Using the IAD Framework to Model the Political Economy of Technological Change in a Regulated Industry: The Case of Transactive Energy*

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Abstract

The substantial technological change taking place in the electricity industry differs qualitatively from the past century's technology history – decentralized, decarbonized, and digital – and policy objectives facing regulators have expanded to prioritize decarbonization. But electricity industry and regulators have a pacing problem, with rates of technological change far outstripping the slow pace of institutional change. The institutional challenges of implementing such changes in a rate-of-return regulated industry are formidable because these new technologies are so different in their features, capabilities, and system implications. This paper uses the Ostrom Workshop Institutional Analysis and Development (IAD) framework to conduct a mapping exercise of utility regulation in the presence of a technology shock. The mapping exercise constructs a conceptual "ideal type" stylized model of the 20th century combination of large-scale electro-mechanical technologies with public utility rate-of-return regulation, with the IAD framework as the structure of the model, and then compares that combination with a stylized model representing the DER and digital technologies and their capabilities. The stylized "technology shock" model is based on transactive energy, which connects energy devices to a local energy market, enables them to submit bids based on owner preferences, and automates device settings in response to market prices to enable decentralized coordination of supply and demand.

Keywords: Electricity, Technology, Regulation, Innovation, IAD Framework, Institutions

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1 Introduction

The substantial technological change taking place in the electricity industry differs dramatically from the past century's technology history. In contrast to the large central station generators and analog meters and controls that dominated the 20th century, new electricity technologies are smaller scale and digital. From the combined cycle gas turbine to wind turbines, solar PV, and electric vehicles and batteries to digital sensors and devices for monitoring and automation, as well as consumer devices that create information capabilities around the edge of the electric grid, they have different combinations of fixed costs, variable costs, and pollution and greenhouse gas emissions. When increasingly integrated into existing electric systems, these diverse technologies will bring distinctive capabilities, will behave differently, and will reshape the entire architecture of electric systems.

If we let them. In this industry, one of the most closely-regulated industries in the economy, technology and institutions are co-determined. The vertically-integrated utility business model arose out of the technological history of the late 19th century and was codified into regulatory law in the early 20th century, creating an institutional framework for ensuring the safety, reliability, and affordability of electric service. The utility business model and its accompanying rate-of-return regulatory framework are well-suited to the operational and financial characteristics of the system of generators, poles and wires, transformers, control rooms, and analog meters that are the iconic symbols of the most important engineered system of the century. In this industry technology and regulation are tightly coupled.

Utility executives and regulators generally recognize that these new technologies bring new capabilities, which when combined with the prioritization of the policy objectives of decarbonization and resilience will create more decentralized and decarbonized electric systems. In 2022 the U.S. Department of Energy published a report from a working group of state public utility commissioners, which identified the growing technology-institution mismatch as one of their key themes:

> Next-generation technologies are generating a plethora of new questions that commissions are asking and are being asked to answer, whether these are fundamentally new questions or more complicated versions of questions commissions have always considered. The growing numbers of participants involved in providing electricity – from prosumers and third-party providers

> – and programs and services offered – from microgrids to DER aggregation – introduce new considerations about the utility business model and the amount of interaction with or control over assets utilities need. They raise questions about data access and the timing of investments. Some questions can be contentious and providing answers often requires commissions to dig deeper into the details about the technology in order to be able to provide specific guidance and direction. Questions that may seem similar to basic ones asked in rate cases can take on new meaning when considered in a high DER future. (U.S. Department of Energy, 2022, p. 7)

The institutional challenges of implementing such changes in a rate-of-return regulated industry are formidable because these new technologies are so qualitatively different in their features, capabilities, and system implications. Utility incentives under regulation do not align neatly with shifting their investments to these new, exogenously-developed technologies. Moreover, these distributed energy resource (DER) and digital technologies present consumers with new capabilities and value propositions, new ways to interact with their electricity choices such as automating how their devices behave. As we have experienced throughout other industries in the economy, digital technologies are dramatic transaction cost reducers, which makes markets more possible as a mechanism for coordination where vertical integration used to be the only feasible organizational alternative. These powerful decentralizing forces raise the question of what the regulatory objective should be and how to implement it. Yet both utilities and regulators, being risk averse due to their shared mission of keeping the lights on, are risk averse and approach both technological and institutional change cautiously.

This paper focuses on one high-level aspect of this technology-institution mismatch: the pacing problem. The pacing problem is the inability of legal and regulatory frameworks to keep up with the speed of technological development and disruptive innovation, resulting in outdated or inadequate rules that struggle to effectively govern emerging technologies and their impacts on society (Hagemann, Huddleston Skees and Thierer, 2018). Technological advancements often outpace the ability of lawmakers, regulators, and legal institutions to craft appropriate rules, restrictions, and oversight mechanisms to properly address the new realities and implications created by those innovations. This pacing disconnect can lead to regulatory gaps, legal uncertainties, and governance challenges that may stifle innovation or fail to adequately protect consumers and public interests.

Institutions change more slowly than technologies, leading to situations in which institutions are maladaptive to economic and technological dynamism; Elinor Ostrom referred to such dynamism as changes in the environment (Ostrom, 2005, p. 72). Ostrom's work and others focus on community self-organization of governance institutions, but the context in this paper is one in which the status quo governance institutions are top-down government regulation. The objective of this paper is to use Ostrom's body of work to analyze the status quo regulatory governance and its fitness with both the process of enabling innovation and the environment in which innovation changes the technology landscape.

Thus the research question examined here is: how well do existing regulatory institutions fit with the evolving ecological, economic, and technological environment? How well do they enable innovation to achieve changing policy objectives? Are our existing regulatory institutions well-suited to enabling DER and digitization innovations to emerge and to change the existing architecture and industrial organization of electricity in ways that are compatible with realizing the benefits of new technologies? For the purposes of this paper I treat the policy objectives as exogenous and hold the business model of a vertically-integrated utility constant.

To understand the pacing problem more systematically, this paper uses the Ostrom Workshop Institutional Analysis and Development (IAD) framework to conduct a mapping exercise of utility regulation in the presence of a technology shock. The mapping exercise constructs a conceptual "ideal type" stylized model of the 20th century combination of large-scale electro-mechanical technologies with public utility rate-of-return regulation, with the IAD framework as the structure of the model, and then compares that combination with a stylized model representing the DER and digital technologies and their capabilities. This mapping enables identification of the dimensions of 20th century utility regulation that are a mismatch with realizing the economic and environmental capabilities of the new technologies. One result of this analysis is recommendations for where institutional change should focus to realize those benefits.

The stylized "technology shock" model is based on transactive energy, which uses distributed energy resources (DERs), other digital consumer energy devices (e.g., thermostats), and communication networks to enable real-time coordination and transactions between various participants in an electricity system. Transactive energy uses automation and algorithmic bidding to enable a consumer's thermostat, water heater, electric vehicle, and/or battery to submit bids and offers in a local energy market, and the resulting market-clearing price serves as the engineering control signal sent to each device.

Section 2 provides a historical analysis of the technologies and regulation of the 20th century that will constitute the traditional utility benchmark, elaborates on the challenges that DER and digital technologies create for that model, and presents the case study of transactive energy. Section 3 develops the benchmark setting model using the IAD framework and then maps that model into the transactive energy setting that reflects the technology shock. Section 4 presents (preliminary) analyses of the results, and Section 5 concludes.

2 Electricity Technology and Regulation

The history of technology and regulation in the electricity industry suggests that institutions are technologically contingent.[1] The form of governance is in part a function of the nature of the issue, and in electricity the dominant issue has been the cost structure of large-scale technologies and their implications for consumers. In the late 19th/early 20th century the nature of integrated system electricity technologies interacted with the Progressive Era concern about exploitation of size to lead to government regulation as the form of governance – top down control, with well-educated and well-intentioned elites making decisions on behalf of less knowledgeable and less well-informed citizens. This was the era of system builders in both technology and institutions (Hughes (1993), Langlois (2023)). But once established, those institutions are difficult to change.

