforts to build a structure that foster knowledge sharing and understanding between IT and OT departments to improve the efficiency of learning by doing. The manager from IOU7 mentioned that they developed an annual strategic planning process that aligns the IT and business—each year, they make sure different technologies are being deployed, or are being proposed, and their business is well coordinated with the road map of the IT infrastructure.

4.2.5 Similarities and Variances in Learning Responses

It is interesting to find that level of knowledge gap, knowledge relatedness, and size play important roles in explaining the variance in the configuration of these practices, as well as the focus and format of some practices.

Level of knowledge gap

Learning from vendors, training, learning by doing and internal knowledge sharing are four main practices adopted by all utilities when overcoming the above knowledge gaps. For utilities that consider both technical and softer aspect of integration as rather easy, which includes coops and a few small-size city municipals (Municipal 3 and Municipal 5), they generally believed the combination of these practices are sufficient to deal with the issues in the integration process.

Utilities with bigger knowledge gaps in smart grid integration have deeper engagement with vendors and are more inclined to hire a third party integrator to smooth both technical and softer side of integration. Several participants mentioned that a solid knowledge transfer from vendors is very helpful in addressing technical related issues, and they have taken efforts to maximize the vendor's help--they have clear and frequent communications between vendors regarding technology and device references and new working procedure, such as device installation codes, as full disclosure of issues between the vendors provided increased confidence and more efficient issue resolution. Some utilities also hire a third-party integrator because they provide support in key issues like data integration, and also help the change management team to measure current performance, brainstorm potential improvements, and facilitate changes in business changes. The manager from IOU3 that considered smart grid integration to be quite challenging added:

"*What we wound up doing was working with a third party integrator that specialize in data integration. We wanted to do it internally, but we realized we really didn't have the skills, and quite honestly, I struggled getting internal support to dedicate people to do it and/or learn it. One of the things that I would recommend to utilities that are looking to implement a large smart grid technology or any large IT-related deployment is to work with an integrator. The key is to go get the right help, although the help is expensive.*"

Knowledge relatedness

However, it should be noted for all utilities, internal learning such as training, learning by doing and internal knowledge sharing still dominate the practices and vendor support and consultants generally play a supportive role. According to several participants, the knowledge required for technical and softer aspect of integration is not completely new to them—they utility industry generally has integration experience with AMI precursor technology (AMR infrastructure) despites the relative small-scale and past technology upgrade often involves changes in business procedures. Such overlap in the knowledge equips them to leverage internal resources to learn to solve the issues.

Size

Size plays an important role in influencing the focus and format of training, as well as the existence or absence of and mechanisms of knowledge sharing. Training in bigger utilities is more formal and extensive. While the main department that was going to utilize the system usually received the training, several departments that were expected to interface with that department, understand the system, and utilize a portion of it are also trained. Due to the large number of employees that are involved, the training often blended in-class tutoring and off-site online material or classes, and lasts for a solid period of time.

Due to the bigger size, these utilities also believed project-required meetings are not enough to support IT and OT integration, given their entrenched silo culture. Many of them emphasized the importance of dedicated efforts to improve learning by doing. There are two cases where utilities made big structural changes to improve the coordination. In one case, IOU6 merged part of their OT groups with the IT department to a new department named Technology Organization. This new department is responsible for a variety of traditional IT and OT duties including all network communication operation and monitoring, as well as all of the data analytics. In another case, Municipal2 located IT and OT teams near each other in control centers—they created a networks operation center, which is physically located near the operational control center that runs the grid. This makes it easier to integrate both teams in key decisions, as well as brainstorming and building trust.

Others efforts focus more on the lower-level knowledge sharing. Many adopted cross training to develop more common ground in IT and OT collaboration-- the OT people learned more about the basics and specifics of their technology and IT personnel developed the understanding of the logics of OT groups. In another case, a utility used both a Kaizen team and a RACI chart to help with the collaboration between the teams. Kaizen is a Japanese management practice made famous by Toyota for continuous improvement. It is usually support by a RACI chart, a tool that helps firms to identify roles and responsibilities during organizational changes. As noted in their interview:

"*One is probably the most interesting and the most effective is we use what are called Kaizen teams. So when we have a specific issue that has both OT and IT components to it, we gather all those people and we put them in a room for either one day, two days, focus on that specific problem and that's the only thing we focus on in terms of that concentrated, 24 hour effort. And then that resulted in some real good solutions and also what we called a RACI chart.*"

For small utilities, training is rather informal. Fewer resources typically result in less funding and limited options for training. In addition, smaller utilities have fewer people carrying the load, which makes it difficult for employees to balance time working with time training. Hence, small utilities are less focused on the formality of training but emphasized the approach that fits their budget. Instead of a traditional model where utilities invite representatives from vendors to introduce the training, a few take a different approach. They send a small group to the vendors to receive the training, and the group goes back to the company to educate more employees. According to these utilities, it is much cheaper and the knowledge sharing is also easier, due to fewer silos in a small company. As noted in the words of the manager from Coop3:

"*So our approach to utilizing the system is we will get one or two or three experts if you will in house that work with the vendor, ensure they have full understanding of what we're trying, trying to use whatever application, software, hardware, whatever. Then we do all of our training from individuals that belong to us, our own employees. Our own employees become the trainers of the rest of the users, and that way we've got internal points of contact if you will.*"

Most small-size utilities also believed that they did not need formal knowledge sharing efforts in addition to project-required coordination to promote IT and OT integration, because it is natural and expected that different departments have good relationships and collaboration regardless of smart grid. For instance, it is common that the outage monitoring through the IT department is done in small utilities whereas in bigger utilities this is usually the responsibility of the OT department. According to an operation manger from Coop2, his office is next to the manager of the engineering department. When issues come up, the managers from each department can meet in person very quickly.

4.3 Big Data

With the IT advancement in many OT applications and the interconnection between various systems and technologies, smart grid generates an overwhelming volume of data. Utilities used to read meters 12 times a year; now they receive 15-minute interval data from smart meters, not to mention the data from other parts of the smart grid. As evidenced by one participant, there is a 73000 percent increase in their data points; making sense of this huge amount of data is challenging. Yet, the effective use and governance of smart grid data enables a more rapid and efficient response in several areas, including operational efficiency and grid reliability, asset management, customer management, energy planning, and load management. All participants have emphasized the potential of data in achieving smart grid success, as echoed by the participant from IOU6:

"*Data becomes a gold mine of information and you got to find those little nuggets by going through with some new skills and by combining data from different sources together and have a clear understanding of what is going on and what might happen in the future*."

4.3.1 Knowledge Requirements

The knowledge requirements in this area include data analytic knowledge to analyze and interpret the data from various parts of smart grid in a meaningful and coherent way, and data management knowledge to govern the full life cycle of data.

4.3.2 Knowledge Gaps in Big Data

Despite the huge potential for using granular data from smart grid, big data is not a traditional area of strength for utilities. All utilities in the sample considered smart grid data analytics and management to be very challenging, as they have no prior experience to draw on. Not surprisingly, they face several knowledge gaps in both data analytics and management.

First, there are knowledge gaps in data analytics. There is a wide claim of a lack of strategic vision when utilities first put AMI in operation and encountered smart meter data. Several participants stated that there was no road map back then and they were haunted by questions like '*what should we do with the data*' and '*what are the things that we can do and going to be most beneficial*'. It took many utilities quite some time to explore the potential application areas before they took the first step in data analytics.

Another challenge lies in data cleaning and transformation. Many participants mentioned that the raw data from smart meters and other devices and systems were not directly usable or appeared in different data scales. Hence, utilities need to understand how the data is configured by different systems and conduct data cleaning and transformation before the data can be used. The manager from Municipal6 mentioned that they expected to get numerical data from the AMI system to be used in the customer billing system but instead they received alphabetic data. They had to transform the data to their preferred format. Yet, preprocessing data in a massive scale was new to utilities, and was complicated by the fact that useful data often is not obvious from simple data screening.

There are also challenges in using advanced analytics to model and understand data. As reflected by many participants, there are no real data analytics in the past. For a long time, the data has predominately been used in an ad-hoc fashion, in which the data was utilized to address specific needs after the problem occurred (Deign & Salazar, 2013). The use of data was rather passive and descriptive, involving high degrees of manual manipulation, for instance calculating customer bills. Yet, smart grid success entails a heightened need for a real-time, predictive use of data, by which utilities can aggregate data across functional silos to derive information-driven insights and bring greater business value (Daki et al, 2017). Hence, there is a big learning curve for utilities in terms of mastering data mining algorithms, understanding new analytic tools, and interpreting analysis results in use cases. For many utilities that have experienced smart grid data for a few years, there is still a knowledge deficiency in conducting more proactive and automated analytics. In the words of a CIO from Coop1:

"*And we're really good at situational using the data. So mostly you have a specific need, you've got the data, you think you can go utilize the data to make determinations, answer questions, whatever. But as far as more of a proactive and I guess more automated use of the data, I think we've got more room to improve there."*

Finally, there is knowledge deficiency in data management. Utilities lack the knowledge to develop and adopt appropriate procedures and architectures to archive, partition, and protect various smart grid data (Deign & Salazar, 2013). A commonly mentioned challenge is how much and how long a utility should keep the data . It is not practical to keep all the data that is generated from smart grid, not to mention that utilities also make copies of data for future exploration. There are also issues around the data storage structure to support efficient data access and analysis. As mentioned by a manager from IOU7:

"The other element is that you really have to focus on how to actually manage the data itself. The volume of data is huge and we need the data governance process. We are setting that up in each of the business line, but it takes time."

4.3.3 Variances in Knowledge Gaps

The general perception is that big data presents a rather new territory and the industry has little or no relevant knowledge to draw from. The majority of utilities, despite the size and ownership form, stated that making sense of and managing big data is one of the biggest challenges for them. The manager from IOU7, which is one of the leaders in smart grid adoption, stated that they also had a hard time when receiving 15-minute interval data:

"*It's a whole new way of doing business. It requires new organizational capabilities that traditional haven't had… it's difficult to sit down together and rigorously march through a consideration of what do we have now and what are the things that we can do that are going to be most beneficial?*"

However, it is also found that a supportive and aggressive regulatory environment could lower knowledge gaps in smart grid data management, although it is only shown in IOU6 and more systematic evidence is needed.

