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Advanced Metering Infrastructure Deployment in the United States: The Impact of Polycentric Governance and Contextual Changes

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Abstract

Advanced metering infrastructure provides the first building block in smart grids by empowering customers and utilities with real-time information regarding energy use. It is a key element in the U.S. government's push for electric grid modernization. Using a panel dataset for 50 U.S. states and the District of Columbia over the years 2007–2012, we evaluate the impacts of a polycentric governance system and socioeconomic contexts on states' performance in smart metering deployment. We find that the advanced metering technological change in the United States has been exclusively created by the interdependencies and interactions between different layers of government. High-tech industry is the only socioeconomic factor that has a negative impact on smart meter deployment, whereas other factors, such as pressures from energy consumers and environmental groups, and electric grid conditions, have negligible impacts.

KEY WORDS: advanced metering infrastructure, technology diffusion, polycentric governance, fixed effects models

Introduction

Traditional power generation based on fossil-fuel use has contributed significantly to the historic increase of greenhouse gas concentrations in the atmosphere (IPCC, 2011). As a result, low-carbon energy technology is at the core of current climate discussions, and is often regarded as a key solution to climate change mitigation (Brown & Sovacool, 2011). A number of issues in this debate have attracted much attention. First, various explanations have been put forward to explain the observed regional heterogeneity in clean energy technology diffusion (Beise & Rennings, 2005; Jaffe & Stavins, 1994). Second, public policies often play a critical role in accelerating clean energy technology deployment (Gallagher & Zhang, 2013; Horbach, Rammer, & Rennings, 2012; Lewis, 2007; Norberg-Bohm, 2000; Ockwell, Watson, MacKerron, Pal, & Yamin, 2008). Previous studies on the impacts of policies on clean energy technology have focused on the policy types (Jacob et al., 2006; Taylor, 2008), political process (Jacobsson & Lauber, 2006), and policy stringency (Beise & Rennings, 2005). They have largely failed to capture the complexity of the energy policy schemes that often involve divided authority across multiple types of actors. To address this gap in the literature, this study takes smart-grid technology as an empirical example to understand how different layers of government influence clean technology diffusion.

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The motivations for smart grids have been promoted through potential shortcomings of the traditional electric grid to handle increased renewable energy development, increased peak loads, and energy security concerns. Calls for grid modernization promote the integration of telecommunication and information technologies with the electricity infrastructure to create an electricity network that can cost-effectively integrate different power generation sources, enable consumers to play an active role in managing energy demand, and operate at high levels of power quality and system security (The European Smart Grid Task Force, 2010). As the cornerstone of a smart grid, the advanced metering infrastructure (AMI or commonly known as smart meters) has experienced large-scale deployment worldwide (Leeds, 2009). AMI meters measure and record energy usage at hourly or more frequent intervals and provide usage data to consumers and energy companies (Federal Energy Regulatory Commission—FERC, 2012). Deployment of AMI meters can bring many benefits, including cost reduction; improved billing accuracy and outage management; and the enabling of dynamic pricing, demand response, and distributed renewable generation (Electric Power Research Institute—EPRI, 2007; Leeds, 2009). Advanced metering and demand response may have mixed impacts on energy saving and carbon emissions. A study by the Brattle Group estimated the potential peak load reduction from a national implementation of AMI and dynamic pricing in the United States to be as much as 11.5% (Hledik, 2009). However, for regions with a lower proportion of combined-cycle capacity and coal-fired power plants, the load shift to coal-fired power plants caused by AMI and dynamic pricing can be as high as 80%, leading to higher carbon emissions (Pacific Northwest National Laboratory—PNNL, 2010).

An estimated net investment between $338 and $476 billion is required to create a fully functioning smart grid in the United States (EPRI, 2011). Significant public funding and policy efforts have been directed toward electric grid modernization. AMI penetration rate in the United States increased from 1.7% in 2007 to 28.2% in 2012, with a total number of 43 million AMI meters installed nationwide (Energy Information Administration—EIA, 2013). However, AMI deployment pattern varies greatly across regions. In 2012, the AMI penetration rates were below 10% in 20 states, but were above 40% in another twelve states and the District of Columbia (D.C.).

The goal of this study is to use panel data of the 50 U.S. states and D.C. from 2007 to 2012 to identify factors that cause states' different performance in advanced metering deployment. The transition to smart grids introduces new regulatory schemes that often transcend jurisdictional boundaries and require increased coordination between different levels of government (National Institute of Standards and Technology—NIST, 2010). To better understand the influence of this complex policy scheme on smart meters, we draw on governance, policy implementation, and technology diffusion theories. In doing so, this study makes two important theoretical contributions. First, we conceptualize smart-meter diffusion as an outcome of policy implementation, and quantitatively evaluate policy effectiveness in technology deployment through the lens of polycentric governance. Second, this study is one of the first to consider the complexity and the multi-tiered structure of the energy governance when investigating determinants of clean technology diffusion. The results contribute to the field of energy and climate change polycentric governance and provide valuable policy implications for clean energy technology deployment.

The rest of the article is organized as follows. The next section provides a brief literature review and presents hypotheses, followed by a section discussing data and econometric methodology. The last two sections present results and discussions, and a conclusion.

Theory Development and Hypotheses

Technology diffusion is the last stage in the Schumpeterian trilogy of "invention-innovation-diffusion" (Schumpeter, 1961). The diffusion of new technology requires the product or process to become widely adopted by various parties in society (Schumpeter, 1961). The existence of many barriers may hinder clean energy technology diffusion, such as information asymmetry, externalities, and heterogeneity among adopters (Jaffe & Stavins, 1994). Government interventions often play a critical role in overcoming these barriers and accelerating the adoption and diffusion of clean technologies (Jaffe, Newell, & Stavins, 2005; Jaffe & Stavins, 1994).