From the 1880s through the 1980s, regulation focused on enabling safe, reliable, affordable large-scale commodity electric service. Technological changes and evolving policy objectives since the 1990s have put that regulatory model under tension, as the pacing problem means that institutions change more slowly that the technologies interacting with the regulated industry.

This section provides a historical overview of electricity technologies and regulation, focusing on the digitalization of the past two decades. It concludes by presenting the development of transactive energy as a case study in digitalization-driven technological change.

[1]The summary in this section draws on and expands ideas from Kiesling (2008) and Kiesling (2016), both of which have more extensive discussions of some of the themes developed here.

2.1 The Co-Determination of Technology and Regulation in the 20th Century

The electricity industry's evolution offers a case study in the relationship between technological change and regulation. From its 19th-century origins in experimentation and trial-and-error, the industry's trajectory was shaped by an interplay between the possibilities presented by new technologies and the regulatory framework established to govern it.

Technological experimentation and entrepreneurial endeavors to harness the power of electric current for practical applications marked the dawn of the electricity industry in the late 19th century. The commercialization of electric lighting, epitomized in the United States by inventor Thomas Edison's Pearl Street facility in New York, not only illuminated cities but also laid the groundwork for further electrification.

The industry's development was also shaped fundamentally by the economic characteristics created by the prevailing technology, which in turn gave rise to the regulatory institutions that have governed the industry throughout much of the 20th century. At the heart of the industry's early development was the rivalry between competing technologies: Thomas Edison's direct current (DC) system and George Westinghouse's alternating current (AC) system. DC systems necessitated localized generation and costly distribution networks, while AC systems, championed by Nikola Tesla and Westinghouse, enabled remote, large-scale generation linked by high-voltage transmission lines.

The AC system, with its centralized generation and one-way power flow from large power plants to consumers, gave rise to a specific technological architecture. The technology system architectures that emerged from the "war of the currents" between AC and DC transmission in large part determined the economic and regulatory models that came to characterize the electric utility. AC technology's triumph, buoyed by economies of scale and facilitated by innovations such as transformers, underscored the pivotal role of technological evolution in shaping the industry's structure. This system provided unprecedented economies of scale, with high fixed costs but low marginal costs for additional output once the capital-intensive infrastructure was in place.

The regulatory landscape of the electricity industry during this period was anchored in the paradigm of natural monopoly, although the economic theory of natural monopoly developed after the formation of the first public utility commissions in 1907 (Plaiss, 2016). Where a single vertically-integrated multi-product firm could provide energy commodity, transmission, distribution and retail service at lowest cost, monopoly pricing could be regulated to align with neoclassical welfare maximization in a zero-profit equilibrium.

This technological economic reality formed the basis for the energence of public utility regulation in the early 20th century. In the early years of the 20th century, the electric utility industry was characterized by monopolistic structures and minimal regulation. Such regulation typically took the form of city council franchise licenses to competing firms. As rivalry led to consolidation, electricity was considered a natural monopoly due to high fixed costs and economies of scale and scope, leading to the emergence of vertically integrated utilities dominating local markets. Concerns over monopoly power and inefficiencies spurred the introduction of regulatory frameworks aimed at ensuring fair rates, reliable service, and equitable access. Instead of rivalrous competition driving price below marginal cost and cuasing industry consolidation, geographic monopolies would be granted exclusive service areas as a legal barrier to entry. In exchange for this monopoly privilege, firms would submit to price regulation and profit constraints by public utility commissions (Macey and Richardson, 2024).

The drivers of regulatory policies adopted during this period can be understood using two theories of regulation: public interest theory and public choice theory. The "public interest" theory, prevalent during the Progressive Era in the United States, viewed regulation as a way to protect consumers from the potential abuses of a monopoly. The public interest theory of regulation motivated reforms that created regulatory bodies like the Interstate Commerce Commission in 1887 and state public utility commissions for electricity, natural gas and telecommunications through the 1930s. Preventing wasteful fragmentation of infrastructure networks while ensuring just and reasonable pricing aligned with the public interest goals of these new regulatory institutions. Public utility commissions aimed to ensure fair pricing and reliable service. Regulation established a "rate of return" model, limiting profit margins for utilities in exchange for a guaranteed return on their investments (Kiesling, 2016).

Public choice theory, on the other hand, suggests that regulated industries may seek regulation actively to stabilize profits and reduce investment risks (Stigler, 1971). The natural monopoly model for regulating utilities also aligned with the incentives of the firms themselves, illustrating public choice incentives for regulation. Figures like Samuel Insull at Commonwealth Edison actively pursued regulation as a way to lower capital costs, secure revenue stability, and protect their monopoly positions – benefiting private interests while also serving the public interest. By securing a stable regulatory environment through lobbying efforts, Insull's Commonwealth Edison secured lower capital costs and enhance investor confidence, leading to further consolidation and expansion within the industry (Platt, 1991).

The theoretical underpinnings of regulatory intervention were rooted in both public interest and public choice theories. The former emphasized the imperative of safeguarding consumer welfare and promoting social welfare objectives, while the latter acknowledged the role of industry actors in shaping regulatory outcomes to serve their interests. Samuel Insull's early business strategy of expansion through affordable customer pricing and acquisition of his bankrupt competitors, along with his strategic pursuit of regulation, exemplified the convergence of economic incentives and regulatory dynamics in shaping industry structure and behavior (Neufeld, 2019).

This symbiotic relationship between technological scale economies and the natural monopoly regulatory paradigm has been the dominant model for over a century. Electricity provision progressed through building ever-larger steam and eventually nuclear plants in pursuit of economies of scale. Recognizing this technological trajectory, state and federal regulators continually refined regulations, policies and organizational forms to encourage "iron in the ground" investments that harnessed economies of scale in the public interest.

Throughout this period, the co-determination of technology and regulation in the electricity industry underscored the interplay between innovation and governance institutions. Technological advancements, driven by entrepreneurial initiative and market competition, reshaped the industry's landscape, while regulatory frameworks sought to temper the excesses of monopoly power and ensure widespread access to electric service.

The evolution of energy generation technologies in the 20th century reflects the interplay of technological innovation, market forces, and regulatory landscapes. From the dominance of coal and hydroelectric power to the emergence of nuclear, natural gas, wind, and solar technologies, the trajectory of energy generation in the United States has been shaped by a number of factors.

In the early years of the electricity industry through the middle of the 20th century, coal and hydropower were the dominant generation technologies. These reliable and well-understood technologies were the workhorses of the electric grid, offering reliability and scalability at relatively low costs. Their economies of scale and scope allowed them to meet the soaring demand for electricity fueled by industrialization and electrification.

While nascent technologies such as nuclear and oil-based generation emerged, they struggled to secure significant market positions. The 1960s saw the rise of nuclear power. Touted as a clean and efficient solution, nuclear plants started competing with coal for a share of the energy portfolio. Hydropower, meanwhile, began to face limitations. Finding new dam sites became difficult, and environmental concerns about disrupting ecosystems gained traction.

The 1970s were an era of both technology and policy disruption as concerns over air pollution catalyzed a shift towards nuclear and a brief fluorescence of oil generation. Buoyed by its perceived environmental benefits and government research, nuclear gained market traction and challenged coal's hegemony. However, a series of high-profile accidents like Three Mile Island eroded public confidence, hampering nuclear's long-term growth prospects.

The 1980s marked a period of maturation and decline for nuclear power, as cost and safety concerns tempered its growth. Oil-based generation also faced setbacks due to price fluctuations and geopolitical tensions in the Middle East. Through this period, coal-fired generation owned by vertically-integrated investor-owned utilities and regulated by state public utility commissions remained the dominant combination of electricity technology and regulation.