Regulatory support

Due to the aggressive policies by state regulators to urge AMI installation and smart grid development, the state where IOU6 operates, Texas, in is one of the few states that enjoy full-scale deployment of smart meters by all its IOUs when many states are still struggling with AMI pilots. Having this foundation, the state regulator initiated the effort to standardize the smart meter data transfer and communications between utilities and other market participants and hired IBM to build the smart meter portal (Zientara, Rankin & Wornat, 2014). It is the only state in the nation having this state-level data repository that store 15-minute data from all state IOUs and provides secure access to customers, electricity retailers, near 150 municipals and coops in Texas, and other authorized market participants. This portal is implemented with a set of standard rules that can accommodate meter data from various formats as a result of different manufactures. Such state-level effort greatly lowers the knowledge barriers in data management, and such benefit is confirmed in my interview with IOU 6 as well as a public statement from another utility in Texas (Delurey, 2013):

"*What that means to us as a utility is, I effectively only have to implement one set of rules, systems, and policies across the state of Texas, and I can be relatively assured that whether I'm serving a customer in Houston or Dallas, that even have different smart meter manufacturers, that the same set of functionality and rules exist between those... Naturally that creates ...the ability to serve our customers very efficiently and provide Smart Grid enabled programs across the competitive regions of the entire state.* "

4.3.4. Learning Responses

Training employees, recruiting full-time professionals and short-term contractors/consultants specializing in big data analytics and management, buying and learning software solutions in data analytics, and outsourcing data management are commonly adopted practices used to overcome the knowledge gaps in big data.

Training

The training on big data is part of the smart grid training. Current employees receive big data training to develop a corporate-level understanding of the value of big data. Particularly, domain experts who dealt with smart grid data usually receive in-depth training to sharpen their knowledge in structuring, organizing, and effectively using the data to optimize the operation. For instance, the majority of participants mentioned that their customer analytic group is trained to analyze and forecast customer data to identify patterns and trends in customer behavior, perceptions, and preferences.

Hiring and consulting

The majority of utilities also hire full-time big data and statistic professionals to increase their internal knowledge. These newly-hired experts help perform advanced analytics in a variety of areas, such as predictive analytics in load planning, distributed generation integration, asset management and new rate structure designing. It is also common for utilities to hire temporary contractors or consultants to meet the specific needs in big data analytics and management.

Buying data analytic solutions

According to several participants, buying software from IT or OT vendors specializing in data analytic and management and working with vendors to deploy and use the needed tools is an effective way to acquire knowledge in big data. These software solutions often have built-in high-performance analytical and management capabilities to handle complex data, which could not be easily developed by utilities internally. Additionally, learning to use the tools also helps utilities to accumulate necessary knowledge in big data.

There are numerous solution choices in the market. There are various data analytic products across functional domains like customer, transmission, distribution, and demand response. Many of these products aim to improve data analytic efficiency in certain functional areas such as customer care and billing, and its analytic and management capability is often restricted to certain types of data (Deign & Salazar, 2013). In recent years, there are also products that are specialized in integration service and aim to provide an integrated platform to accommodate, analyze, and manage data from different systems (Deign & Salazar, 2013).

Outsourcing

Outsourcing is a popular practice in data management. While all utilities in the sample have adopted AMI, the majority employed a vendor-hosted meter data management system (MDMS) in which vendors manage the smart meter data and provide data access to utilities. In many cases, vendors are responsible for storing, cleaning, transforming, and sending data to utilities for further analytic use. The manger from Coop6 felt that it is much easier and safer in this way:

"*Everything here at the office, we had disaster recovery plans for a lot of different things, tornadoes, fires, whatever, but if we have that type of thing, that hosting allows us to have that in an off-site situation and the hosting provides two different operation centers that maintain the same thing. From a security data standpoint, it's a very safe way to do it. You don't have all your eggs in one basket.*"

One manager from Municipal4 regretted that they did not choose vendor-hosted MDMS. According to him, it was quite a burden on them:

"*But they're not running the system for us. Although that was an option. In fact, if I had to do it over, I would take a serious look at just having- not necessarily just Itron, but you have that entity in the environment meters, you put it in, and they manage your IT stuff for you. It's just a lot simpler and IT people cost a lot of money.*"

4.3.5. Similarities and Variances in Leaning Responses

Knowledge relatedness

Due to the low knowledge relatedness between big data requirements and utilities' traditional knowledge base, learning efforts generally involve several practices that transfer external knowledge. According to most participants, despite their size and ownership form, big data is new to them and the existing utility knowledge cannot support effective internal exploration and research. Hence, they need to at first learn from vendors and external professionals to build up a certain amount of big data related knowledge and expertise and initialize the project. As a matter of fact, most participants regard vendors, contractors and consultants as efficient and helpful in the short run, and plan to increase the internal research and exploration after internal employees accumulate necessary knowledge and expertise in data analytics and management. As in the words of one manager from a big IOU:

"*It's a relatively unexplored area. We wanted to do it internally, but we realized we really didn't have the skills, and quite honestly, I struggled getting internal support to dedicate people to do it. One of the things that I would recommend to utilities that are looking to proceed in big data or any large IT-related deployment is to work with experienced vendors and consultants. The key is to go get the right help, and even the help can be expensive.*"

Risk-averse culture

While utilities generally use external learning to overcome the knowledge gaps in big data, they varied in the scale of many learning practices. The analysis showed that risk-averse culture plays a significant role in influencing the learning choices. It is found that the majority of utilities make conservative efforts in learning due to the long-term risk-averse culture. Compared to technology selection and evaluation and smart grid deployment and integration, big data is far from utilities' existing knowledge and learning involves more risks and uncertainties compared to the other two areas. As a result, the long-term risk-averse culture dominates most utilities' choice to avoid risks, responding to the challenge with conservative learning that takes the form of buying one-off data analytic solutions, limited training, and preference of hiring temporary contractors and consultants over full-time professionals. Such patterns have been observed in both big and small utilities. It includes many cooperatives and city municipals with fewer than 50 employees and limited financial resources. A common explanation is that they are not big enough to afford any mistakes in big data investment. As noted in the words of a senior manager: "*And I think for us, as a smaller utility, we have that problem that is greatly exacerbated, because we really have to place our bets the right way on our big data investments. Because we know we have to make some, but we can't afford mistakes. We'd rather let the people that have five million customers and $200 million to spend on it make their mistakes and learn from them, and make good investments*."

Yet, interestingly, it also includes several bigger utilities that are quite cautious in learning, involving a number of IOUs (IOU2, IOU3, IOU4, IOU5, and IOU8) and big city municipals (Municipal1 and Municipal 6). They also have very limited use of data. Several utilities admitted that they only utilized a fractional percentage of the data they are receiving, and many areas remain unexplored. Compared to most cooperatives and municipals in the sample, they are much bigger in size. Despite their relative abundant resources, the risk associated with high investment and maintenance costs and complexity of data management is a big concern for them and holds back the learning to basic analytics. Particularly, for big utilities, the massive increase in smart meters and grid devices entail significant investment in data infrastructure and storage. As several participants mentioned, the sheer complexity of data in combination with issues like data access and privacy cause too many uncertainties in learning, and they would rather wait for the move from industry leaders and learn from their mistakes.

Among these utilities, many have only a vendor-hosted MDMS to analyze and manage smart meter data, and a few have invested in additional analytic solutions in certain functional areas. For instance, a great number of them have used 15-minute smart meter data in customer analytics and outage analytics to improve billing accuracy, identify electricity theft and leakage, and improve outage responses. Yet, they still lack a more predictive and automated use of data to achieve higher value opportunities in smart grid, such as demand and consumption forecasting, distributed generation planning, predictive asset maintenance, tariff modeling, etc. Also, they generally have not invested in other data management solutions to store the data from other parts of smart grid or simply stored the data in a self-built data warehouse. The manager from Coop4 mentioned that they even switched to a less powerful MDMS solution to lower the cost. At the price of a smaller storage capability, they went from storing 3-year data to 3-month data. According to him:

"*Well, it's a lot less powerful, but I had one or two instances where their [original] meter data was pretty helpful, and it wasn't enough to justify the cost. It's a huge cost and that has been the struggle with lots of the cooperatives, a lot of rural cooperatives. You can't say 'hey guys, this is a really great investment that can deal with all information and only by the way it's $500,000 not to mention the annual maintenance of 20% each year*.'"

Big data training is usually less formal and intensive among these utilities. According to several participants, they are busy engaging other on-going projects and their existing human labor and knowledge base is only able to handle the basic analytics, which is already enough to support the daily operations. Hence, training on more advanced analytics would be the beneficial but is not necessary.

Short-term consultants and contractors are also preferred, as full-time employees are more costly and these utilities do not want to spend too much when they are still monitoring the moves from industry leaders. According to the manager from Municipal3, hiring a full-time data scientist is quite expensive as such an employee would command a salary higher than that of the mayor. Among several cooperatives, it is common to hire one or two technical consultants to help the data modeling.

Top management support:

Top management support also plays an important role in influencing learning choices. In this study, a few utilities were proactive in big data and made dedicated efforts in learning practices. All these utilities have a corporate vision that values big data, and one of the firm priorities is to be more data-driven. The manager from IOU6 mentioned the importance of top management support in their big data initiatives:

"*It's important that you have top-down support. You should have support from executives and leadership in those positions that set aggressive goals but also have an attitude that we will get it right and we are going to do things in a right way. What we are doing is cutting-edge and it does require strong leadership, a clear strategy and excellent relationships.*"

Some of them are big utilities, including IOU6, IOU7, and Municipal2. Driven by the desire to take full advantage of smart grid data to improve operational efficiency and customer satisfaction, they were willing and able to make dedicated efforts to overcome knowledge gaps and build up internal expertise in big data.