Modernization efforts in the energy infrastructure system that spans across multiple and interconnected regulatory scales bring new challenges to policy making (Goldthau, 2014; Pasqualetti & Brown, 2014; Sovacool, 2011). Past studies postulated that polycentric governance provides more efficient overall solutions and facilitates the transition to a clean energy future (Brown & Sovacool, 2011; Goldthau, 2014; Pasqualetti & Brown, 2014). However, there is very limited evidence on how multi-scale governance arrangements work in an empirical setting. Studies in this area mostly focus on the coexistence of policy instruments (Oikonomou, Flamos, & Grafakos, 2010; Oikonomou, Jepma, Becchis, & Russolillo, 2008; Spyridaki & Flamos, 2014), or rely solely on qualitative approaches (i.e., multi-criteria analysis [Konidari & Mavrakis, 2007] and case studies [Smith, 2007; Sovacool, 2011]). Very few studies have quantified the interactions and consequences of government actions at multiple levels (Andersson & Ostrom, 2008). Smart-meter deployment in the United States governed by a polycentric system offers an interesting test case to investigate this question (see Figure 1). To quantitatively measure the policy impact, we break down the smart-meter polycentric governance into a set of policy variables. Only policies adopted before 2012 are considered in the analysis.

The federal government has taken a series of actions to support smart grid and smart meters. Section 1252 of the Energy Policy Act of 2005 (EPACT) directs utility regulators to consider demand response programs and requires utilities to provide each customer a time-based rate schedule and a time-based meter on request ("Energy Policy Act of 2005," 2005). This policy is not mandatory and each state regulatory authority is only required to issue a decision whether it is appropriate to implement Section 1252 in its jurisdiction. The Energy Independence and Security Act (EISA) of 2007 directs the Department of Energy (DOE), the FERC, the states, and utilities to carry out programs to facilitate smart metering deployment ("Energy Independence and Security Act," 2007). EISA also directs the National Institute of Standards and Technology (NIST) and FERC to develop and implement smart grid technological standards. Since these two federal laws have similar legal effect for

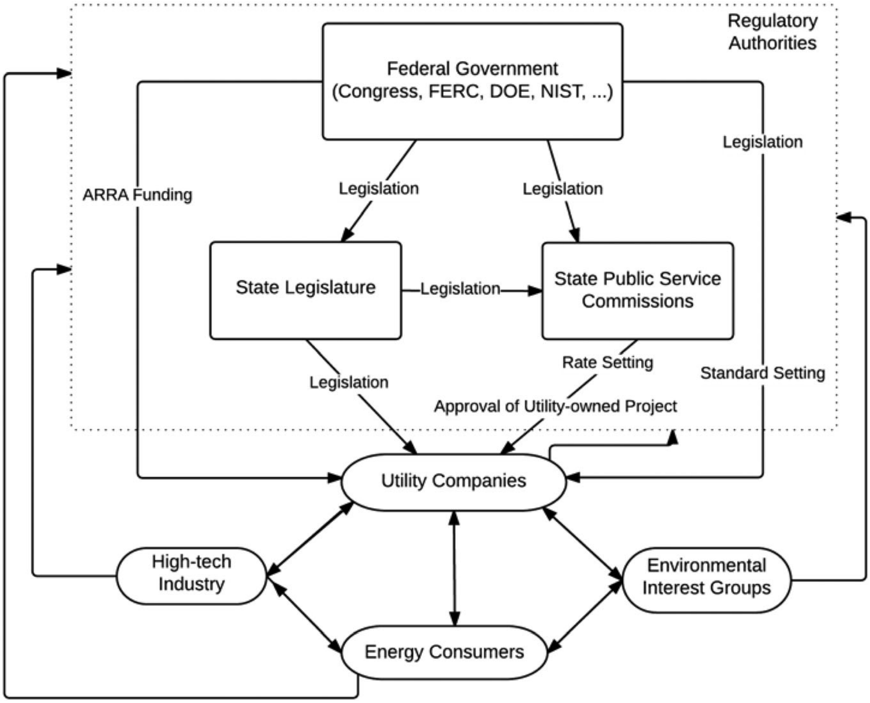

Figure 1. Polycentric Governance of AMI Deployment

every state and their impacts have largely been reflected on state policy activities, which will be discussed in the next section, we do not test them in our model.

The American Recovery and Reinvestment Act (ARRA) of 2009 appropriates \$4.5 billion in matching funds for electricity delivery and energy reliability modernization efforts.[1] Applicants need to pass an initial eligibility review and a comprehensive merit evaluation. Evaluation focuses on the project plan, approach for addressing interoperability and cyber security, plan for data collection and cost benefit analysis, and how projects will enable smart grid functions (DOE, 2009). The final selection of applications also ensures a diverse group of projects is selected. Details about project evaluation criteria are presented in the Supporting Information online Appendix A.

During 2009–2012, \$2.69 billion was awarded to 61 AMI projects in 43 states (Smartgrid.gov, 2013). Over two-thirds of the total 15.5 million AMI meters were installed before October 2012 (FERC, 2012). The amount of stimulus money received by states varies considerably, with projects focusing on different smart-grid technologies. In this study, we use per capita amounts of ARRA funding allocated to AMI projects for each state in a year as an indicator of federal AMI policy activity. We expect that federal ARRA funding be an important factor that explains states' AMI deployment status.