2.2 Technological Change into the 21st Century

Technological change in energy into the 21st century has been qualitatively different from previous technologies: decentralized and distributed, smaller scale, shorter useful lives, and enabling lower emissions of criteria pollutants and greenhouse gases. Since the 1990s in particular these generation technology innovations have reduced the economies of scale in generation, and these technologies have different portfolios of (both good and bad) characteristics. Overall, technologies like the combined cycle gas turbine, wind generation, solar photovoltaics, and the storage technologies of electric vehicles and batteries have a different portfolio of features compared to traditional large-scale generation technologies.

Another qualitatively different set of new technologies are digital, exogenously developed and originating from internet and other research outside of the electricity industry. Through the process of grid modernization, digital technologies are slowly being applied to the industry and the grid is digitalizing.

These qualitative differences suggest the merit of revisiting the question posed at the beginning of this section of how the nature of the issue affects the form of governance. The decentralizing and transaction cost reducing forces in these technological changes change the nature of the issue, and thus should change the form of governance; hence this exploration of the pacing problem in regulation.

From the 1990s to the present, natural gas, wind, and solar technologies have undergone significant advancements, reshaping the energy landscape. Enhanced natural gas combined cycle technology, coupled with abundant natural gas reserves, has propelled natural gas to the forefront of electricity generation in many regions, displacing coal and contributing to reduced emissions. The advent of the combined cycle gas turbine (CCGT) technology revolutionized the electricity generation industry, enabling the establishment of competitive wholesale power markets and paving the way for a more sustainable energy mix. CCGTs offered significantly higher thermal efficiencies compared to traditional steam turbines, resulting in lower fuel consumption and greenhouse gas emissions per unit of electricity generated (Kehlhofer et al., 2009). This improved efficiency, coupled with the relatively low capital costs and shorter construction times, made CCGTs an economically attractive option for power producers, fostering competition in the deregulating wholesale power markets (Joskow, 2008). Furthermore, the ability of CCGTs to respond rapidly to fluctuations in demand and their relatively low emissions compared to coal-fired plants facilitated the integration of intermittent renewable energy sources, thereby creating flexibility and contributing to the decarbonization of the generation portfolio (Chu and Majumdar, 2012).

The evolution of wind and solar technologies exemplifies the S-curve life cycle model, with both technologies transitioning from infancy to maturity stages in turn over the past decade (Christensen, 2013). Wind turbines, after years of research and development, achieved commercial viability in the late 1990s, propelled by advancements in design and manufacturing as well as federal tax credits. Solar photovoltaics, with their roots in the 1950s, underwent decades of refinement before reaching commercial prominence in the 2010s. Government tax and research incentives and technological breakthroughs accelerated the adoption of solar, driving down costs and expanding deployment.

Focusing more on recent developments in DERs, the adoption of residential rooftop solar photovoltaic (PV) systems has grown considerably in the United States over the past decade. States like California, Texas, Arizona, and Florida have been at the forefront of this solar revolution, driven by a combination of favorable climatic conditions, declining costs of solar technology, and supportive state policies. According to a report by the Solar Energy Industries Association, the residential solar market in the U.S. grew at an annual rate of 11 percent between 2010 and 2020, with over 2.7 million residential solar installations nationwide as of 2022 (Solar Energy Industries Association, 2023).

Another growing set of DER technologies is the storage-focused set of electric vehicles and battery storage. The mid-2010s marked a shift in the adoption of electric vehicles (EVs) and battery storage technologies in the United States. As concerns over greenhouse gas emissions and the need for sustainable energy solutions grew, the demand for EVs and energy storage systems grew, catalyzed by federal and state government tax credits. According to data from the International Energy Agency, the sales of EVs in the US increased from around 115,000 units in 2014 to over 755,000 units in 2022 (International Energy Agency, 2023). This growth was fueled by technological advancements in battery technology, which led to improved range and affordability of EVs, as well as supportive policies and incentives implemented by various state and federal governments.

The evolution of energy technologies in the 20th and early 21st centuries reflects a complex interplay of technological innovation, market dynamics, and regulatory influences. From the dominance of traditional fossil fuels to the rise of renewables and the prospects for battery storage, the energy landscape has undergone profound transformation, setting the stage for a more sustainable and resilient future.

2.3 Challenges of Digital and DER Innovation to 20th Century Regulation

Throughout the mid-20th century, state public utility regulation evolved in response to changing economic and technological dynamics, but its foundations in natural monopoly theory and rate-of-return regulation remained unchanged. The electrification of rural areas, the growth of interstate electricity transmission networks, and advancements in generation technologies posed new challenges for regulators. The mid-20th century saw growing dissatisfaction with the monopoly model (Hirsh, 1999). Concerns mounted about rising costs, slow technological advancements, and limited consumer choice. Regulators grappled with issues such as pricing for long-distance transmission, balancing supply and demand, and accommodating emerging technologies like nuclear power. The 1970s oil crisis further exposed vulnerabilities in the system, highlighting the need for diversification and energy security.

However, as the century progressed, the landscape of public utility regulation began to shift. Technological advancements, such as the development of more efficient power generation methods (like the CCGT) and the growth of the telecommunications industry, challenged the static, neoclassical notion of natural monopolies. Concerns over the inefficiencies, nuclear plant construction cost overruns, and potential abuse of monopolistic power by utilities also prompted calls for deregulation and increased competition.

The seeds of deregulation were sown with the passage of the Public Utility Regulatory Policies Act (PURPA) in 1978 (Hirsh, 1999). PURPA encouraged independent power producers and cogeneration facilities, introducing competition in electricity generation. The seeds germinated further in the 1980s and 1990s with federal legislation promoting wholesale competition in electricity markets.

The 1990s witnessed a wave of restructuring initiatives aimed at introducing competition into previously monopolized markets. This period saw the unbundling of generation from the transmission and distribution functions of the vertically-integrated utility, allowing for competitive wholesale power markets with greater participation by independent power producers and modest liberalization for competitive retail suppliers. States experimented with various models of deregulation, with some opting for retail competition and others retaining regulated monopolies for all segments of the industry except for generation.

However, the implementation of deregulation was not without challenges. Concerns emerged regarding market manipulation, price volatility, and the adequacy of regulatory oversight. The California electricity crisis of 2000-2001 serves as a cautionary tale, highlighting the risks of market manipulation and inadequate regulatory safeguards (Joskow (2008), Wolak (2005)).

In recent years, the trajectory of state public utility regulation has involved some states reevaluating their deregulatory initiatives and reintroducing elements of regulation to address the impetus for decarbonization and to ensure system reliability. This ongoing evolution underscores the complex and iterative nature of utility regulation in the United States. Today 13 states and the District of Columbia have restructured regulation to allow competitive wholesale power markets and retail competition, but they have retained incumbent default service for residential customers and have thus retained a considerable entry barrier into that market (Kiesling, 2014). Two states (California and Michigan) have hybrid restructured systems with wholesale power market participation and strict limits on the extent and nature of retail competition. One state, Texas, has a fully restructured regulatory system with competitive wholesale and retail markets, restricting the regulated utility footprint to the transmission and distribution wires network.[2]

New regulatory challenges have emerged in the 21st century, including the integration of distributed and renewable energy sources, the need for grid modernization, and the increasing importance of energy efficiency and conservation. State regulators have been tasked with adapting their regulatory frameworks to address these evolving issues, trying to strike a balance between promoting innovation and ensuring the reliability and affordability of electric service. Smart grid, grid modernization, and digitalization are all names for utility industry and regulatory efforts over the past 15 years to address these challenges.

The relevant digitalization technologies include smart grid technologies, automated control systems, and bidirectional communications. Digital tools like smart meters and advanced sensors provide real-time data on energy usage and grid conditions. These data can be used to optimize grid operations, predict and prevent outages, and integrate DERs more effectively. Digitalization allows for automated grid management systems that can adjust power flows, optimize energy use, and respond to changes in demand and supply in real-time. Two-way communication between utilities, DER owners, and consumers becomes crucial. This capability enables utilities to send price signals, manage DER participation, and empower consumers to make informed choices about their energy use. It also enables consumers to automate their choices and participate in transactive systems. Figure 1 represents the categories of these technologies and their roles in the distribution system (utility technologies) or as a customer-owned or third-party-owned resource.