In general they made more extensive investments in big data solutions. They generally have purchased one-off solutions during their early phase of data analytics, but they soon recognized its limitation and the importance of a holistic big data platform that can accommodate, manage and analyze all types of data. Luckily, the senior managers decided to move on from early mistakes. With the support from top management, they made big investment in data infrastructure products that aim to build an integrated platform to accommodate various types of data. The manager from Municipal2 mentioned that their newly-purchased SAS package can pull data from an array of smart grid systems and devices and can accommodate a variety of data, including data from spreadsheets, text files, Oracle database files, and more. This sophisticated platform allows their analytic team to examine and use various data to conduct cross-function analytics over several areas. In their case, there is disagreement within the company regarding the later-on investment due to its high costs and big impact on organizational processes, yet, their budget proposal is approved and many engineers are allowed to temporarily stay away from their daily jobs and focus on the big data projects.

Additionally, the training on big data was more extensive and formal, as top management in these utilities recognize that big data is not just a technology investment but involves change in skillset, mindset and even culture. Hence, it requires more efforts to educate internal employees. In these cases, they get both financial and human support from top management to enable a comprehensive training on big data. It often took various forms that include formal in-person tutoring and less formal ones like online-learning, covering a variety of computer and big data courses to their employees. Many of these utilities also have certain budget to routinely send key engineers to industry sessions or seminars to update their knowledge. With abundant financial support, they also hire full-time professionals to develop a specialized data analytic team that is able to use large sets of data, software, and the application of advanced analytics to resolve complex problems. These utilities often collaborated with several academic institutions on projects with significant analytical and statistical work to attract a large group of talented students to join them after graduation. They also used contractors in some cases; however, the reason was mainly to reduce the pressure on current employees rather than a knowledge deficiency.

This group also includes a few small size utilities, including one smaller IOU (IOU2), one coop (Coop6) and small city municipal (Municipal 4). Despite their small size and constrained resources, they were proactive in big data and dedicated to the aforementioned learning practices. The managers said that they had the push from the senior executives to make the best use of smart grid data to improve operational efficiency, grid reliability, and customer relationships. Particularly, IOU2 had the experience of buying one-off products during the early phase of smart grid adoption, in which they found the capability of original MDMS to only be useful relative to the smart meter data and their millions of investment was a waste to other smart grid data. Yet, they did not step back. There are a few senior executives who were advocates of big data investments, and they were urged to reevaluate the road map in big data and allocated both human and financial resources to support the internal growth. Driven by the top-management decisions, IOU2 hired IBM to assess the needs in customer and grid analytics and bought the new solution to enhance overall IT infrastructure, conducted routine training to develop the in-house skills, hired a number of full-time data scientists, and delayed a few other projects to devote more time, money, and labor to their big data investment. According to the manager:

"*We were eager to develop some of this expertise inside, and we're not waiting on the move from others. There were trials and errors, but the [data] use is slowly occurring in customer* *service group, engineering and planning, We managed to develop a highly skilled group embedded in the business and it's very capable of the analytics tools that we're leveraging. We are small, but we are leading [in big data]*".

4.4 Customer Management

Utilities used to be the center of the electric utility industry, with limited customer interactions. But the advent of smart grid entails a customer-centered model where customers are encouraged to actively engage in the grid and use energy more efficiently. Hence, customers are playing a more important role in the electric system, and their level of participation and engagement also determines the sustainability of smart grid technology. The expectation that customers can use energy data to make better energy decisions or take ownership of distributed renewable generation and electric vehicles necessitates a very different customer management strategy.

4.4.1 Knowledge Requirements

The knowledge requirements in this area include the customer outreach knowledge to ensure the smooth installation of smart meters and home technologies as well as the enrollment into various smart energy programs and customer engagement knowledge to promote customer participation in various energy conservation programs on a long-term basis.

4.4.2 Knowledge Gaps in Customer Management

Similar to big data, customer management is also a new territory for utilities. The majority of utilities have encountered knowledge gaps in both customer outreach and engagement.

First, there are marketing and communicating knowledge gaps to convey essential information regarding meter installation, program offerings, event occurrences, and other energy conservation initiatives. According to a recent report from Smart Grid Consumer Collaborative

(2016), prior to smart grid, few utility projects or upgrades involved active engagement and management of customers, and the average customer spent just nine minutes a year interacting with his or her electricity provider. Most of these interactions revolved around outages, billing problems, or other issues with a negative connotation. Not surprisingly, most customers have little knowledge regarding smart grid technology, and many hold negative attitudes towards utilities. The common fears about smart grid are either "big brother" feelings where customers fear utilities and federal agencies use smart grid technologies to spy on them, higher bills, or health consideration, in which a belief exists that radiation from smart grid can harm a person's health (Smart Grid Consumer Collaborative, 2011). Yet, the demands in customer education and communication are challenging to many utilities. The manager from IOU5 mentioned:

"*We've practically ignored customers for more than 50 years. It wasn't until recently that we began referring to them as 'customers' instead of 'ratepayers'. So I feel that there's been a knowledge challenge in the area of trying to introduce smart grid technologies and change the perception of customers that we are spying on them.*"

Second, a widely reported knowledge gap in customer engagement is developing and managing digital platforms including web, mobile, and social media to promote customer participation on a long-term basis. The adoption of digital initiatives is a fundamental step toward customer engagement in smart grid, because social media as well as web and mobile apps are rapidly becoming the preferred channel for customers to interact and they expect experiences with service provides to be consistent (Smart Grid Consumer Collaborative, 2016). Yet, it involves knowledge in data visualization and presentation over multiple digital channels, and is beyond the traditional knowledge realm for utilities.

4.4.3 Variance in Knowledge Gaps

Almost all utilities confirmed the aforementioned knowledge gaps in their smart grid journey, yet they in general considered customer engagement to be quite challenging. However, the data indicates that certain service territory characteristics could lead to even bigger challenges faced by some utilities.

Service territory characteristics:

It is determined that utilities operating in states with cheaper generation sources particularly in the South and Northwest, including IOU5, IOU6, Municipal1, Coop1, Coop4, and Coop5, tend to face bigger challenges in customer engagement. According to participants from these regions, power supply in these areas still relies on cheaper coal and nuclear plants, which leads to lower energy costs. As a result, the requirements on customer engagement and program designing are more demanding, as customers are less motivated to price signals due to the existing low electricity price. In the words of Municipal1:

"*It's tougher for us in consumer engagement and their use, and it's probably driven by the fact that energy prices have been low in XX state for a long time, and when energy prices are low, there's little thought to their involvement. They don't care, it's not top of mind.*"

Also, utilities operating in service territories with all-season humid weather and general low-income residents face greater challenges in customer engagement. Both managers from Municipal3 and Municipal 6 mentioned that their service territory features both characteristics, and they explained that in the former situation customers are generally less attracted to energy conservation programs due to hot weather, whereas in the latter situation a lot of poorer-than-average neighborhoods already constrain their energy usage and do not respond to price signals. Municipal3 even discontinued their home area network (HAN) programs after the pilot:

"The difficult thing is we were, it's not a poor town, but it's not an overly rich town either so we have a lot of customers with very small houses that use very little electricity, less than 750 kilowatt hours a month. And over 50% of our customers use less than 750. So to the point of thermostat at those locations, they're just not going to have a very big effect. And the other thing is you have huge amounts of humidity here where states like Oklahoma or Arizona or something doesn't. Here, if you turn them off here for an hour, you sweat to death."

4.4.4 Learning Responses

To overcome the knowledge gaps in customer management, utilities usually involve the following learning practices: training in the customer department, recruiting full-time professionals and temporary contractors/consultants specialized in marketing, communication, and engagement, and buying and learning solutions in customer outreach and engagement.

Training

Customer service representatives, especially those with direct contact with customers, such as agents in the call center, receive training on various product/program offerings and the capability to use available data and customer information to troubleshoot common customer questions, such as high bills, energy consumption, the best energy usage practices, and suggestions on energy conservation. In one case, customer representatives are trained to use a software tool to categorize customers based on their requests and personalities, and frame responses according to the guidance under the category the customer belongs to. Additionally, the installation contractors are also educated to cover a number of frequently asked AMI and smart grid questions and to serve as customer service representatives.

Hiring and consulting

Many utilities have hired both full-time professionals and temporary contractors/consultants in marketing, communication, and customer relationships to strengthen their customer groups. Particularly, candidates with extensive experience in branding, channel strategy, and communications are in high demand, as they will help the marketing team to develop tailored customer programs and coordinate outreach activities.

Buying customer engagement solutions

Buying customer engagement solutions/products is another widely adopted practice to overcome the knowledge gaps in customer engagement. On one hand, the capabilities embedded in the products fill the missing link in customer knowledge. On the other hand, the direct experience of learning to use the tools also helps utilities develop valuable knowledge in customer engagement. Numerous vendors, including traditional IT giants like IBM and software companies targeting at cooperatives and small city municipals such as NISC, as well as energy-focused vendors like Opower and Bidgely, have offered a suite of products in customer engagement (PWC, 2014). The majority of these products generally offer a digital platform to increase billing experience where customers can access their energy-usage and bill information, view usage comparison information, and receive customized suggestions (PWC, 2014). A few products centered on a more complete customer experience—in addition to the above capabilities, customers can participate in demand response programs, manage their daily energy consumption, and even receive outage alerts through various digital channels (Smart Grid Consumer Collaborative, 2016).

4.4.5 Similarities and Variances in Learning Responses

In general, utilities made dedicated efforts to overcome the communication barriers in customer outreach when implementing AMI, as they had to create customer acceptance to install smart meters. Several participants mentioned they have conducted training on customer representatives, and recruited full-time marketing and communication professionals to smooth the meter installation process. Many utilities also hired consultants that are specialized in customer service to conduct market research, including deploying customer surveys, conducting telephone or one-on-one interviews, and running focus groups in their service territory to identify consumers' needs and interests. These consultants helped utilities analyze customer data and provided evaluation and suggestions to develop outreach programs. The data also showed that the customer outreach on AMI and smart meter is generally successful, with only a small amount of customer resistance in most cases.