ARRA funding data were obtained from Smartgrid.gov, a website maintained by U.S. DOE. We divided the total project award amount by project time span to get the annual ARRA award amount for each project, assuming that money is spent evenly across the project timeline. We then summed up the annual award amount for all projects in a state to get the annual total ARRA AMI funding for that state.

> **Hypothesis 1**: States receiving more federal funding are likely to have a higher AMI penetration rate.

Second, we consider state energy policy making as an important layer of the smart-meter governance. State governments take actions through legislative branches and public service commissions (PSCs), as smart-meter deployment often involves approval of utility infrastructure investments and provision of time-variant electricity prices, both of which are subject to state jurisdiction. Some states have adopted policies pursuant to federal legislation such as Section 1252 of the EPACT and the EISA. Others have taken their own smart meter policy initiatives. We expect states with more policy activities more effectively deploy smart meters, controlling for federal expenditures and other independent variables.

Following recent research that shows a correlation between policy count and policy stringency (Matisoff, 2008; Schaffrin, Sewerin, & Seubert, 2015; Viscusi & Hamilton, 1999), we use policy counts to measure state policy activities. Two policy types are considered. The first is AMI promotion policy, which directs utilities to consider smart-meter roll out, or requires utilities to file smart-meter deployment plans with PSCs. The second policy addresses smart meter data security and privacy concerns. We only count state legislation, and PSCs' orders and decisions. We exclude government reports, recommendations, or policy analyses, as they do not go through the rule-making processes in the legislative branch or PSC. Policy data were extracted from state PSC and legislature websites, and several policy documents (Delurey & Pietsch, 2008; EIA, 2011; FERC, 2007, 2008, 2009, 2011, 2012, 2013; Pietsch, 2011). A summary of state AMI policies is presented in the Supporting Information online Appendix B.

> **Hypothesis 2**: State legislative and regulatory actions are likely to drive its AMI penetration rate.

The way PSCs regulate cost recovery processes for utility investments represents another important jurisdiction for smart-meter governance. In the United States, smart-meter deployment depends on investment decisions by utility companies. Utility regulators have legal obligations to balance the interests of electricity consumers and utility investors. They set electricity prices to allow utility firms to recover all prudently incurred investment costs, which are also just and reasonable for consumers. This rate-setting process may create uncertainty depending on how regulators interpret legal obligations to balance investor and consumer interests and allow cost recovery for prudent investments. Studies have found that regulatory uncertainty is one of the most important barriers to clean energy technology deployment (Brown & Chandler, 2008; Fuss, Szolgayova, Obersteiner, & Gusti, 2008; Yang et al., 2008). Regulatory uncertainty, and the prospect of regulators allowing predictable cost-recovery for investments can be an important factor for investors to consider when undertaking large costly investments in smart-grid technologies.

> **Hypothesis 3**: States with higher regulatory uncertainty have a lower AMI penetration rate.

We use SNL energy division regulatory research associates (RRA) ranking of PSCs to measure regulatory uncertainty for utility investments (see also Jha, 2014).

Table 1. Coding Method for Regulatory Uncertainty

RRA Ranking	Uncertainty
Above Average 1	1
Above Average 2	2
Above Average 3	3
Average 1	4
Average 2	5
Average 3	6
Below Average 1	7
Below Average 2	8
Below Average 3	9

SNL RRA ranking is a credit-style rating of state PSC and its willingness to return investment costs to investors. We also use this metric to capture how cost recovery rules are interpreted differently by changing utility commissions. RRA ranking includes three principal rating categories: Above Average, Average, and Below Average. Within each category, there are three relative positions indicated by numbers 1, 2, and 3. We coded Above Average 1 as “1” and Below Average 3 as “9” (see Table 1). A lower score indicates a lower regulatory uncertainty for utility companies: PSC is more likely to pass input costs through to consumers, hence the regulatory environment is more stable and favorable to investors, representing more incentives for utilities to invest in new technologies.

A polycentric perspective requires scholars to look beyond the performance of a government unit and consider the relationships among government actors at different levels (Andersson & Ostrom, 2008; Ostrom, 2009; Ostrom, Tiebout, & Warren, 1961). Interactions between state and federal policy making in the United States can lead to problematic outcomes, such as in the cases of state and federal renewable electricity and clean energy standards, and motor-vehicle fuel efficiency standards (Goulder & Stavins, 2011). In some other cases, federal and state policies may have positive interactions. States may adopt policies to complement or augment federal policy (Lanahan & Feldman, 2015). States may also trigger the adoption of more stringent federal policy, or serve as laboratories for experimenting with innovative policy approaches (Goulder & Stavins, 2011).

The environmental federalism literature shows that how each governmental unit acts may enhance or undermine the effectiveness of a policy adopted by the other layers of government with authority over the same area (Shobe & Burtraw, 2012). The federalism challenge in energy regulation has been well documented in a variety of areas such as energy efficiency (Vandenbergh & Rossi, 2013), interstate transmission of renewable energy (Klass & Wilson, 2012), and green building codes (Klass, 2010). The tension between federal and state energy regulation may have adverse impacts on smart grid deployment (Eisen, 2013). In this study, we posit that multilevel policy interactions are important factors that shape AMI implementation. By including interaction terms between state AMI promotion policies, PSC regulatory uncertainty and federal ARRA funding, we test whether the effects of regulatory uncertainty and federal funding differ depending on state efforts in promoting smart meters. We also include an interaction between the two types of state policies to test whether AMI data security and privacy policies could facilitate and reinforce AMI promotion policies.