These digital technologies complement DER by increasing flexibility and resilience. DERs offer greater flexibility in grid operations by providing additional capacity for load balancing, peak shaving, and voltage regulation.[3] For instance, battery storage systems can store excess electricity from solar panels and release it during periods of

[2]The effects of Winter Storm Uri in Texas in 2021 have led to legislative actions to remove some features of the Texas model; for more discussion see Littlechild and Kiesling (2021).

[3]The intermittent nature of solar PV production means that although it can be a flexible resource, it does still require other generation sources for reliability purposes. As storage technologies improve that requirement may change in the future.

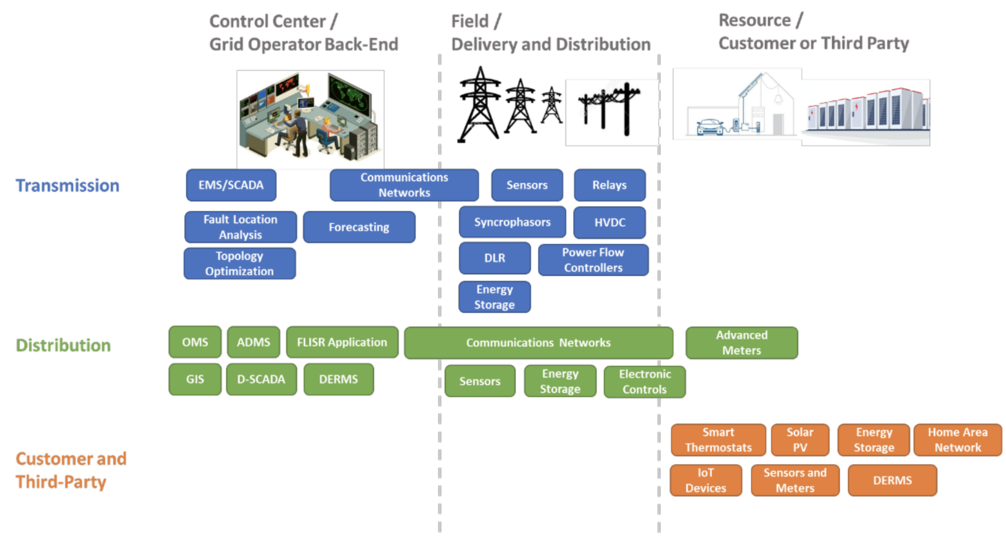
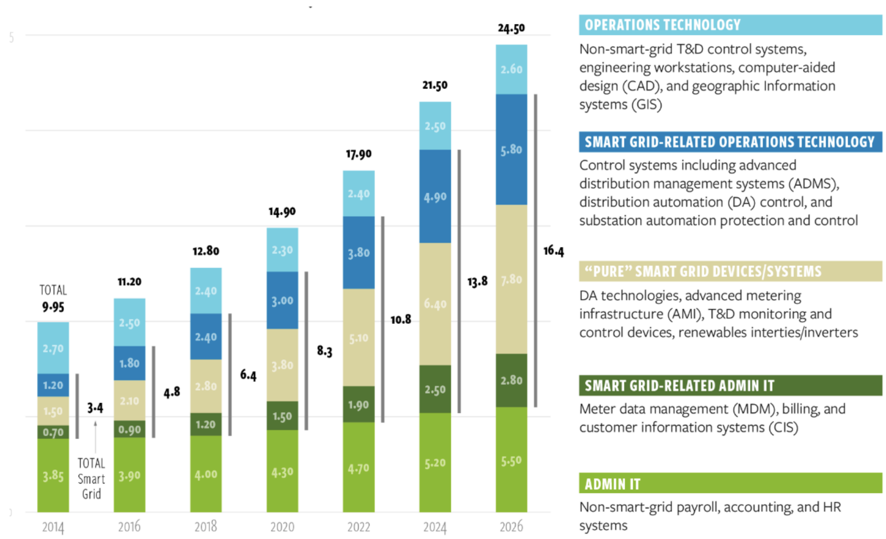


Figure 1: Smart Grid Technologies Across Sectors
Source: (DOE Office of Electricity, 2022, p. 37)

high demand, helping to stabilize the grid and reduce the need for expensive peaking plants. Digitalization enables real-time monitoring, control, and optimization of DERs, allowing grid operators to manage resources more efficiently and respond rapidly to changes in supply and demand. Distributed generation and storage assets enhance grid resilience by reducing dependence on centralized infrastructure that may be vulnerable to natural disasters, cyberattacks, or other disruptions. DERs can continue to operate independently or in microgrids during grid outages, providing critical services such as emergency backup power to hospitals, emergency shelters, and essential services. Digitalization enables autonomous operation and coordination of DERs, improving resilience and reliability at the distribution level.

Utilities have been inveting in these technologies and are forecast to increase investment. Figure 2 presents data on utility investments in smart grid and grid modernization technologies (actual 2014-2020, forecast 2022-2026).

As DER interconnection and digitalization occur, they change the traditional architecture and operation of the electric grid fundamentally in several ways (Taft, 2019). Traditional grids were designed for one-way power flows from centralized generation sources to end-users. With DERs like rooftop solar, energy storage, and small-scale generators, power can now flow in multiple directions, creating more complex grid management challenges. DERs introduce bidirectional power flows, allowing energy to



Source: Newton Evans. Data represent total electricity sector, as extrapolated from market studies and direct surveys representing 10%–30% of U.S. or North American markets, in terms of customers services, number of substations, or revenues.

Figure 2: Smart Grid Technology Investments, 2014-2020 (actual), 2022-2026 (forecast)
Source: (DOE Office of Electricity, 2022, p. 38)

flow not only from centralized generators to consumers but also from consumers back to the grid. Bidirectional flow requires grid architectures that can manage and control power flows in multiple directions, including technologies such as smart inverters and advanced grid management systems.

Grid architecture also becomes more decentralized. Instead of relying solely on large, centralized power plants, DERs enable generation to be dispersed and located closer to consumption points, reducing transmission losses and potentially increasing resilience. Traditional grids rely on large centralized power plants to generate electricity, which is then transmitted over long distances to consumers. DERs, such as rooftop solar panels, wind turbines, and battery storage systems, enable electricity generation at or near the point of consumption. Decentralization reduces reliance on large, centralized generation and transmission infrastructure, making the grid more resilient to disruptions and reducing energy losses during transmission.

Digitalized grid architecture will also involve more automation. Advanced metering infrastructure (AMI), smart sensors, and communication networks enable real-time monitoring, control, and automation of grid operations, facilitating the integration and optimization of DERs. Instead of centralized control systems, the digitalized grid incorporates distributed intelligence and decision-making at various points, such as smart inverters, energy management systems, and virtual power plants. Advanced analytics and machine learning algorithms enable grid operators to make data-driven decisions in real time, improving grid efficiency, reliability, and performance. Advanced grid management systems use data analytics, automation, and control algorithms to optimize grid performance, integrate DERs, and enhance grid resilience. Artificial intelligence (AI) and distributed control algorithms enable autonomous operation and coordination of grid assets, maximizing efficiency and reliability.

These changes are sufficiently large to be disruptive for existing business models and regulatory institutions. Regulatory frameworks in the electricity sector have historically been designed around centralized generation, transmission, and distribution systems. The rise of DERs and the digitalization of electricity systems present several challenges for state public utility regulation. These changes require state regulators to become more flexible and adaptable.

DERs are decentralized and interconnected with the traditional centralized grid. This integration requires new technical standards, interconnection rules, and grid management practices to ensure reliability, safety, and efficient operation of the grid. Grid upgrades are crucial to accommodate DERs and optimize the benefits of digitalization. Regulators might need to establish mechanisms to facilitate these digital investments, which are different types of assets from traditional assets, with different useful lives and depreciation treatment for accounting purposes. The proliferation of digital devices, sensors, and communication networks generates massive amounts of data that need to be managed securely, raising cybersecurity concerns.