Knowledge relatedness

Similar to big data, there is low knowledge relatedness between new knowledge required for customer engagement and utilities' traditional knowledge base, hence, learning efforts generally involve several practices that transfer external knowledge. Not surprisingly, utilities generally choose to first learn from vendors and external professionals to build up a certain amount of knowledge and expertise.

Risk-averse culture:

While utilities generally use external learning to overcome the knowledge gaps in customer engagement, they varied in the scale of many learning practices when overcoming knowledge gaps in customer engagement. It is found that risk-averse culture is an important factor that can help explain the variance. The analysis showed that the majority of utilities make constrained efforts in learning as a result of risk-averse culture. Similar to big data, customer engagement is far from utilities' existing knowledge and learning involves more risks and uncertainties. Grounded in the regulated culture, many utilities are afraid that extensive investments in customer engagement would lead to a big brother feeling. They usually focus only on billing experience, by which customers can have a disaggregated view of home consumption, similar home comparisons, bill payments, and customized suggestions and promotions on web portals and mobile applications. According to several participants, they would like to see the customer responses before they make further investments. The manager from Coop2 mentioned:

"*We definitely value our customers. But we are just a 20-some company and we're member-owned. Every decision I make, I'm spending our members' money. So I need to be very careful…we have the portal and mobile app, and that costs us a lot.*"

Such patterns have been observed in both big and small utilities. It includes most cooperatives and a few city municipals (Municipal3 and Municipal5), with fewer than 50 employees in most cases. It also includes several bigger IOUs (IOU2, IOU3, IOU4, IOU5, and IOU8) and city municipals (Municipal1 and Municipal 6). Many of them (IOU3, IOU4, IOU5, Municipal1 and Municipal 6) also took a wait-and-see approach in customer engagement and responded to the challenge by making conservative efforts in buying solutions. Several participants mentioned that senior managers are quite cautious in making aggressive investments, and are monitoring what others are doing. Top managers are more conservative among utilities operating in a state featuring low electricity prices, such as in the case of IOU5 and Municipal6. They have only a web portal as their approach to customer engagement. These participants stated that their customers are much less motivated due to low energy costs, weather, or other reasons, and what worked in other states may still not be effective in their service territory. According to the manager from IOU5.

"*And so far, that's been kind of a failure. I don't think we've changed anyone's habits at all, we've charted the last couple years, taking out temperature and weather variances, people are using electricity in the exact same way they always have…. customer engagement is very challenging and that other utilities have done a very poor job of that. And that's why we've hold it for a while and see how the industry is going."*

Top management support

In comparison, a few utilities were willing and able to make dedicated efforts to overcome knowledge gaps and enhance customer experience due to top management support. Participants from these utilities stated that there is a corporate vision that values customers and smart grid provides a good opportunity to improve customer satisfaction and relationship. With top management support, they are able to purchase a suite of customer engagement solutions that focus not only on improving billing experience but also promoting energy efficiency and demand response through various digital platforms, such as desktop and mobile websites, mobile applications, and social media, despite the high costs of such investments. Several utilities also include web-chat services in their package to improve general customer experience, through which they provide service at the same level as their call centers. As one manager mentioned:

"*We always put the consumers at the heart of it. That's essentially what we are doing. I believe that a lot of what we are doing is cutting-edge and it does require strong leadership, a clear strategy and excellent relationships with the technology companies. A key thing is that there is very little concern about what we are trying to do. Everybody knew what you are trying to take.*

Since we were in some brave trails, we are building and designing as we need and have the success together, and value together. ”

It includes a few big utilities (IOU6, IOU7, Municipal2 and Municipal 4) with abundant resources. Those big utilities are generally supported by senior managers who value greater customer centricity and urge customer engagement, including those with low electricity prices in the service territory. IOU6 is a big utility with low electricity prices and less motivated customers, yet they had the push from senior management to make a full range of efforts to engage customers. The manager from IOU6 mentioned that they asked the same customer engagement platform vendor to redesign their website to improve the customer experience, including enabling service in multiple languages and improving the ability for customers to find their interest areas through a convenient web search. In addition to the customer engagement platform, they also bought a digital dashboard from the vendor to integrate user statistics from the web page, social media, email, and electronic ads to determine what customers are talking about, what they are interested in, and how they can be better served. The manager added that they have noticed a change in the customer behavior.

Interestingly, the impact of top management has also been observed in a few small utilities. The data revealed that two small utilities—one coop and one city municipal—are also proactive in customer engagement and made extensive investments in customer engagement solutions. Both managers mentioned that their senior management is fully dedicated to the shift from an electricity provider to a service provider, and an immediate corporate priority towards greater customer centricity. In both cases, the business case of customer engagement is quickly approved and dedicated money and people are allocated to support the investment and learning.

4.5 Summary of Findings Across Four Knowledge Areas

This section compares and integrates findings from four knowledge areas that are essential in smart grid adoption, including smart grid technology selection and evaluation, smart grid deployment and integration, big data, and customer management, and highlights similarities and differences across these four areas. To better present the results, I create two tables (table 7 and 8) to summarize and compare the findings from these four knowledge areas.

	Smart grid technology selection	Smart grid deployment and integration	Big data	Customer management
Knowledge requirements	Identifying potential technologies and evaluating vendor solutions	Installing, linking, and managing systems and devices; coordination between functions, attitudes and principles	Data analytics and management	Customer outreach and engagement
Knowledge gaps	Smart grid standards	Physical-layer communication, system assumptions, and order of integration; new business processes adjustment and IT &OT coordination	Lack of strategic vision; data cleaning and transformation; advanced modeling; data archiving and partitioning	Communication; digital customer engagement
Factors related to variance in knowledge gaps	Support from National Rural Electric Cooperative Association (NRECA); relevant experience	Service territory characteristic, ownership forms, size, and IT sophistication	Regulatory support	Service territory characteristics
Learning responses	Searching, learning by doing, and consulting	Learning from vendors, consulting, training, learning by doing, and internal knowledge sharing	Training, hiring full time and/or consultants/contractors, buying analytic solutions, and outsourcing data	Training, hiring full time and/or consultants/contractors, and buying software solutions

			management	
Factors related to variance in learning responses	Level of knowledge gaps, knowledge relatedness and size.	Level of knowledge gaps, knowledge relatedness, and size	Knowledge relatedness, risk-averse culture and top management support	Knowledge relatedness, risk-averse culture and top management support

Table 8 A Summary of Findings across Four Knowledge Areas

		Smart grid technology selection	Smart grid deployment and integration	Big data	Customer management
IOU6, IOU7, Municipal2, Municipal4	Level of knowledge gaps	Smaller gap in smart grid standards	Smaller gaps in technical integration; bigger gaps in soft part of integration	Big gaps	Big gaps (even bigger for IOU6)
	Learning practices	Wide searching and bigger-scale learning by doing	Learning from vendor, formal and extensive training, learning by doing, and knowledge sharing through structure change	Formal and extensive training, hiring full-time professionals, extensive and continuous investment in data analytic solutions, outsourcing data management	Formal and extensive training, hiring full-time professionals, and extensive and continuous investment in customer engagement solutions.
IOU1, IOU2, IOU3, IOU4, IOU5, IOU8, Municial1, Municipal6	Level of knowledge gaps	Bigger gap in smart grid standards	Bigger gaps in both technical and soft aspects of integration	Big gaps	Big gaps (even bigger for IOU5 and Municipal6)
	Learning practices	Wide searching and bigger-scale learning by doing; engagement of consultants	Learning from vendor, engaging consultants, formal and extensive training, learning by doing, and knowledge sharing through cross-training and brainstorming	Depend on culture and top management attitude towards big data	Depend on culture and top management attitude towards customer engagement

Municipal 3, Municipal 5, All cooperatives	Level of knowledge gaps	Smaller gap in smart grid standards	Smaller gaps in both technical and soft aspects of integration	Big gaps	Big gaps (even higher for Municipal6, Coop1, Coop4, and Coop5)
	Learning practices	Deep and local searching, small-scale learning by doing	Learning from vendors, informal and flexible training, and learning by doing	Limited training, hiring contractors over full-time professionals, limited or no investment in data analytic solution; outsourcing data management	Flexible training, hiring contractors over full-time professionals, and limited investment in customer engagement

Table 9 Variances in Knowledge Gaps and Learning Responses Across Utilities

Answer to RQ1: What knowledge requirements are critical for smart grid adoption?

As shown in table 7, this study revealed four areas of knowledge requirements that are critical in smart grid adoption, including smart grid technology and vendor selection, smart grid deployment and integration, big data and customer management. *Smart grid technology and vendor selection* includes knowledge about identifying different technologies and solution options and evaluating and selecting the most appropriate vendor solutions to meet the utility expectations. *Smart grid deployment and integration* includes technical knowledge necessary to install, link, and manage various physical devices, systems, and communication platforms of electrical grids, as well as the business and organizational knowledge to manage soft part of integration including coordinating people, resources, and activities across functions, and adjusting business procedures and processes to enable an efficient operation of the smart grid devices and systems. *Big data* includes data analytic knowledge to interpret the data from various parts of smart grid in a meaningful and coherent way, and data management knowledge to govern the full life cycle of data. *Customer management* includes customer outreach knowledge to ensure the smooth installation of smart meters and home technologies and enrollment into various smart energy programs, as well as the customer engagement knowledge to promote customer participation and interest in energy saving on a long-term basis.

Answer to RQ2: What knowledge gaps are utilities facing with smart grid adoption? How do utilities vary in the level of knowledge gaps?

According to table 7, utilities face several knowledge gaps in these four areas. The knowledge gap in *smart grid technology and vendor selection* is the lack of knowledge on smart grid standards when selecting and evaluating potential vendor solutions. The knowledge gaps in *smart grid deployment and integration* are physical-layer networking, understanding of different systems' assumptions, order of integration, new business processes adjustment and IT&OT coordination. The knowledge gaps in *big data* are strategic visions for big data, data cleaning and transformation, advanced modeling and data archiving and partitioning. The knowledge gaps in *customer management* are communication and digital customer engagement.