Hypothesis 4: The multilevel policy interactions are crucial determinants of states' smart meter penetration rates.

It is important to consider the social context and stakeholders in the technology diffusion process, as particular groups and forces could shape technologies to their ends and lead to different outcomes (Cronberg, 1992; Devine-Wright, 2007; Wüstenhagen, Wolsink, & Bürer, 2007). New technology innovation gains faster deployment if social interests and groups are more supportive.

Energy consumers represent a cornerstone in AMI deployment. Their potential rejection of smart meters could pose a significant threat to a successful rollout (Alabdulkarim, Lukszo, & Fens, 2012). While data on public perception of smart meters are currently not available, we use income level as a proxy to measure consumers' attitude. Studies have demonstrated that people's attitudes toward clean energy technology vary across income groups. Environmental concern is often considered as a "luxury" (Hökby & Söderqvist, 2003). Wealthier people are more likely to place a higher value on environmental protection (Del Río González, 2009; Plassmann & Khanna, 2006), and they have the ability to invest more heavily in clean energy technologies (Batley, Colbourne, Fleming, & Urwin, 2001; Carley, 2009; Roe, Teisl, Levy, & Russell, 2001; Zarnikau, 2003). We expect that states with higher real gross state product (GSP) per capita are more likely to deploy smart meters. GSP data were obtained from U.S. Bureau of Economic Analysis.

Hypothesis 5: A state is more likely to have a higher AMI penetration rate if its consumers have a higher level of income.

Pressure from interest groups may play a role in promoting smart metering deployment. In this study, we consider the impact of environmental groups and high-tech companies. Environmental groups may support the replacement of traditional meters by smart meters, due to the environmental benefits brought by AMI and smart grid. Environmental groups are likely to play a key role in educating the public about the new technology, as well as lobbying and advocating to advance the political and business interests in smart meters. Following a few studies (Daley, 2007; Daley & Garand, 2005; Matisoff & Edwards, 2014; Potoski & Prakash, 2005), we measure environmental interest group pressure using the number of Sierra Club members in one thousand people. Sierra Club is one of the largest environmental nonprofit organizations (NGOs) in the United States. Membership data were obtained directly from the Sierra Club.

The high-tech industry is likely to affect AMI deployment, as the entire smart-meter system consists of measuring, collecting, communicating, and managing energy usage data, and it is highly dependent on computer hardware and software for data processing and analyzing (Henton, Grose, Kishimura, & Harutyunyan, 2011). AMI provides huge potential for information, telecommunication, and other high-tech companies to expand their activities to include products and services related to smart-grid operations (Henton et al., 2011). To further their business interests, it is likely that high-tech companies support smart-meter deployment through donation and lobbying efforts, such as in the case of German solar cell industry (Jacobsson & Lauber, 2006). We posit that states with a stronger and more vibrant high-tech sector are more supportive toward smart-meter and smart-grid deployment. We use the number of high-tech jobs in one thousand people as an indicator for pressure from the high-tech sector. We following Hecker's definition of the high-tech sector and obtained employment data from the U.S. Bureau of Labor Statistics (Hecker, 2005).

> **Hypothesis 6**: A state is more likely to have a higher AMI penetration rate if it receives more pressure from environmental interest groups and high-tech companies.

Technological regimes also face "selection pressures" that emanate from the technological system itself (Smith, Stirling, & Berkhout, 2005). Grid modernization efforts may be affected by the levels of distributed renewable energy and energy efficiency, as states tend to invest in smart grids and smart meters to meet the challenges of integrating increasing amounts of intermittent renewables, and to advance energy efficiency through consumer engagement in demand response programs (PNNL, 2011).

In this article, we use energy intensity and per capita distributed renewable energy consumption as two indicators for pressures from the electric grid system. Energy intensity is defined as total energy consumed per dollar of GSP in a state. We divided the total consumption of distributed solar photovoltaics, solar thermal, and wind by state population to obtain the per capita distributed renewable consumption. We obtained energy intensity, solar, and wind energy consumption data from the U.S. EIA. Population data were obtained from the U.S. Census Bureau. Including these two variables in our analysis presents a potential endogeneity problem, as smart-meter technology and policy development may affect renewable energy and energy efficiency. One approach that is commonly employed to avoid the simultaneity bias is to replace the suspected endogenous variable with its lagged values (see Bania, Gray, & Stone, 2007; Edwards, 1996). In our model, we lag both variables by one year to isolate this casual arrow.

> **Hypothesis 7**: A higher level of energy intensity or distributed renewable energy in the electric grid in the previous year is likely to drive AMI penetration rate in the following year.

In our analysis, we also control for two variables that may influence the diffusion of smart meters: electricity price and time trend. We use year dummy variables to represent secular technology change patterns.

Data and Methodology

Data Sources and Description

We analyze a panel dataset of American states' AMI deployment between 2007 and 2012, with a total number of 305 observations. Table 2 provides the list of variables, their operationalization, and data sources. Descriptive statistics are presented in Table 3. We use 2007 as the starting year for the analysis because it was the first year EIA began tracking the number of smart meters in the United States. Sixteen out of the 51 jurisdictions had no smart meters installed at that time, and the average AMI penetration rate in the country was 1.3%. Moreover, all state smart metering policies were adopted after the year 2007, except one by Texas in 2005 and one by Illinois in 2006. At the time of this study, the most recent release of smart meter