Traditional utility business models and rate structures were designed for centralized generation and one-way power flows. With DERs and two-way power flows, regulators need to reevaluate rate designs, cost allocation methodologies, and incentive structures to fairly compensate utilities, DER owners, and customers for their respective roles and contributions. Existing regulations may not be suitable for the new energy landscape, and for removing barriers to innovation and DER adoption while ensuring grid stability and consumer protection.

Traditional regulatory frameworks focus on ensuring reliability and affordability, which can stifle innovation. Regulators need to update regulations to create a more conducive environment for innovation in DER technologies, grid management systems, and business models. This may involve implementing regulatory mechanisms such as performance-based regulation or outcome-based incentives that reward utilities for adopting innovative technologies and practices (Newton Lowry and Woolf, 2016). Regulations should encourage the development and deployment of new technologies that improve efficiency, sustainability, and consumer choice in the electricity market.

Finally, DERs and digitalization enable new market participants, such as aggregators, energy service companies, and virtual power plants. Regulators need to create frameworks that promote competition, innovation, and consumer choice while ensuring fair and non-discriminatory access to the grid and markets.

2.4 Case Study: Transactive Energy

An application of digitalization, transactive energy (TE), presents a case study in technological change that is the motivation for the IAD framework analysis in Section 3. Transactive energy applies principles of market economics and decentralized coordination to the management of modern power grids, enabling a more flexible and dynamic way to match supply and demand compared to traditional centralized control methods. The GridWise Architecture Council defines transactive energy as "... a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter." (GridWise Architecture Council, 2019)

As an example, consider a neighborhood where each household has a smart, digital thermostat connected to a shared digital communications network. The residents are able to program their thermostats with preferences that reflect their willingness to pay for heating or cooling at different times of day or under varying circumstances; typically this programming is implemented by the resident choosing a user profile that best matches their preferences. Through the transactive energy system, these smart thermostats autonomously submit bids into the local energy market at frequent intervals, based on the household's programmed preferences.

When a particular thermostat's bid price is lower than the current market clearing price, this signals that the household is willing to curtail energy consumption for heating or cooling in order to save money at that time, and the thermostat will adjust the household's temperature settings automatically to reduce energy use. Conversely, if a thermostat's bid price is higher than the market clearing price, this outcome communicates that the household places a premium on maintaining thermal comfort and is willing to pay more for heating or cooling during that period. The thermostat will then keep temperature settings within the preferred range, allowing higher energy consumption. By responding to real-time market prices, the networked thermostats optimize energy usage across the neighborhood based on aggregated household preferences.

Several key technologies enable the automation, market participation, and control that are essential for transactive energy systems. Digital meters provide high-resolution data on energy consumption and production at the consumer level. This granular data is required for automated bidding into transactive energy markets based on real-time conditions. Automated control and optimization algorithms automate the process of bidding into transactive energy markets based on inputs like customer preferences, grid conditions, weather data, and market prices, and they optimize the dispatch of distributed energy resources (DERs) based on market clearing prices. Internet of Things (IoT) devices and home/building automation enable sensors, thermostats, appliances, lighting, energy storage, electric vehicle chargers, and other "smart" devices in homes and buildings to allow automated control and coordination for demand response based on transactive signals. DERs like rooftop solar, battery storage, flexible loads (HVAC, water heaters), and vehicle-to-grid integration enable localized supply and demand management based on transactive pricing. Reliable, low-latency communication networks integrating grid operations with DER, smart devices, and market platforms are critical for real-time coordination and control in transactive systems. Cloud-based platforms allow efficient aggregation and processing of large data streams from smart meters and devices needed for transactive optimization algorithms. Edge computing devices provide localized intelligence. Finally (and most importantly), given the distributed and automated nature of transactive systems, robust cybersecurity measures like encryption, access control, and intrusion detection are essential.

These technologies enable key TE capabilities like automated demand response, DER integration and coordination, real-time pricing and market operation, all while allowing active participation from consumers, utilities, aggregators, and system operators.

The first transactive energy project, the GridWise Olympic Peninsula Testbed Demonstration Project, was a field experiment in 2006-2007 that demonstrated the ability to use market signals to coordinate a system of thermostats autonomously ((Hammerstrom et al., 2008), (Chassin and Kiesling, 2008)). The TESS (Transactive Energy Service System) platform developed by SLAC National Laboratory and the Post Road Foundation is a current TE research project, with funding support from the

U.S. Department of Energy's Connected Communities program.

TESS employs a synthesis of economic market design principles and control systems, with a strong emphasis on enabling more expressive, preference-based bidding from both the demand-side and DER owner/operator perspectives. At the heart of the TESS project is the goal of creating a decentralized, market-based coordination mechanism that can manage the growing complexity of modern electricity grids. As renewable energy sources and DERs like rooftop solar, energy storage, and electric vehicles become more widespread, traditional top-down control approaches are struggling to manage and balance supply and demand. TESS aims to address this challenge by empowering end-users to participate actively in the optimization of the system. Figure 3 presents a schematic diagram of the design of the TESS platform's physical and data flows.

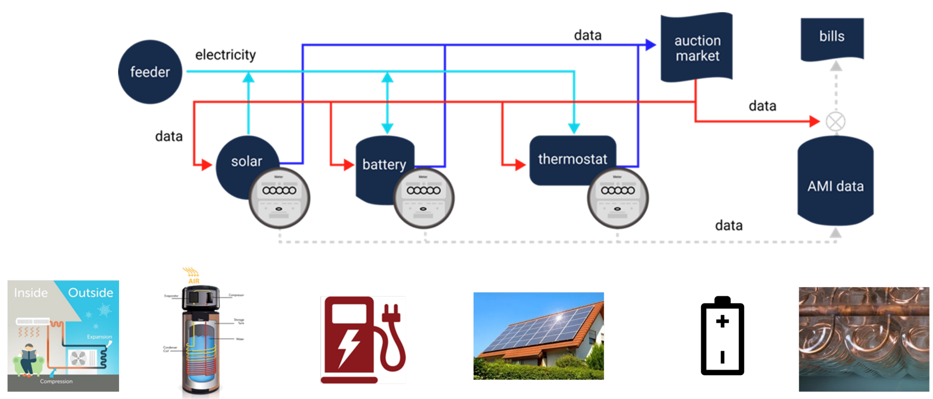


Figure 3: TESS Transactive Energy Platform

The economic foundations of the TESS approach draw from multiple strands of economic theory. A key tenet is the recognition that individuals have unique and private characteristics, preferences, and subjective valuations over the goods and services they consume. In the context of transactive energy, this premise means that consumption bids should reflect the consumer's marginal willingness to pay for energy services, rather than just a cost-minimization objective. Producers (i.e., DER owners) face opportunity costs that may be unknown, heterogeneous, and even subjective in nature. Subjectivism in economic theory acknowledges that personal preferences and opportunity costs are inherently private knowledge, not fully accessible to others.

Subjective value poses a fundamental coordination challenge – if the preferences and opportunity costs of consumers and producers are not fully known, how can an efficient allocation of resources be achieved? The answer lies in the price system, a decentralized mechanism for gathering and learning about this dispersed, subjective knowledge.

Within a well-designed institutional framework, the market process of mutual learning and decision-making can enable prices to emerge that coordinate the actions and plans of all system participants. These prices incorporate both supply and demand information, reflecting the collective understanding of the value and opportunity costs involved (Kiesling, 2015).

The TESS platform is built on a synthesis of advanced economic market design principles and sophisticated control systems. It employs a double-auction mechanism that allows both consumers and DER owners/operators to submit bids and offers simultaneously. In a DA, buyers submit bid schedules and sellers submit offer schedules of price and quantity. The centralized auction platform then performs a clearinghouse function, arranging all the buyers' schedules into a market demand curve and all the sellers' schedules into a market supply curve. This enables a market-clearing price to emerge that reflects the collective understanding of the value and opportunity costs involved.