Evidenced in table 8, the level of gaps perceived by utilities vary--some utilities have bigger gaps in certain knowledge areas whereas others perceive much smaller or even no gaps. Such variance is associated with an interaction of factors, including IT sophistication, size, regulatory push/support, ownership forms, service territory characteristics, and support from National Rural Electric Cooperative Association (NRECA). These factors influencing the level of knowledge gaps by either influencing the level of knowledge requirements or impacting on the level of existing organizational knowledge. While relevant experience and IT sophistication are two factors that affect knowledge gaps by accumulating utilities' existing level of knowledge, the rest of these factors affect knowledge gaps by raising or lowering knowledge requirements.

It is noted that utilities vary in the levels of knowledge gaps in smart grid technology and vendor selection and smart grid deployment and integration, but in general have big gaps in big data and customer management. To utilities, the first two areas still have overlap knowledge with their existing knowledge base whereas the last two areas present rather new territory and the industry has little or no relevant knowledge from which to draw. On one hand, big data analytics and management is disruptive to utilities as a result of change in the vision, procedures, analyzing software and algorithms, and data governance structures. On the other hand, the new customer management is considered a huge shift that moves from utility-centric management model to customer–centric management model.

Answer to RQ3: How do utilities overcome the gaps through learning? How do utilities vary in the learning choices?

As illustrated in Table 7, to overcome these knowledge gaps, the common learning practices include searching, learning by doing through trial-and-error, internal knowledge sharing, training, learning from vendors, buying software solutions, consulting, and hiring full-time professionals/temporary contractors. No utilities rely on a single activity but employ a selection of learning activities to overcome the knowledge gaps in smart grid adoption. Yet, they vary in the configuration of these practices, the scale and extensiveness of some practices, and focus of and mechanisms behind some practices. The variance in learning responses is jointly determined by level of knowledge gaps, knowledge relatedness, size, risk-averse culture and top management support.

The dynamics of these factors are interesting. On one hand, knowledge relatedness and level of knowledge gaps are two factors influencing the configuration of practices. When knowledge areas have more relatedness with the existing knowledge base, as in smart grid technology selection and smart grid deployment and integration, the learning involves a greater portion of practices that develop knowledge internally. It should be noted that different knowledge gaps require different combinations of practices in internal development, for instance, searching and learning by doing are most employed in smart grid technology and vendor selection and training, learning by doing, and internal knowledge sharing are common practices in smart grid deployment and integration. Learning in these two areas also involve practices that transfer knowledge from external parities, which play a rather supportive role. Learning from vendors is the most common form of external knowledge acquisition; yet, the adoption of additional practices is subjective to level of knowledge gaps--utilities with bigger gaps in these two areas often engage hiring full-time professionals and recruiting consultants.

In knowledge areas that present a clear departure from utilities' existing knowledge base and generally perceived as quite challenging, such as big data and customer management, learning mainly involves a great portion of practices that transfer and assimilate knowledge from vendors, consultants and experienced professionals. Practices include purchasing solutions from vendors, hiring full-time professionals and/or temporary contractors, and recruiting consulting service. There is little involvement of practices that use intentional efforts to acquire knowledge through direct experience, due to the minimal knowledge relatedness in these two areas.

On the other hand, size, knowledge relatedness, risk-averse culture and top management support can influence the focus and scale of many learning practices. When it comes to learning to overcome the knowledge gaps in areas that are more related to utilities' existing knowledge base, as in the case of smart grid technology selection and smart grid deployment and integration, size is more important. Big utilities generally conduct more extensive search and learning by doing and enable formal training due to their abundance of resources. When overcoming the knowledge gap in IT & OT coordination, in addition to regular project meeting, they often entail additional efforts to encourage cross-functional knowledge sharing to facilitate the effectiveness of learning by doing, either through higher-level structural change or lower-level cross training and brainstorming. In comparison, small utilities tend to have a different focus in these practices that can still ensure learning effectiveness, given limited resources and budget. For instance, they prefer local and deep search rather than extensive search. Also the training is often more flexible and take the advantage of a less siloed structure to encourage internal knowledge sharing, as opposed to formal and extensive training that requires bigger budget and more human resources and time. The internal knowledge sharing is also less formal and flexible as their small structure often entails a cross-functional collaboration prior to smart grid.

When it comes to learning to overcome the knowledge gaps in areas that are far from utilities' existing knowledge base, as in the case of big data and customer management, risk-averse culture and top management support are key factors. Due to low knowledge relatedness between the knowledge requirements of these two areas and utilities' existing knowledge base, learning involves more uncertainties and risks. Hence, the majority of utilities with risk-averse cultures took a conservative attitude in learning which often leads to limited training, one-off data applications that support analysis in functional areas or customer engagement solution focusing only on billing, and preference of contractors over full-time professionals. A few utilities that have strong top management support take a more active attitude towards learning, which involves more extensive training, investment in big data infrastructure that supports accommodating various types of data and customer engagement solution that improves customer experience in billing and participation in other energy conservation programs, and hiring both full-time professional and contractors.

5 Discussions and Conclusions

This chapter covers the discussions of findings and the implications of this research. Based on the results of this research, key research finding are discussed and considered along with prior studies. In the implications section, theoretical contributions of this research are discussed, and then practical implications are presented with regard to utilities, regulators and other industries or economies. Lastly, the limitations of this research, and suggestions for future research are provided.

5.1 Discussion of findings

5.1.1 The Relationships Among Knowledge Requirements, Gaps and Learning

The findings indicate that knowledge requirements, knowledge gaps and learning responses interact in a dynamic way. To better present the logic, I develop an integrative framework that links knowledge requirements, gaps and learning together in the context of complex IT adoption. As shown in Figure 2, the level of knowledge gaps depends on the relationship between knowledge requirements and existing knowledge, which are influenced by a set of organizational and environmental factors. Furthermore, the level of knowledge gaps along with other knowledge and organizational factors determine the learning choices in IT adoption. There have been a few efforts that applied organizational learning perspective in IT adoption research (Roberts et al., 2012), yet they mainly used proxy constructs to represent learning and investigated its predictability on IT adoption while only three studies started to investigate the underlying learning processes or dynamics in IT adoption (Robey et al, 2002; Santhanam et al, 2007; Woiceshyn, 2000). Hence, this framework represents another empirical investigation in the latter direction by proposing and conceptualizing the interaction between knowledge challenges and learning in IT adoption.

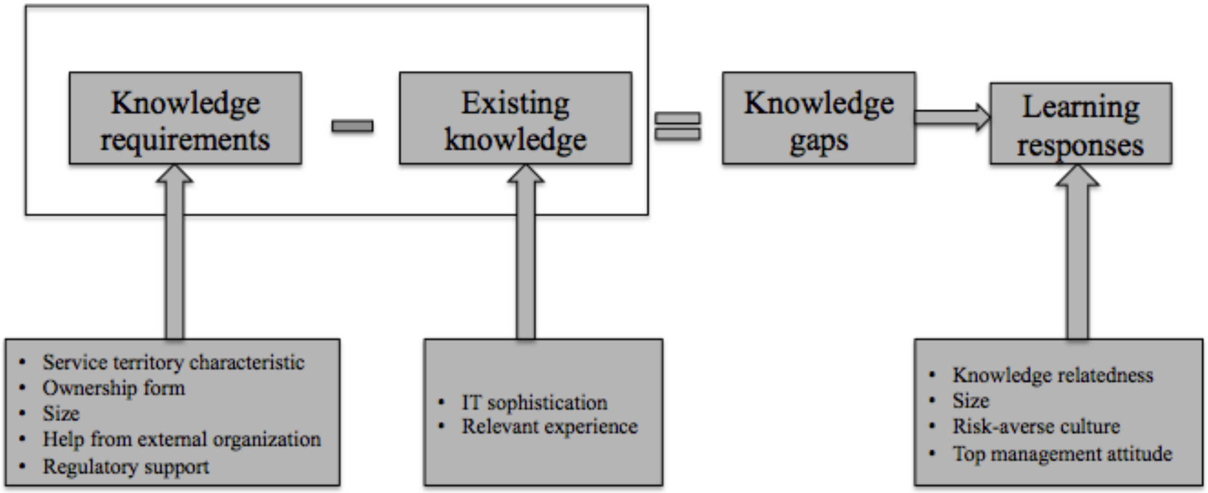

Figure 2 A Conceptual Model of Knowledge Requirements, Gaps and Learning Responses

5.1.2 The Knowledge Requirements and Gaps

This study revealed four broad areas of knowledge that are essential in smart grid adoption, including smart grid technology and vendor selection, smart grid deployment and integration, big data, and customer management. This finding is consistent with the IT adoption literature concerning the importance of both technical and business knowledge in IT adoption (Armstrong & Sambamurthy, 1999; Fichman & Kemerer, 1997; 1999; Markus & Tan, 2000; Robey, Ross, & Boudreau, 2002), yet it indicated a broader requirement of technical knowledge as a result of different nature of smart grid. While traditional technical requirements such as technology and vendor selection, hardware and system installation, and system management are important in smart grid adoption, smart grid also entails high demand in integration between physical devices, communication platforms and hardware and software systems that has been rarely mentioned in the literature (Department of Energy, 2008; Hardcastle, 2013).

Additionally, the findings added to IT adoption literature by showing that data analytics and management, in addition to technical and business knowledge, are also critical knowledge in complex IT adoption nowadays. New IT applications are collecting more data than ever before, and it is important for companies to analyze and manage data to obtain full-range value and sustain competitive advantage. Moreover, this study confirmed that customer knowledge is important in IT innovations involving customer engagement (Karakostas, Kardaras, & Papathanassiou, 2005; Lin and Lee, 2005).

Also, this study evidenced that knowledge gaps vary depending on the technology types and study context. For instance, the knowledge gaps related to technical knowledge in smart grid adoption are smart grid standards, physical communication, system assumptions, and order of integration, which are different from those identified in the literature such as system configuration (Robey, Ross, & Boudreau, 2002). When it comes to the business knowledge, in addition to the commonly mentioned lack of understanding in new business processes or procedures (Edmondson et al, 2001; Fichman & Kemerer, 1997; Markus, 2004; Robey, Anderson & Raymond, 2013), utilities also face the challenge of cross-functional collaboration.