Table 2. Variables, Operationalization, and Data Sources

Variable	Operationalization	Data Sources
AMI penetration rate	Penetration rate of AMI meters (%)	U.S. Energy Information Administration
Federal ARRA funding	Per capita ARRA funding allocated to AMI projects (2013 dollars)	Smartgrid.gov website
Number of state AMI promotion policies	The total number of effective policies that promote or mandate smart metering deployment	Primary data sources
Number of state AMI data security and privacy policies	The total number of effective policies that regulate smart meter data security and privacy concerns	Primary data sources
PSC regulatory uncertainty	SNL energy division regulatory research associates (RRA) ranking of PSCs	SNL Financial
GSP per capita	Real gross state product per capita (chained 2005 million dollars)	U.S. Bureau of Economic Analysis
Sierra memberships	Number of Sierra Club members in a thousand people	Sierra Club
High-tech jobs	The number of high-tech jobs in a thousand people	U.S. Bureau of Economic Analysis
Energy intensity	Total energy consumption per dollar of GSP (ten thousand BTU per dollar of GSP)	U.S. Energy Information Administration
Distributed renewable energy consumption per capita	Per capita distributed renewable energy consumption (hundred thousand BTU per capita)	U.S. Energy Information Administration, U.S. Census Bureau
Electricity price	Average retail electricity price (cents/kWh)	U.S. Energy Information Administration

Table 3. Descriptive Statistics of the Panel Data

Variable	Obs	Mean	Std. Dev.	Min	Max
AMI penetration rate	305	10.33	17.26	0	95.37
Federal ARRA funding	305	1.76	4.57	0	27.53
Number of state AMI promotion policies	305	0.49	0.84	0	4
Number of state AMI data security and privacy policies	305	0.072	0.35	0	3
PSC regulatory uncertainty	305	4.96	1.53	1	9
GSP per capita	305	4.36	1.67	2.80	15.13
Sierra memberships	305	2.01	1.11	0.43	6.44
High-tech jobs	305	18.80	9.89	7.64	80.12
Energy intensity [t−1]	305	0.97	0.55	0.06	2.78
Distributed renewable energy consumption per capita [t−1]	305	1.94	4.21	0	33.43
Electricity price	305	9.98	3.80	5.06	34.04

data was for the year 2012, when a majority of the ARRA AMI projects have been completed (Smartgrid.gov, 2013).

The dependent variable is AMI penetration rate. We obtained utilities' AMI meter counts and total electric meter counts data from File 8 and File 2 of Form EIA-861 (Annual Electric Power Industry Report) (EIA, 2013). We summed up the utility level AMI meter and electric meter counts, respectively, for all utilities in a state to obtain the cumulative numbers for that state in a given year. We then divided total AMI meter counts by total electric meter counts to obtain the AMI penetration rate.

File 8 of Form EIA-861 includes information for two types of meters: automated meter reading and AMI. This study only focuses on AMI, which are meters that have "built-in two-way communication capable of recording and transmitting

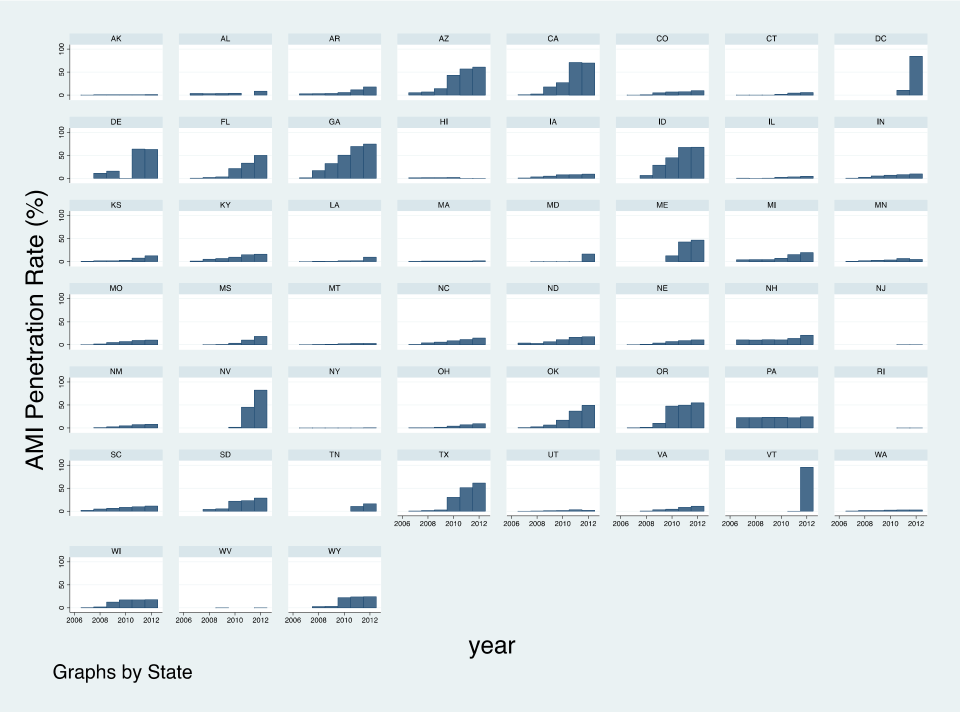

Figure 2. AMI Penetration Rate by State between 2007 and 2012

instantaneous data (measured and recorded usage data at minimum, in hourly intervals, provided to both consumers and energy companies at least once daily)" (EIA, 2010). While AMI can be further categorized into meters based on radio frequency (RF) technology, meters based on power line carrier (PLC) technology, and other types that use a hybrid design, File 8 of Form EIA-861 does not distinguish between technology differences of AMI: it only collects data on total AMI meter counts.