These economic principles and insights form the foundation of the TESS approach to market design and device bidding function specification. The key objective is to enable the implementation of bidding functions that allow users to communicate their preferences for dispatch and their availability for flexible dispatch more directly, rather than relying solely on cost-based or technical heuristic approaches.

By enabling users to express their preferences more directly through the bidding functions, TESS seeks to create a closer alignment between the cleared market outcomes and the users' actual values and constraints. This alignment, in turn, reduces the incentive for users to deviate from the operator's dispatch instructions, as the outcomes should better reflect their personal priorities.

The TESS platform is currently being developed, deployed, and tested in the Connected Community project site in Maine. This pilot will involve the integration of a diverse range of DERs and flexible loads, including rooftop solar, battery energy storage, heat pumps, electric vehicles, and smart appliances. The goal is to demonstrate how the TESS market-based coordination mechanism can optimize distribution system operation in rural communities while also providing valuable insights and lessons for future deployments.

3 Modeling the Interaction of Technology and Institutions in Electricity

3.1 Overview of the IAD Model

The Institutional Analysis and Development (IAD) framework is an analytical tool for studying the complexities of collective action and the institutions used for common pool resource (CPR) management by diverse groups of individuals. The framework emerged from Elinor Ostrom's seminal work on the management of shared resources, which challenged the "tragedy of the commons" conventional wisdom that CPRs inevitably lead to overexploitation and depletion. Ostrom built on work in economics, political science, and sociology to challenge this conventional wisdom, highlighting the importance of institutional arrangements in governing these resources sustainably (e.g., Ostrom (2010), Dietz, Ostrom and Stern (2003)).

The IAD framework is a multi-tier conceptual map that outlines the various elements influencing the decision-making processes and outcomes within a given action situation (Ostrom, 2005). The framework consists of several key components:

1. Physical Conditions: The physical characteristics of the resource system, such as its size, boundaries, and the mobility of the resource units.

2. Community Attributes: The socioeconomic characteristics of the individuals involved, their cultural norms, and their mental models or shared understanding of the situation.

3. Rules in Use: The formal and informal rules that govern the behavior of individuals within the action situation, including operational rules, collective-choice rules, and constitutional rules.

4. Action Situation: The core of the framework, where individuals interact, make decisions, and take actions based on the incentives and constraints imposed by the other components.

5. Interactions and Outcomes: These are the patterns of interactions and the resulting outcomes, which can be evaluated in terms of various criteria specific to the circumstances.

The IAD framework emphasizes the importance of understanding the interdependencies among these components and how they shape the incentives and behaviors of individuals within a given institutional setting (Ostrom, 2011). By analyzing these relationships, the framework aims to identify the factors that contribute to the successful management of CPRs and the design of effective institutions. Figure 4 provides a visual representation of the IAD framework, including arrows showing directions of impact and dashed arrows showing feedback channels to capture the dynamics of change.

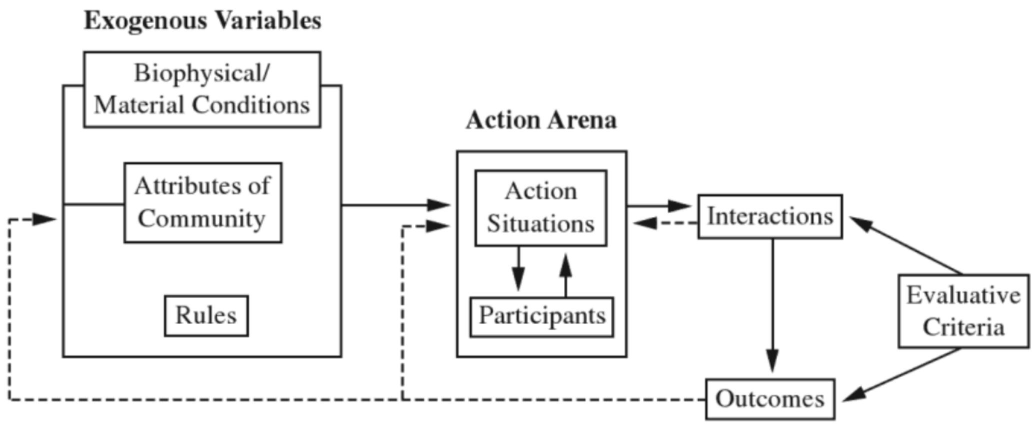


Figure 4: Schematic of the IAD Framework
Source: (Ostrom, 2005, p. 15)

The IAD framework has been applied widely to study diverse resource systems, including fisheries, forests, irrigation systems, and urban commons (Poteete et al., 2010). It has also been extended and adapted to address various challenges, such as climate change adaptation and environmental policy design. For example, Dietz, Ostrom and Stern (2003) highlighted the importance of adaptive governance approaches that allow for experimentation, learning, and adaptation over time, and applied those insights to global climate policy. They demonstrated that successful CPR governance is possible when institutions are designed to align with local social norms and ecological conditions, fostering cooperation and sustainable resource use. In this analysis I apply the IAD framework for policy analysis as described in Polski and Ostrom (2017).

3.2 IAD Model of Traditional Utility Regulation

As Section 2 makes clear, the techno-institutional setting of traditional utility regulation is complex, and technological change is amplifying those complexities. In applying the IAD framework I impose some assumptions and make some simplifications that abstract from specific details of each utility-regulator action setting. The resulting model will be a stylized and generalized representation of the traditionally regulated 20th century vertically-integrated utility setting.

3.2.1 Actors

I model this setting as having five communities of actors: regulated utilities and their executives, regulatory agencies and regulators, consumer advocates, legislators, and consumers. The setting is more complicated and has more actors than these five sets, but for this mapping exercise I focus on these actors.

Regulated utilities and regulators are the primary actors in this setting. Regulated utilities are historically vertically-integrated, owning and operating the entire supply chain in the provision of electric service: generation, high-voltage transmission, low-voltage distribution, and the retail relationship with end-use customers. They operate without competition due to the legal protection of their service territory monopoly afforded by state public utility regulation. Regulated utilities are also private investor-owned firms with a fiduciary duty to their shareholders in addition to their obligation to serve all customers in their service territory.

Public utility regulators are state employees working for a state's public utility commission, the agency with the responsibility for implementing the state's utility regulations. Commissions typically have a number of commissioners (often three or five) who are appointed, although 10 states have elected commissioners. Commissions also have staff comprising lawyers, economists, engineers, and policy analysts, although the analysis in this paper focuses on commissioners.

States also have formal consumer advocates whose statutory mission is to represent the interests of consumers in the formal regulatory proceedings of the commission. In practice consumer advocates prioritize representation of low-income and elderly consumers.

State legislators are also actors in this setting. The fundamental role that legislators play is determining the mission of the public utility commission and formulating the policies that the commission is charged to implement.

IAD domain	*Traditional VI ROR regulation*
Physical World	Vertically integrated technology systems of power plants, wires networks, meters
	Large scale generation for supply
	Producers and consumers are distinct agents in the system
	Large scale wires networks at two different levels
	Wires network architecture is one-way flow
	Infrastructure assets have long useful lives (30-40 years)
	Analog controls and metering

Figure 5: IAD Framework, Physical World in Traditional Regulation

The final set of actors in this setting is consumers, generally customers of the regulated utility. Consumers use electricity as an input into their production and consumption activities, so their demand for electricity is a derived demand.

3.2.2 Physical World

The physical world for the traditional utility model is characterized by large-scale electro-mechanical technologies and networks. Utilities invest in generation technologies including hydroelectric, coal, and then later oil, nuclear, and single-cycle gas. Generation at large scale benefits from economies of scale, leading utilities to make high fixed cost investments to reap those advantages.

Generation is built at a distance from population centers, and utilities use AC high voltage transmission and low voltage distribution to transport electricity from generators to end-use consumers with low losses compared to other methods of organizing the system. The physics of AC networks means that if the wires network involves more than one line connecting two parties, electrons will follow the path of least resistance and the physical path of the quantity of electricity in a transaction will not match the contract path of that transaction. The grid architecture is designed specifically at the distribution level for the one-way flow of current from the transmission grid to end-users, from generators to consumers.