Finally, there is a gap in IT adoption literature that investigated how adopting companies vary in the level of knowledge gaps in IT adoption. This study helps to fill the missing link by discovering that knowledge gaps in smart grid adoption mainly depend on a few organizational factors such as length and richness of utilities' relevant technology experience, the level of advance in IT infrastructure, and the scope of integration, as well environmental factors including the service territory characteristics and support from outside organization (e.g. NRECA).

5.1.3 Learning responses and factors influencing the choices

This research shows that the learning practices adopted by utilities in smart grid adoption are not different from those reported in the literature, suggesting that the fundamental learning practices are mostly the same despite the industry and study context. As evidenced in this study, practices including searching, learning by doing, internal knowledge sharing, training, learning from vendors, buying software solutions, consulting, and hiring full-time professionals/temporary contractors, are consistent with the organizational learning literature (Argote, Miron & Spektor, 2011; Friesl, 2012; Huber, 1991; Jansen, Bosch & Volberda, 2006; Song et al, 2003). Additionally, the configuration of learning practices discovered in this study still falls into the internal and external framework (Bierly & Chakrabarti, 1996; Choi, Poon, & Davis, 2008; Kessler, Bierly, & Gopalakrishnan, 2000). Yet, this research showed that utilities not only varied in the configuration of learning practices, but also in terms of the scale of the practices, and the focus of and mechanisms behind some practices. Findings regarding how the dynamics and interactions among factors influencing learning choices is particularly interesting.

Choices on internal and/or external learning and related factors

This study demonstrates that knowledge relatedness and level of knowledge gaps are two main factors influencing the internal and external learning choices. Compared to the literature in which perceived value of knowledge, organizational age and relevant experience were found influential (Argote and Miron-Spektor, 2011; Bierly & Chakrabarti, 1996; Gopalakrishnan and Bierly, 2006; Kessler et al, 2000), only the argument regarding relevant experience is indirectly supported on the ground that relevant experience is a key factor influencing the level of knowledge gaps. Yet, the contribution of this study does not only lie in the identification of two new factors but also how these three factors interact that goes beyond simple linear model.

This research finds that when knowledge areas have more overlap with the existing knowledge base, utilities generally make mixed efforts in both internal learning and external learning. Not surprisingly, internal learning makes up a good portion and learning by doing is the most frequently employed practice. Such finding is consistent with the argument that overlapping knowledge equips organizations with absorptive capacity to support the experimentation, evaluation and reflection with new knowledge (Clercq & Dimov, 2008; Huber, 1991). Yet, external learning is also observed in all utilities and learning from vendors is the most common form of external knowledge acquisition. This is not surprising as vendors are a very important knowledge source in technology adoption. However, the inclusion of other forms of external learning depends on level of knowledge gaps. Utilities with bigger gaps often engage additional practices such as hiring full-time professionals and recruiting consultants.

In knowledge areas that are far from utilities' existing knowledge base, utilities generally follow a very external learning approach involving a number of practices that transfer and assimilate knowledge from vendors, consultants and experienced professionals. It should be noted that learning also involves practices that develop internal knowledge such as training, but there is little involvement of practices that use intentional efforts to acquire knowledge through direct experience, due to the minimal knowledge relatedness in these areas. This finding supports the argument that when there is a big incongruence between existing knowledge base and new knowledge, developing knowledge internally is too time-consuming and challenging and learning from external parities is beneficial (Clercq & Dimov, 2008). This finding also suggested a condition to the argument that firm-valued, core knowledge is more likely to be internally developed as opposed to external acquisition (Bierly & Chakrabarti, 1996; Cohen & Levinthal, 1990), but such argument is only valid when there is some overlap between the new knowledge and existing knowledge base.

These findings further support the argument that internal and external learning are complementary, as firms cannot rely on a single approach to acquire all needed knowledge and skills (Cassiman & Veugelers, 2006; Grimple & Kaiser, 2010). On one hand, the most internally oriented utilities still collaborate with vendors to meet specific demands; on the other hand, utilities following an external oriented approach still have some form of internal learning such as training to help assimilate external knowledge.

Choices on the focus and scale of learning and related factors

This research demonstrates that despite the variance in internal vs. external choice, utilities also vary in the scale and format of many learning practices, which are influenced by the interaction between knowledge relatedness, size, risk-averse culture and top management support. Interestingly, knowledge relatedness again is a key factor here. When the new knowledge has some relatedness with utilities' existing knowledge base, size becomes a dominant factor impacting the format of learning—the learning among bigger utilities can be featured as extensive and formal learning due to their abundance of resources whereas learning among smaller utilities are flexible and less structured given limited budget and resources, and lower barriers between organizational siloes. When the new knowledge has low relatedness with utilities' existing knowledge base, culture and top management attitude are key factors. The majority of utilities grounded in the risk-averse culture conduct conservative learning which often leads to limited training, one-off data applications that short-term and basic needs, and preference of contractors over full-time professionals. A few utilities that have strong top management support take a more active attitude towards learning, which involves more extensive training, extensive investment in software, and hiring both full-time professionals and contractors.

While findings regarding several factors such as risk-averse culture and influence from powerful organizational members are consistent with the literature (Brodtrick,1998; Geiger et al., 2005), this research reveals the importance of knowledge relatedness as well as the interactions between these factors. Additionally, contrary to the argument that bigger size often promotes learning whereas smaller size impedes learning (Crossan et al, 1999; Woiceshyn, 2000), this research indicates the influence of size is often conditioned by other factors. More importantly, as evidenced in this study, small firms can also promote learning. Yet, they have different formats and styles in many learning practices aligned with their limited resources to achieve best results.

The role of regulatory environment on learning

While the literature recognizes the importance of external environment on organizational learning, there is little empirical investigation examining the impact of regulatory environment on learning. This study addressed this limitation by demonstrating that a regulated environment can influence learning by both affecting the level of knowledge gaps and nurturing a risk-averse culture that impedes learning. On one hand, regulation has a negative impact on learning, as it leads to risk-averse cultures. For a long time, the utility industry focused on providing the required electricity service to customers to meet the regulatory compliance, which has translated into a risk-averse mentality (Energy Information Administration, 2000). Such entrenched mindset leads to the fact that the majority of utilities make constrained learning efforts when it comes to knowledge areas involving big gaps and uncertainties. As shown in this study, they don’t want to make full commitment to a knowledge area that may create major problems if they take a wrong step. Rather, they prefer make the minimal learning to meet required needs and take a wait-and-see approach for the next step. One interesting finding is that a few utilities pushed by their top mangers are fully committed in learning to overcome the gaps. This also foreshadows possible direction for future research: what drives those managers to be aggressive and risk-taking in such a risk-averse industry? Does it stem from their internal culture or other factors as a result of smart grid?

On the other hand, regulatory environment can have a positive impact on learning. According to the results, supportive state regulators can drive utilities to actively participate in the smart grid standards development to increase the internal knowledge base and in one state to initiate an effort to build a smart meter portal to lower the data management requirements. So it appears that the nature of the regulatory environment varies by state, influencing learning strategies.

5.2 Implications

This study has several implications of theoretical and practical importance, as discussed below.

5.2.1 Theoretical Implications

Implications on organizational IT adoption research

First, this study addresses the limitations of two dominant paradigms in IT adoption research (Fichman, 2004). On one hand, the bulk of researchers treated the adoption process as a black box and mainly concerned with explaining the general propensity of an organization to adopt and assimilate an IT innovation. Hence, there has been an extensive body of research using variance models to identify antecedent conditions that predict and explain IT adoption (Armstrong & Sambamurthy, 1999; Hsu, Lee & Sraub, 2012; Ven and Verelst, 2012; Zhu et al, 2006). However, the limitation of such variance models is that they don’t assume factors affecting IT adoption can interact in complex ways that go beyond simple, linear interaction effects. Yet, this study lends empirical support that there are complex interactions among factors influencing post-adoption behavior in the case of complex IT adoption. The results reveal a set of organizational and environmental factors determining the level of knowledge gaps faced by adopting organizations, whose interaction with other knowledge and organizational factors further determine the learning choices in complex IT adoption. On the other hand, another stream of researchers uncovered the black box of IT adoption by examining sequences of events that take place along the adoption process (Robey, Ross, & Boudreau, 2002). There have been different stage models to conceptualize the adoption process (Cooper & Zmud, 1990; Damanpour & Schneider, 2006; Markus & Tanis, 2000; Zhu, Kraemer & Xu, 2006), and they assumed that organizations would strictly follow the sequence to move to the next stage. Yet, such assumption is often violated in reality. More importantly, agreeing with Robey and his colleagues' (2000) argument, process research provides more description than explanation and little is known about the dynamic underlying the adoption process. This study brings insights to this stream of research by applying the organizational learning perspective in IT adoption process-- it uncovers underlying learning practices as well as the dynamics among these practices in overcoming knowledge gaps in the context of a complex IT adoption. As a result, this empirical investigation made a further step in advancing the process research.

Second, this study adds to the IT adoption literature by enriching the understanding regarding knowledge requirements and gaps along IT adoption. Although the knowledge requirements and gaps identified in this study are specific to the smart grid context, the findings of this study are consistent with the literature that technical and business knowledge are fundamental in IT adoption (Attewell, 1992; Fichman & Kemerer, 1999; Seddon et al, 2010). Furthermore, it demonstrates the importance of data analytic and management knowledge in future IT adoption. Additionally, while previous studies recognized that knowledge gaps always occur in IT adoption (Attewell, 1992; Fichman & Kemerer, 1997), there is little discussion on whether and how adopting organizations vary in knowledge gaps. This study fills this gap by confirming that utilities varied in the knowledge gaps in smart grid adoption and determining that such variance is determined by an interaction of organizational and environmental factors.