Penetration rate is a continuous and non-negative variable. As shown in Table 3, the average AMI penetration rate is 10.3%, with a standard deviation of 17.3%. Thirty-eight out of the 305 observations have zero AMI penetration rate, accounting for 12.5% of the total. Figure 2 presents AMI penetration rate for each state between the year 2007 and 2012. Large advanced metering deployments clustered in Western states, such as California, Idaho, Oregon, Nevada, and Arizona. Some Southern states, such as Florida and Georgia, also have a penetration rate around or over 50% in 2012.

Methodology

Based on our hypotheses, we formulate a regression model to analyze the conditions under which smart meters are likely to deploy. The model is written as follows:

$$Y_{it} = \beta_0 + \beta_1 X_{1,it} + \ldots \beta_k X_{k,it} + \alpha_i + u_{it} \tag{1}$$

where Y_{it} is AMI penetration rate for state i in year t; $X_{1,it} \ldots X_{k,\ it}$ are independent variables, including a set of indicators for regulatory governance, social acceptance/

stakeholder support, and technological pressure. Our empirical analysis tests two models: model (1) does not include policy interactions, while model (2) does. $\beta_1 \ldots \beta_k$ are coefficients for independent variables to be estimated. α_i is the intercept for each state, which represents all factors that affect AMI penetration rate that do not change over time, such as geographical features; u_{it} is the error term.

For each state i, we average this equation over time:

$$\bar{Y}_i = \beta_0 + \beta_1 \bar{X}_{1,i} + \ldots \beta_k \bar{X}_{k,i} + \alpha_i + \bar{u}_i \tag{2}$$

where $\bar{Y}_i$, $\bar{X}_{1,i}$, and $\bar{X}_{k,i}$ are the averages of Y_{it}, $X_{1,it}$, and $X_{k,it}$.

Subtracting (2) from (1), we obtain that

$$Y_{it} - \bar{Y}_i = \beta_1 \left(X_{1,it} - \bar{X}_{1,i}\right) + \ldots \beta_k \left(X_{k,it} - \bar{X}_{k,i}\right) + \left(u_{it} - \bar{u}_i\right) \tag{3}$$

After demeaning the variables using the within transformation, we obtain fixed effects estimators through estimating Equation (3) using standard statistical package Stata. This fixed effects model controls for unobserved and time-invariant heterogeneity across states.

Wooldridge (2011) and Cameron and Trivedi (2009) suggest that clustering and obtaining robust standard errors produces asymptotically valid inference and works well to correct for serial correlation and heteroskedasticity when panel is short with a large cross sections (Cameron & Trivedi, 2009; Wooldridge, 2010, 2011). This article follows this approach, and uses clustered robust standard errors in both models.

Results

Table 4 presents estimated coefficients for the two models. The *F*-test and the Breusch-Pagan test show that both fixed and random effects exist in the data. The Hausman test rejects the null hypothesis that random effects coefficients are the same as those estimated by the fixed effects model. Hence in this case, fixed effects models are appropriate.

In model (1), estimated coefficients for federal financial incentives and PSC regulatory uncertainty are both significant, with signs being positive and negative, respectively. After including interaction terms in model (2), estimated coefficients for both variables become insignificant, with signs unchanged. The interaction of these two variables with state AMI promotion policies is significant in model (2). Results support hypothesis 1 and 2 and demonstrate that more federal ARRA funding and reduced PSC regulatory uncertainty could promote smart meter deployment; however, these are indirect impacts and are dependent on state AMI promotion policies.

Estimated coefficients for the two types of state AMI policies are insignificant in both models. Estimated coefficients for AMI promotion policy are positive, while AMI data and privacy policy is positive in model (1) and negative in model (2). The interaction between the two policies in model (2) is positive and significant. The results suggest the two types of state policies drive smart-meter deployment through their positive interaction, and through interacting with other government actions. This supports hypothesis 3 and hypothesis 4.

Table 4. Estimated Coefficients of the Models2[2]

Variables	(1)	(2)
Federal ARRA funding (a)	0.757***	0.273
	(0.187)	(0.406)
State AMI promotion policy (b1)	0.939	6.723
	(2.209)	(4.383)
State AMI data security and privacy policy (b2)	4.178	−5.997
	(6.184)	(5.359)
PSC regulatory uncertainty (c)	−3.971**	−2.722
	(1.621)	(1.810)
GSP per capita	−11.90	−10.45
	(11.44)	(10.88)
Sierra memberships	−3.578	−4.112
	(6.157)	(5.758)
High-tech jobs	−1.675	−2.282*
	(1.599)	(1.290)
Energy intensity [t−1]	4.970	0.704
	(10.16)	(10.47)
Distributed renewable consumption per capita [t−1]	1.306	1.108
	(1.174)	(1.196)
Electricity price	−2.229*	−2.525**
	(1.115)	(1.160)
ARRA funding × State AMI promotion policy (a × b1)		0.393**
		(0.160)
Uncertainty × State AMI promotion policy (b1 × c)		−2.081**
		(0.921)
State AMI promotion policy × State AMI data security and privacy policy (b1 × b2)		4.868***
		(1.358)
Constant	127.5***	136.0***
	(45.05)	(44.95)
Observations	305	305
R-squared	0.505	0.551
Number of stated	51	51

Robust standard errors in parentheses.
***p < .01, **p < .05, *p < .1.