The electro-mechanical nature of the system's technologies means that all switches and monitoring controls are mechanical, not digital. Communication technologies are limited to telephone lines connecting generator nodes in the network with control room operators. These technologies and the "human in the loop" operators maintain the real-time balance of supply and demand to keep the system safe and reliable. Figure 5 enumerates the dimensions of the physical world in the traditional utility setting.

3.2.3 Community Attributes

The community attributes section of the IAD framework specifies characteristics and relationships of the communities in which the actors participate and that create their shared mental models. In this complicated setting I delineate some community attributes of the entire community as well as some specific attributes of each sub-community of actors.

The community comprises five different actors: a firm (the regulated utility) and its executives, a regulatory agency and its commissioners and staff, a consumer advocate, legislators, and consumers. One important shared attribute at the community level is an emphasis on caution and prudence, embedded in risk-averse preferences. Risk aversion arises from the physical nature of the large infrastructure and the safety aspects of electricity as well as the financial least-cost mission of rate-of-return regulation. Electricity is a complicated engineered infrastructure system, and mistakes can be deadly. The safety focus combines with the concern about costs and affordability in a monopoly system to yield a generally cautious approach to regulatory decision-making and utility capital investment. The focus on regulatory proceedings as the governance framework means that the culture is also formal and hierarchical, and often adversarial. A final dimension of shared community attributes is asymmetric information; the regulated utility knows its costs much more accurately than any other actors, and each actor knows their own motivations but can only speculate on the motivations of others based on observed decisions.[4]

The regulated utility's community attributes include its vertical integration, its nature as a large investor-owned firm with a legally-protected monopoly, and its resulting objective function of profit maximization within its regulated constraints. Historically the utility has had regulatory approval to charge averaged rates to all customers, rates that reflect the agreed-upon revenue requirement with the regulators and do not vary over the time of day or season, even if the underlying cost of providing electric service did vary.

Community attributes of regulators reflect their statutory mission as economic regulators focusing on enabling the least-cost provision of electric service to all current and future customers in a utility's service territory. As appointed or elected commissioners

[4]An extensive literature in economics explores the problem of regulating a monopolist in the face of asymmetric information; see for example Baron and Myerson (1982), Laffont and Tirole (1986), Laffont and Tirole (1988), Laffont and Martimort (1997).

they are political actors in political roles, but as economic decision-makers affecting the investment decisions of the regulated utility and the consequences of those investments for consumers.

Consumer advocates have attributes reflecting their representation of specific consumers and their role as intervenors in formal regulatory proceedings to represent those interests. At a very high level their existence and approach reflects an attempt to counteract the collective action problem articulated by Olson (1965) of regulation as having concentrated benefits and diffuse costs. Individual consumers have less incentive or ability to participate in regulatory proceedings affecting their outcomes; consumer advocates see their role as counteracting that imbalance, pabig-skip rly for low-income and other vulnerable consumers.

The community attributes for state legislators are multi-faceted, given their roles and the variety of issues they confront. For the purpose of this analysis, legislators determine the statutory mission of the commission and the policy objectives that regulatory commissions implement. In doing so they interact with a range of other actors, including both their voters and other organized interests for whom legislative decisions can affect their outcomes.

Finally, as a community consumers have attributes that are a consequence of the combination of technology and regulatory institutions. In the regulatory context they are formally categorized into residential, commercial, and industrial customers of the utility. Under the cost-based flat pricing that characterizes regulated rates, consumers have inelastic demand because they face averaged time-invariant rates; the rates they pay typically only vary when a utility files a rate case that includes an increase and the regulators approve it. Thus pricing changes only infrequently and in a very discrete manner, and consumers do not observe their consumption or expenditure until they receive a bill at the end of the month. A final important community attribute is that residential customers have more inelastic demand than commercial or industrial customers, but they are also voters. Commercial and industrial customers may participate in organized interests to attempt to influence legislators or regulators. Figure 6 displays the overall community attributes and the specific sub-community attributes.

3.2.4 Rules in Use

Given the central role of regulation in this setting, it is no surprise that the rules in use are crucial and numerous in this application of the IAD framework. Recall that the

IAD domain	*Traditional VI ROR regulation*	
Community Attributes	Culture is hierarchical, formal, often adversarial Firms know their costs, asymmetric information Risk aversion	
	Actors	Firms: regulated utilities and their executives Regulators Consumer advocates Legislators Consumers
	Community Attributes: Firm	Vertical integration Large investor-owned firm with legally protected monopoly Profit maximizing with average cost pricing
	Community Attributes: Regulatory Agencies	Economic regulation of utility Regulators are in political roles but as economic decision-makers
	Community Attributes: Consumer Advocates	Prioritize interests of specific consumers (e.g., low income, elderly) Intervene in regulatory proceedings representing those interests
	Community Attributes: Legislators	Legislators determine policy objectives Legislators influenced by voters and by organized interests
	Community Attributes: Consumers	Formally categorized into residential, commercial, industrial Inelastic demand arising from flat, averaged regulated rates Residential have more inelastic demand but are voters

Figure 6: IAD Framework, Community Attributes in Traditional Regulation

rules in use comprise both formal rules and informal norms governing the interactions and decisions of the actors; below I discuss the formal rules and then the informal norms that characterize this setting.

Two foundational rules in use are the legal status of the utility and the policy objectives the legislators specify. The regulated utility is a monopoly firm with legal entry barrier protection within its service territory (Kahn, 1988). The regulatory definition of the utility's business is the generation and delivery of a commodity, so the electricity transaction is deliberately framed as a commodity transaction between the utility and its customers. In the traditional regulation benchmark case, regulators are charged with overseeing and the utility is charged with achieving three policy: safe, reliable, and affordable electric service. Quantitative metrics exist for all three objectives – safety and accident records, engineering measures of the duration and frequency of outages (SAIDI and SAIFI), and the rate structure that determines customer pricing.

The rule in use with the highest impact is cost-recovery-based rate-of-return (ROR) regulation. Under ROR regulation, the utility's revenue requirement is determined using its operating expenses (variable costs) and its capital expenditure (fixed costs), plus a market-benchmarked rate of return on its capital expenditure. That revenue requirement is then used to calculate rates for residential, commercial, and industrial customers:

$$\sum_{i=1}^{n} p_i q_i = Expenses + sB$$

where p = price, q = quantity, $i \in \{R, C, I\}$ customer category, s = "normal" rate of return, B = capital in rate base.

Applying the economic theory of regulation (Kahn, 1988), the rate of return represents the opportunity cost of the utility's capital. When combined with cost recovery on its expenses, this rate of return ensures that the regulated utility earns zero economic profit and positive accounting profit and yields the cost-minimizing level of revenue that is consistent with a utility with high fixed costs continuing to be willing and able to operate the electric system. Thus revenue depends on capital base and volume sold, and the formal regulatory process determines the revenue requirement. A rate-setting process turns the revenue requirement into a rate structure, which historically has involved various forms of fixed, averaged rates that differ for residential, commercial, and industrial customers. Cost-based rate-of-return regulation creates volumetric incentives for the utility to increase their revenue by selling more energy

In anticipation of changing economic conditions within its service territory that may affect demand, and knowing that with inelastic demand reliability requires supply to meet that demand, the utility performs long-term planning to invest to achieve the stipulated policy objectives. Regulators exercise authority over this planning and investment to achieve policy objectives, and to ensure that the utility does so in a prudent manner consistent with least-cost provision of a commodity service.

At any point in this summary of the formal regulatory rules in use, practice can and does depart from theory. This summary of the formal regulatory rules in use, though, does represent the legal landscape well enough to characterize rate-of-return regulation for the purpose of this analysis.