Implications for broader IS research

As Attwell (1992) and Fichman (2000) pointed out, all new technologies require some extent of organizational learning to be adopted and assimilated. Yet, complex IT initiatives fall on the more demanding end of spectrum for associated knowledge and skills, as evidenced in this research. Hence, organizational learning plays a key role in surviving and smoothing complex IT adoption. However, researchers largely consider IT adoption and organizational learning research as two independent streams, with only a few efforts to integrate insights from two streams. This research has the potential to contribute to the broader IS field by developing an integrative framework demonstrating the links among knowledge requirements, knowledge gaps and learning responses in IT adoption efforts. The dynamics among them, in which the contingent and interaction effects of different knowledge, organizational and environmental factors influence the level of knowledge gaps and the choices of learning practices, are particularly interesting. In the future, organizations and sectors will face a range of new landscape-changing IT, for instance, big data and the Internet of things as well as artificial intelligence to name but three. Thus, future IS research could seek to further elaborate and empirically test a more general theoretical model around these factors, thereby shedding new light on complex IT adoption processes and the associated organizational learning practices.

Implications for organizational learning research

This study also has the potential to contribute to organizational learning research by examining learning in a historically slow-moving, regulated industry faced with disruptive new technologies, which has been rarely explored before (Rashman, Withers & Hartley, 2009). While all the learning practices discovered in this study have been reported in the literature and the configuration of learning practices still fall into the internal vs. external categorization (Damanpour & Schneider, 2006; García-Morales, Ruiz-Moreno, & Llorens- Montes, 2007; Naot *et al*. 2004; Storck & Hill, 2000; Weick 1996), the findings support the argument that internal and external learning are complementary, as firms cannot rely on a single approach to acquire all needed knowledge and skills (Cassiman & Veugelers, 2006; Clecq & Dimov, 2008).

Furthermore, findings regarding the factors that influence the preference over internal or external learning as well as the format and scale of learning practices add new perspectives to the learning literature. While the literature suggests that perceived value of knowledge, organizational age and prior experience could influence the internal or external learning choice (Bierly & Chakrabarti, 1996; Gopalakrishnan & Bierly, 2006; Jansen et al, 2006), this study only lends support to the last factor—prior experience is one of the many factors shaping level of knowledge gaps that further impacts the internal or external learning orientation. It also highlights the importance of a new factor, knowledge relatedness. Additionally, although the majority of factors (size, risk-averse culture and top management support) that influence learning focus and scale are consistent with the literature (Crossan et al, 1999; Geiger *et al*., 2005; Storck & Hill, 2000; Weick 1996; Woiceshyn, 2000), a unique contribution of this study is identifying the dynamics among these factors and how such dynamics impact the learning. Moreover, this research not only confirms the previous finding that regulatory environment influences learning by leading to an entrenched risk-averse culture (Brodtrick, 1998), but also provides empirical support that regulatory environment can impact learning by influencing the level of knowledge gaps.

5.2.2. Practical implications

The results of this study provide several practical implications for utility companies, regulators and other regulated economies.

Utilities

This research has significant implications for utilities that have adopted smart grid or plan to adopt smart grid. The results demonstrate that whereas external factors such as regulatory attitude and uncontrollable factors such as knowledge relatedness, size and service territory characteristics are key factors shaping level of knowledge gaps in smart grid adoption, internal organizational capabilities also influence the knowledge gaps. As evidenced in this study, utilities with prior communication and IT experience have lower gaps and smaller challenges in smart grid adoption. Therefore, utilities should be more active in incorporating IT investment in its R&D efforts to lower knowledge barriers for future technology adoption or upgrades, as this is the trend for future technology.

When it comes to learning, this study shows that top management support and level of resources play crucial roles in learning. The findings illustrate the importance of top management support in knowledge areas with great uncertainty and risks. In a few cases, top management support drives utilities to make dedicated learning efforts regardless of big knowledge gaps, as opposed to the majority of utilities that make limited learning efforts in the same knowledge areas. However, a sound and forward-looking top management requires an organizational culture that encourages innovation and accommodate mistakes, and such culture is missing in the majority of utilities due to long-term regulation. This calls for managerial attention to create an innovative culture that is beneficial to utilities in the long run. Particularly for managers that practice more conservative learning in big data and customer engagement, they should be more proactive in the learning processes, even if they move more slowly in these two areas.

Managers should also factor in their level of resources when making decisions on learning choices- they need to consider how to allocate the human resources and time to improve the effectiveness of learning. While bigger utilities have more resources to support bigger scale of learning, it doesn't suggest that utilities with smaller size would have bad learning outcomes due their limited budget and human resources. As indicated in this study, smaller utilities could embrace more flexible and less formal learning in training, sharing and learning by doing to align with their resource conditions.

Regulators

The findings indicate that regulators can play a significant role in lowering knowledge gaps in smart grid adoption. As evidenced in the results, a few state regulators are very proactive in smart grid—not only do they collaborate with standards organizations in the smart grid standards development to ease the interoperability issue but they also push regulated utilities to participate in the process. One state regulator also initiated an effort to establish a smart meter portal to better manage the data. This offers some encouraging evidence that regulatory authority should develop a positive attitude towards and be actively involved in the smart grid adoption to support utilities.

Furthermore, given the fact that most utilities make limited learning efforts in big data and customer engagement as a result of long-term regulation and associated risk-averse culture, there is the practical implication that state regulators should create an environment that encourages innovation and exploration among utilities. Like many regulated industries, electric utility companies for a long time have operated in a relatively predictable and slowly changing technology environment, having no incentive to take advantage of technological advances (Energy Information Administration, 2000). Not surprising, compared to other firms in other industries (e.g. IT companies), utilities are widely recognized as risk-averse and lacking innovation. Clearly, a regulatory environment that allows mistakes would help lower the entrenched risk-averse state of mind and promote a more proactive attitude in smart grid learning. Yet, the regulators should think about what are the mechanisms to bolster an open and innovative environment for utilities. The existing regulation model is a “cost-plus” model in which revenues are based on the utility’s total costs of providing service and utilities are guaranteed a percentage return on any approved investments (Energy Information Administration, 2000). This is where the risk-averse culture and lack of innovation is rooted. An alternative regulation is called performance-based regulation that emphasizes incentives for good performance (Lazar, 2014). There has been heated discussion around this new model, but only a few states in U.S. have adopted it (Lowry, Woolf, & Schwartz, 2016). Yet, it could be the future model and deserves regulators’ attention.

Other industries or economies

The aforementioned implications also apply to other regulated industries or other economies that are adopting complex information and communication technologies. As IT is incorporated in every industry, many organizations face a range of new landscape-changing IT initiatives and struggle to implement and use them efficiently and effectively. Sometimes challenges arise because an organization simply does not have the knowledge required, and they need to learn to acquire the knowledge. However, both firms and regulators could make efforts to smooth the learning. On one hand, firms could increase their R&D budget to support more IT investment to lower the knowledge gaps for potential technology upgrades, and develop an innovative culture to encourage and stimulate learning. The format and scale of learning should also be aligned with their resource level to achieve maximum efficiency. On the other hand, regulators should play a supportive role in complex IT adoption to lower the knowledge gaps and create an environment that rewards innovation among regulated firms to promote learning.

5.3 Limitations and Future Research

This study has a number of limitations that can provide opportunities for future research. First, a single respondent strategy is used for interview data collection. Due to the fact that several utilities declined to continue participation in the study when asked to volunteer the time of multiple informants, I pursued key informant strategy–I interviewed either a smart grid director or a senior manger that is responsible for smart grid within each organization– in exchange of more interview opportunities. Yet, the use of a single key informant has the potential of biased and inconsistent results whereas using multiple informants are more desirable to increase the validity of the information when studying organizational-level constructs (e.g., Kumar et al., 1993; Huber & Power, 1985). Building on results from this study, future studies could embrace a few in-depth case studies with multiple respondents to investigate what knowledge requirements and challenges are perceived by managers in different departments (e.g. IT and customer service) and what learning practices are taken departmentally to overcome the gaps.

Second, this study focuses on U.S. electric utilities and excludes utility companies from other countries. In addition to U.S., European countries like Germany and Asian countries like Japan are also active in smart grid adoption (Giordano, Gangale & Fulli, 2011). Yet, their motivation of smart grid is different—while utilities in U.S. that adopt smart grid are generally motivated by the urge to improve grid reliability and operational efficiency, many utilities in Europe adopt smart grid because of renewable energy (DERlab, 2016). With different focus and national regulations, the types of smart grid technologies that are deployed by other countries could be different, which could entail different knowledge requirements, gaps and even learning dynamics in other countries. Hence, future studies could focus on utilities in other countries to investigate the effect of macro-level differences on the knowledge requirements, gaps and learning choices in smart grid adoption.

Third, this study discovers common learning practices in overcoming the knowledge gaps and variances in the learning choices in smart grid adoption. It would be interesting to explore whether the learning patterns such as the configuration and focus of learning practices are path-dependent in previous technology upgrades. If not, it would be valuable to examine what are the factors that can explain the change in a utility's learning strategy. Moreover, it is worth investigating what drives the senior managers in a few small-size and medium-size utilities to be proactive in learning big data and customer engagement when most utilities of similar size are risk-averse in these two areas.

Finally, the last limitation is the nature of qualitative design, from which there is a general concern of limited generalizability from relative small sample qualitative research (Myers, 2009). However, the aim of this study is not a broad generalization but a better understanding of knowledge requirements, gaps and learning practices in a specific context: smart grid adoption in U.S. electric utility firms. Yet, future studies could benefit from a quantitative design of a larger sample of utilities and increase the generalizability of the study by building on the notion of learning activities and statistically investigating some of the claims found in this study. One possible direction is to use the cluster analysis to generate different learning strategies based on the configuration of learning activities. When combined with the findings from this study, it is interesting to statistically examine whether the type of knowledge, level of knowledge gaps, size, and top management attitude play important roles in the choice of learning strategies. Moreover, future research could also test whether different learning strategies lead to different learning outcomes or long-term firm performance.