Estimated coefficients for income and Sierra memberships are all negative and insignificant in both models, which are different from expected. Coefficients for high-tech sector employment are negative in both models, but are insignificant in model (1) and significant in model (2). Therefore, we reject the null of hypothesis 5 and part of hypothesis 6, and conclude that energy consumers and environmental groups do not appear to exert significant influence on smart-meter deployment. High-tech employment has a significant and negative impact on smart-meter deployment after controlling for policy interactions. Model results provide no support for hypothesis 7. Although the signs for energy intensity and distributed renewable energy are all positive and as expected, the estimated coefficients are all statistically insignificant, failing to find conclusive evidence in support of conditions of the electric grid system and their impact on smart meter deployment.

Discussion and Policy Implications

The federal government has not adopted a specific compliance target to ensure smart-metering adoption; instead, financial incentives are provided to reduce the costs of smart meters and encourage utility investments. The results show that a federal matching fund explains much of states' smart-meter deployment status, but this matching funding works in conjunction with other policies. The effect of ARRA funding depends on state AMI promotion policy: federal funding more effectively drives AMI installations in states that have adopted more AMI promotion policies. Literature suggests that federal incentives could stimulate policy activities within and between states (Hofferbert, 1974; Strumpf, 2002; Welch & Thompson, 1980). In the case of AMI policies, it is unlikely that federal ARRA funding encouraged state smart metering policy adoption, because ARRA funding was put together quickly and in response to the financial crisis. While states may have anticipated the future availability of federal funds, our data do not support the idea that the federal funding drove changes in the policy environment.

Our results support earlier studies' findings that regulatory uncertainty inhibits clean energy investment (Fabrizio, 2013; Fuss et al., 2008; Yang et al., 2008). It also confirms PSCs can provide the certainty that is critical to clean energy technology deployment through approval of utility-owned projects and cost-recovery mechanisms (Monast & Adair, 2013). Our results further demonstrate that regulatory risk becomes more relevant when states adopt more policies to direct utilities to consider AMI rollout or require utilities to file AMI deployment plans with PSCs. The number of AMI promotion policies adopted may represent a way for states to articulate their energy policy goals, which can greatly influence PSC approval of innovative energy technology deployment projects (Monast & Adair, 2013). This might also indicate a fear of change in state AMI policy environment. Investors may be left exposed when a state legislature that has adopted AMI promotion policy reverses its decisions.

It is interesting to note that estimated coefficients for the two types of state AMI policies are statistically insignificant in both models. These two policies indirectly affect AMI penetration rate and their impacts are dependent on other government actions. State-level policy activities may represent one part of the policy signals that utilities need to consider when they make decisions for AMI investments. State legislatures and PSCs may be more likely to adopt policies to encourage utility proposals for smart meter demonstration projects or deployment plans when they know that utilities in the state are not actively investing in smart meters, and vice versa. For instance, Alabama decided not to adopt Section 1252 of the EPACT because the Alabama power company already offers time-of-use rates to all available customer classes and is deploying smart meters (Delurey & Pietsch, 2008). Including policy interactions shows the two types of state policy tend to be jointly adopted and mutually supportive. The impact of AMI promotion policy is stronger when states adopt more policies to regulate data and privacy issues.

The model results show that energy consumers and environmental groups do not have a significant impact on smart meter deployment and their estimated coefficients are all negative. The Sierra membership variable may represent the conflictual relationships between utilities and environmental groups in the process of energy infrastructure upgrades—local environmental groups often do not trust the information and intentions of investor-owned utilities (Huijts, Midden, & Meijnders, 2007). It is also possible that local environmental groups and higher income people are more sensitive to the privacy and (real or imagined) health concerns with smart meters; for instance, the San Francisco chapter of Sierra Club has taken a position against smart meter installations due to concerns of increased electromagnetic frequency radiation and potential impact on wildlife. The estimated coefficient for high-tech jobs is negative and significant after controlling for policy interactions, showing that states with a higher concentration of high-tech jobs are less likely to deploy smart meters. People working in high-tech sectors may be less trusting of the data generated by smart meters because of their knowledge and concern with cyber security and privacy issues (Hadley, Lu, & Deborah, 2010).

Conditions of the electric grid system have negligible impacts: neither a higher level of distributed renewable energy consumption nor energy intensity in a state could drive smart-meter deployment. The weak influence of these factors may be because of two reasons. First, the development of renewable energy and energy efficiency in U.S. electric grid system is itself highly influenced by government policies. Without effective policy interventions, it might be difficult for the system to respond to these pressures and stimulate regime changes. Second, in the short term, competition may exist between different clean energy technological regimes: smart meters, renewable energy, and energy efficiency. Resources may be dispersed in different technological regimes, and pressures may act incoherently, which lead to system responses in different directions (Smith et al., 2005).

The three socioeconomic metrics (income, Sierra Club membership, and high-tech employment) represent our best attempts to capture social conflicts around smart-meter deployment. We were unable to find a time and spatially variant metric that would more closely capture public perception toward smart meters or concerns over health, privacy, and environmental impacts. This limitation of our study might be improved by integrating results of public perception surveys on smart meters in the future. It is also likely that differences in ideology, market structure, or other socioeconomic factors could influence smart-meter diffusion. We exclude these variables in our analysis because they are time invariant during the period of study (2007–2012), and hence are captured with the state fixed effect. This is a tradeoff of implementing a two-way fixed effect model that reduces concerns of excluded variable bias or endogeneity issues at the expense of not being able to capture temporally invariant spatial characteristics.

The findings of this article have two policy implications. First, as multiple regulatory authorities and stakeholders are involved in a polycentric governance system, more resources and attention can be devoted to solving a single problem, which may create a regulatory "safety net" and provide a higher probability to solve it (Brown & Sovacool, 2011). In this case, while state legislative and regulatory actions alone are ineffective in driving smart meter installations, federal government and state PSCs could influence the technology diffusion by providing financial incentives and reducing long-term regulatory uncertainty for utilities. Policy making at different levels complements each other and works together to facilitate smart meter diffusion. Second, authority governing AMI deployment is dispersed among government agencies: none of the governance levels are solely responsible for AMI deployment, and not all three levels of government are individually effective in promoting smart meters. The impact of AMI governance at one level is highly dependent on the other levels. State AMI promotion policy leverages federal ARRA spending on AMI, leading to positive interactions. Regulatory uncertainty inhibits smart meter installations, and state AMI promotion policy amplifies this negative effect. State AMI data security and privacy policy does not affect the impacts of federal funding or regulatory uncertainty; however, it positively interacts with state AMI promotion policy. While a mandatory smart meter rollout plan at the national level is not likely to be politically feasible in the United States, successful smart-meter deployment requires understanding of the complex interdependencies between divided authorities in electricity system governance as well as effective coordination between governance levels.

Conclusion

Decarbonization of the energy sector offers a cost-effective way to combat climate change. The energy infrastructure system transcends geographical and jurisdictional boundaries and is often governed by multiple layers of governments, with authorities and responsibilities divided across the regulatory structure. The transition to a low-carbon energy future introduces new regulatory considerations and requires more coordination among government actors. Smart-meter deployment in the United States, with its unique governance system, offers a rich opportunity to evaluate the policy impacts of multiple institutional arrangements on clean technology diffusion. This study estimates two fixed effects models using panel data for the 50 U.S. states and Washington, D.C. from 2007 to 2012. Results suggest that the smart meter diffusion pattern in the United States is mainly created by a polycentric governance system, where the interdependencies and interactions between different layers of government play a critical role. Although none of the policy actions analyzed in this research directly affect smart-meter deployment, their impacts are dependent on interactions with other governance activities: increased federal funding and reduced PSC regulatory uncertainty more effectively drives smart-meter installations when states have adopted more AMI promotion policies; the two types of state AMI policies tend to be jointly adopted and mutually supportive. Socioeconomic factors are surprisingly unimportant. Conditions of the electric grid system and pressures from energy consumers and environmental interest groups do not seem to exert any significant influence.

This study highlights the need to reexamine policy effectiveness in clean energy technology diffusion through the lens of polycentric governance. This is particularly important for countries like the United States, where the federal–state tension has been demonstrated to exist in a variety of energy policy issues (Klass, 2010; Klass & Wilson, 2012). While neither state, federal, nor PSC has authority over AMI deployment, government actions at multiple levels together form policy signals that utilities need to consider when making smart-meter investment decisions. The results reinforce the importance of coordinating and aligning multi-level policy efforts to improve the effectiveness and efficiency of energy and climate change policy instruments (Carley, 2011; Schot & Geels, 2008).

Like the United States, smart grid technology deployment worldwide has largely been government-driven, with different policy instruments adopted to overcome barriers and leverage drivers (Brown & Zhou, 2013). In Europe, a total of 459 smart-grid projects have been launched since 2002 in 28 EU member states, with 49% of the total €3.15 billion investment coming from government funding sources (Covrig et al., 2014). Korea's smart-grid policies are government-led and export-oriented to encourage the government–industry–consumer collaboration for smart-grid technological innovation (Ngar-yin Mah, van der Vleuten, Chi-Man Ip, & Ronald Hills, 2012). The

Chinese government's strategies mainly focus on the supply-side, which drive R&D, technical knowledge, and manpower in eleven state-owned power companies to foster the smart grid industry (Lin, Yang, & Shyua, 2013).

Experience in Korea and the EU supports our findings that regulation of electricity distribution and cost recovery rules are important in smart grid technology deployment in both regulated and liberalized electricity market (Cossent, Gómez, & Frías, 2009; Ngar-yin Mah et al., 2012). Our results are also consistent with case studies in the United States that demonstrate the critical role of state PSCs in implementing innovative energy technologies such as carbon capture and sequestration and offshore wind (Monast & Adair, 2013). Our findings show that state-level AMI data security and privacy policies indirectly affect smart-meter deployment in the United States through their positive interaction with state AMI promotion policies. Cyber security needs special attention and should be considered as an essential dimension of the smart grid policy framework, as has been demonstrated in Europe (Pearson, 2011). Although we do not find significant evidence for consumers' impact on smart metering diffusion, case studies on Hong Kong and Korea have noted that demand-side measures to facilitate consumer engagement should be priorities for policy change in the future (Mah, van der Vleuten, Hills, & Tao, 2012; Ngar-yin Mah et al., 2012).

There are several avenues to expand on this work. First, more detailed case study analysis using interviews or survey results will provide valuable information to help us understand the multilevel regulatory processes and contextualize the findings. The second direction for future research is to examine smart meter adoption decision at different decision-making units, such as utilities and PSCs. It would be particularly interesting to explore how distribution utilities consider smart meter roll out in states with different electricity market restructuring activities, and how the design of wholesale market rules (i.e., auction-based forward capacity markets) affect demand for smart metering technology.

Notes

1 Grant recipients receive federal financial assistance for up to 50% of their project costs.

2 Time trend variables are included in the model. Due to page limit, the coefficients are not presented here. We have also tried a couple of different specifications using aggregated policy counts and policy counts excluding the privacy policies. Results are largely consistent with what we presented here. Details about other model specifications and results are available on request.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Appendix A—Smart Grid Investment Grant (SGIG) Program Selection Criteria

Appendix B—A Summary of State Smart Metering Policies between 2007 and 2012