5.4 Conclusion

This study uses a qualitative approach to investigate knowledge requirements, knowledge gaps, and learning responses in a regulated industry faced with disruptive technology adoption. The results indicate four broad areas of knowledge requirements and several knowledge gaps that utilities are likely to encounter in smart grid adoption. The data shows that utilities vary in the level of knowledge gaps, depending on a mix of organizational and environmental factors. The findings of this research also reveal several learning practices adopted by utilities to overcome the knowledge gaps and how utilities vary in the choices of these learning practices as a result of an interaction between knowledge and organizational factors. This study enriches IT adoption, broader IS research and organizational learning literature in several ways. It also has practical implications for utilities, regulators and other regulated industries and economies.

Appendices

Appendix 1: Interview Protocol for Main Study

Background:

Can you give me a little update on your smart grid deployment? How far you are in terms of deployment? At this stage, how many systems are connected?

Knowledge gaps and learning:

1) Smart Grid Technology

Do you have any knowledge challenges with regard to the installation and evaluation of smart grid technologies? If so, how do you address them?

2) Smart Grid System Integration

Do you have any knowledge challenge in the system integration?

If so, how do you address them? What protocols you are using to tie systems together?

3) Data Management & Analysis

How is data being used at this stage?

Do you have any challenges in data analytics and governance? If so, how do you address them? Is IT group involved in data storage and analytics?

4) Smart Grid Organizational Change

Do you have any knowledge challenges in assimilating new business as result of smart grid adoption? If so, how do you address them?

On the department level, do you have any challenges in the IT and OT convergence? If so, how do you address them? Do you have any organizational routines to encourage the collaboration between different departments?

5) Customer Education and Engagement

How are your customers' responses to the web portals/pricing plans?

Do you have any knowledge challenges in customer education and engagement? If so, how do you address them?

Warp up:

Have you encountered any knowledge challenges that are not being discussed?

Appendix 2: Project Description

This study is part of a bigger project led by Prof. Jason Dedrick in Syracuse University and supported by a grant from the U.S. National Science Foundation (SES-1231192).

The U.S. electric utility industry is facing a number of challenges today, including aging infrastructure, growing customer demand, CO2 emissions, and increased vulnerability to overloads and outages. Utilities are under greater regulatory, societal and consumer pressure to provide a more reliable and efficient power supply and reduce its carbon footprint. In response, utilities are investing in smart grid technologies. Despite various definitions of smart grid, it is characterized by employing a set of sophisticated sensing, processing and communicating digital technologies to enable a more observable, controllable, and automated power supply.

Yet, the adoption of smart grid technologies presents significant knowledge challenges to electric utilities. Smart grid is challenging in terms of its scale and complexity by which it comprises a vast amount of technologies including physical devices, communication platform and hardware and software systems. The dynamics between different layers of technology creates a great deal of complexity and uncertainty and thus entail big knowledge challenges for utilities. Industry reports have already revealed some challenges as utilities move forward in smart grid adoption: 1) the need for IT and data-related knowledge and skills, 2) the need to break down organizational silos to integrate smart grid technologies across functional boundaries in the organization, and 3) the need to interact with customers in new ways (Berst, 2014; Valocchi, Schurr, Juliano, & Nelson, 2014; Witt, 2014). All these challenges are fundamental to utilities, as they require utilities to develop knowledge that many don’t have, and never needed before.

This study aims to advance the understanding of knowledge challenges in smart grid adoption by focusing on the following research questions:

1) What knowledge requirements are critical in smart grid adoption?

2) What knowledge gaps are utilities facing in smart grid adoption?

   How do utilities vary in the level of knowledge gaps?

3) What learning practices utilities take to overcome those knowledge gaps?

   What factors influence the choice of these learning practices?

Appendix 3: Consent for Participation in Interview Research

Knowledge Requirements, Gaps and Learning Practices in Smart Grid Adoption: An Exploratory Study in U.S. Electric Utility Industry

My name is You Zheng, a PhD candidate in School of Information Studies at Syracuse University. Writing this email, I would like to invite you to participate in my research study, which concerns the knowledge challenges in smart grid adoption and how utilities take learning actions to overcome these gaps.

If you agree to participate in my research, I will conduct an interview with you at a time and location of your choice. The interview will involve questions about knowledge requirements, gaps your company encounter in smart grid adoption and how you overcome the gaps. It should last about 35-40 minutes. With your permission, I will audiotape and take notes during the interview. The recording is to accurately record the information you provide, and will be used for transcription purposes only. If you choose not to be audiotaped, I will take notes instead.

All responses will be strictly confidential and will be aggregated with other replies. Therefore no individual or company will be connected to responses since I will remove all identifier information.

__I have read the above and agree to participate in this research

__I agree to having the interview recorded

Appendix 4: Sample Coding of Individual Utility Case

		Level of challenge	Practice	Format and scale	Motivation
Tech and vendor selection	Compare communication technology				
	Interoperability evaluation				
Smart grid deployment & integration	Different system's assumption				
	Order of integration				
	Position change				
	IT & OT integration				
Big data analytics & management	Lack of strategic vision				
	Data cleaning and transformation				
	Lack of advanced modeling				
	Data archiving, partitioning and accessing				
Customer management	Communication barrier				
	Digital customer engagement				

Appendix 5: Table of Cross-Utility Analysis

		IOU1				…	Coop6			
		Level of challenge	Practice	Format & scale	Motivation	…	Level of challenge	Practice	Format & scale	Motivation
Tech and vendor selection	Compare communication technology									
	Interoperability evaluation									
Smart grid deployment & integration	Different system's assumption									
	Order of integration									
	Position change									
	IT & OT integration									
Big data analytics & management	Lack of strategic vision									
	Data cleaning and transformation									
	Lack of advanced modeling									
	Data archiving, partitioning and accessing									
Customer management	Communication barrier									
	Digital customer engagement									

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Curriculum Vitae

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Education

Syracuse University, School of Information Studies

PhD, in Information Science and Technology, August 2010-present

University of Maryland-College Park, College of Information Studies

MS, Information Management, 2010 GPA: 3.857

Wuhan University of Technology, Management School, Wuhan, China

BS, Management Information System, 2007 GPA: 3.63

Publications

Zheng, Y., & Dedrick, J. Learning Strategies in Smart Grid Adop.tion: An Explorative Study in the U.S. Electric Utility Industry. iConference 2015 Proceedings. https://www.ideals.illinois.edu/handle/2142/73677

Zheng, Y.; & Dedrick, J. Learning from Adopters: Critical Factors for Achieving Smart Grid Value. AMCIS Proceeding 2014.

Dedrick, J. & Zheng, Y. Adoption and impact of smart grid technoloiges: results of a survey of U.S. electric utility companies. Paper presented at Industry Studies Association Conference, May 24th-26th, 2016, Minneapolis, MI.

Dedrick, J. & Zheng, Y. Smart Grid Adoption by U.S. Utilities: Organizational Drivers and Impacts. Paper presented at 2014 Grid of the Future Symposium. Houston, TX - October 19 - 21, 2014

Dedrick, J., Venkatesh, M., Stanton, J., Zheng, Y. and Ramnarine-Rieks, A. "Adoption of smart grid technologies by electric utilities: Factors influencing organization innovation in a regulated environment." Electronic Markets 25: 17-29.

Dedrick, J., & Zheng, Y. (2013). Information systems and smart grid: New directions for the IS community. iConference 2013 Proceedings (pp. 897-899).

Zheng, Y., & Tang, J. Literature Review on Technology Adoption: What Can Individual-level and Organizational-level Studies Learn from Each Other? Pre-ECIS Workshops: Building up or Piling Up? The Literature Review in Information Systems research, June 5th, Utrecht, Netherlands.

Dedrick, J. & Zheng, Y. Smart Grid Adoption in a Regulated Industry: Comparative Case Studies in Electric Utilities. Paper presented at Industry Studies Association Conference, May 28th-31st, 2013, Kansas, MO.

Dedrick, J. & Zheng, Y. Smart Grid Adoption: A Strategic Institutional Perspective. Paper presented at Industry Studies Association Annual Conference, May 31st -June 3rd, 2011, Pittsburg, PA.

Teaching Experience

Syracuse University, School of Information

IST 449: HCI (Human-Computer Interaction)

Practicum: Presented two lectures in HCI

IST616, Information Resources: Organization & Access, 2010

Practicum: Presented a lecture on meta-data; monitored online class discussions

IST669, Library & Information Services to Students with Disabilities, 2011

Practicum: Assisted in syllabus development, including text selection and assignment development

IST755, Strategic Management of Information Resources, 2011

Practicum: Presented a lecture on green IT; graded papers

Research Experience

Syracuse University, School of Information Studies

Research Assistant to Prof. Jason Dedrick, 2010 fall-2016 fall

NSF grant writing of smart grid adoption; Literature review; Interview transcribing and analysis; Survey design and statistical analysis; Academic writing

Research Practicum with Prof. Nicolas Jullien, 2012 spring

Design a survey that explores the practices of digital work consumption and the impact of the recent copyright infringement initiative on these practices; also responsible for statistical analysis and interpretation.

Research Practicum with Prof. Ruth Small, 2011 fall

Create, pilot test, and implement a survey that explores the motivation for and information needs of young innovators from age 8 to 15.

Research Practicum with Prof. Ping Zhang, 2010 fall-2011spring

Literature review and summary in social commerce; Developed a theoretical paper with Ping Zhang that examines the potential effectiveness and efficiency of social commerce from the perspective of strategic alignment between business strategies and IT strategies and infrastructures.

Awards

Dean's Award, University of Maryland College of Information Studies, 2009. Selected by Dean for Niels Bohr Library & Archives Information Audit Program.

Service

2013-2014, Doctoral Student Representative, Doctoral Program Committee, School of Information Studies, Syracuse University

2012-2013, Doctoral Student Representative, Faculty Meeting Committee, School of Information Studies, Syracuse University

Conference Review: ECIS (2011); AMCIS (2012-2016) ICIS (2013-2016) iconference (2013-2016) Communications of the Association for Information Systems (2015-2016)