Rate case proposals in the 20th century typically involved utility investments in a narrow, well-defined scope of technologies known as "iron in the ground" – large-scale (generally fossil fuel) generation, transmission and distribution poles, wires, and substations, and consumption meters.[5] The stability of this technology set meant that both regulators and utilities were comfortable with the financial and reliability implications of investing in these technologies. Regulators could be more confident that these investments were prudent, and utilities proposing them could be more confident in having their rate cases approved. Thus a convention of status quo bias emerged between a risk-averse utility and its risk-averse regulators, leading to a preference for proposing and approving, respectively, “iron in the ground” investments.

From the perspective of the regulatory agency, regulators do not see their role as policymakers, but rather as decision-makers in the implementation of policies specified by legislators (Baron, 1988). Regulators also operate under administrative procedures for public notice and participation as well as internal procedural rules for regulator transparency, such as limitations on *ex parte* communications with respect to open cases.

Another important rule in use is the regulatory jurisdiction split between state and federal regulators. In the traditional vertically-integrated regulated utility model, utilities were members of regional power pools for emergency backup purposes. When those contractual agreements crossed state lines, the backup transaction became interstate commerce and the federal regulator (now called the Federal Energy Regulatory Commission, or FERC) exercised jurisdiction to ensure that the terms for the interstate transaction were “just and reasonable”. For the purpose of this analysis focusing on a vertically-integrated utility within a state, I abstract from the many complicated issues arising from this jurisdiction split, which is the subject of further research beyond the scope of this analysis.

A final, more informal, set of rules in use relate to consumers and their expectations. Consumption of electricity as a derived demand suggests that the consumer value proposition for electricity is the value derived from its uses, articulated by Amory Lovins as “hot showers and cold beer” (Fickett, Gellings and Lovins, 1990). In this representation of the value proposition, consumers are indifferent to characteristics of the inputs into electricity generation and supply, and are only interested in it as an input into other activities. Similarly, consumer expectations about their interaction with the electric system are usually characterized as “I flip the switch and the light goes on” dependability and convenience. Figure 7 shows the rules in use specified in this model.

[5]The mid-century development of nuclear power posed a substantial challenge to this technology set, with repurcussions that are still felt in the industry and in regulation (Hirsh, 1999).

Rules in use	Monopoly firm with legal entry barrier protection Policy objectives: Safe, affordable, reliable Electricity framed as a commodity transaction Cost-recovery-based rate-of-return regulation Revenue depends on capital base and volume sold Regulatory process determines revenue requirement A rate-setting process turns the revenue requirement into a rate structure Utility performs long-term planning to invest to achieve policy objectives Regulators exercise authority over prudent investment to achieve policy objectives Utility and regulators prefer status quo scope of investment, "iron in the ground" Regulators do not see their role as policymakers Administrative procedures for public notice and participation Procedural rules for regulator transparency (e.g., ex parte) Federal-state jurisdiction split (except for Texas) Consumer value proposition: "Cold beer and warm showers" Consumer interaction with system: "I flip the switch and the light goes on" dependability

Figure 7: IAD Framework, Rules in Use in Traditional Regulation

3.2.5 Action Situations

In this setting I decompose the action situation into two separate but interdependent action situations in which the utility and regulators are the primary actors: the formal and informal action situations.

The formal action situation is the arena in which the utility makes investment decisions, starting with the formal rate case that a utility presents to the commission. All interactions regarding a rate case are mediated through a formal regulatory proceeding, and the parties are not permitted to communicate about the proceeding outside of the formal process.

The utility and the regulators are the primary participants, with the utility preparing a rate case for regulatory review and approval. The rate case includes both investment proposals and a proposed rate structure to meet the policy objectives of safety, reliability, and affordability. Utility implementation requires regulatory approval; the regulator can approve, reject, or ask for modification of the proposal. The consumer advocate can submit testimony on the effects of the proposals, usually with a focus on affordability.

The utility can revise proposal if needed; once the proposal is approved, the utility enters the financial market to implement investment decisions.

In the informal action situation, the utility expends resources in an effort to influence regulatory decision-making to align with the financial interests of the utility. This action situation highlights the interest, influence, and rent-seeking aspects of the regulatory process. Regulators have ethics codes restricting financial interactions and follow procedural rules intended to reduce opportunities for and consequences of influence. But utilities face considerable influence incentives. Another locus of influence also exists between a utility and its legislators.

These two action situations interact, most notably in the sense that utility influence is intended to shape regulatory decision-making in formal regulatory proceedings. Figure 8 specifies the characteristics of the two action situations in the traditional utility setting.

3.2.6 Interactions, Outcomes, and Evaluation

INCOMPLETE

The five types of actors interact in these formal and informal action situations, generating specific outcomes.

Formal rate case regulatory proceedings with highly structured participation Information flows through party filings, proceeding testimony, and published decisions Informal interactions through other professional events Utility information, event sponsorship etc. to influence information set of regulators

which yield:

Regulator generally approves utility investments (asymmetric information and/or capture) Investment decisions, typically "iron in the ground" Technology choices are cautious, seen as prudent Little incentive to propose technological change Cautious technology choices have historically been consistent with affordability Pricing is generally flat, averaged rates Reliability Distribution control room operators perform system control Utility ROR and shareholder returns

Action Situation 1	Primary participants: Utility and regulator
(Formal)	Mediated through a formal regulatory proceeding
	Utility prepares rate case with investment and rate proposals to meet policy objectives
	Regulator-approved investment and rates
	Regulator can approve, reject, ask for modification of proposals
	Consumer advocate can submit testimony on the effects of the proposals
	Utility can revise proposal if needed or enter financial market to implement investments
Action Situation 2	Influence and rent-seeking
(Informal)	Utility takes actions to influence regulatory decisions in their favor
	Regulators have ethics codes restricting financial interactions
	Utility expends resources on information (conferences, "education" sessions)

Figure 8: IAD Framework, Action Situations in Traditional Regulation

The final step in the IAD framework is the set of performance metrics used to evaluate the outcomes generated. In this setting evaluation would include measurement of how well the utility achieves the stated policy objectives of safety, affordability, and reliability, as well as a simultaneous evaluation of both customer satisfaction and utility/shareholder profits.

Safety metrics Reliability as measured by SAIDI/SAIFI Utility ROR and shareholder returns Rates

Although it does not reflect the full detail in the previous domain-specific discussions, Figure 10 represents the traditional vertically-integrated regulated utility setting using the IAD framework diagram in Figure 4. This diagram represents the exogenous factors, action situations, interactions, outcomes, and evaluation for a vertically integrated regulated utility setting. The IAD model summarized in Figure 10 is the benchmark against which to compare the technological changes and institutional implications of the transactive energy (TE) setting.

Patterns of interactions	Formal rate case regulatory proceedings with highly structured participation
	Information flows through party filings, proceeding testimony, and published decisions
	Informal interactions through other professional events
	Utility information, event sponsorship etc. to influence information set of regulators
	which yield:
Outcomes	Regulator generally approves utility investments (asymmetric information and/or capture)
	Investment decisions, typically "iron in the ground"
	Technology choices are cautious, seen as prudent
	Little incentive to propose technological change
	Cautious technology choices have historically been consistent with affordability
	Pricing is generally flat, averaged rates
	Reliability
	Distribution control room operators perform system control
	Utility ROR and shareholder returns
Evaulation	Safety metrics
	Reliability as measured by SAIDI/SAIFI
	Utility ROR and shareholder returns
	Rates

Figure 9: IAD Framework, Interactions, Outcomes, Evaluations in Traditional Regulation

3.3 Applying the IAD Model to Technological Change

Having established the benchmark model of vertical integration and regulation, consider a stylized setting in which the technology shock described in Section 2.4 occurs but the vertically-integrated utility business model and the regulatory model remain the same. Digitalization and the affordable availability of DERs have changed the technology space so that transactive energy is an available and attractive platform (the TE setting).

This setting represents an incremental step of a vertically-integrated utility adopting transactive energy as part of its business model and operations. More decentralized models that this innovation makes possible are microgrids and retail unbundling from the vertically-integrated monopoly to enable retail competition, but those settings are beyond the scope of this analysis.

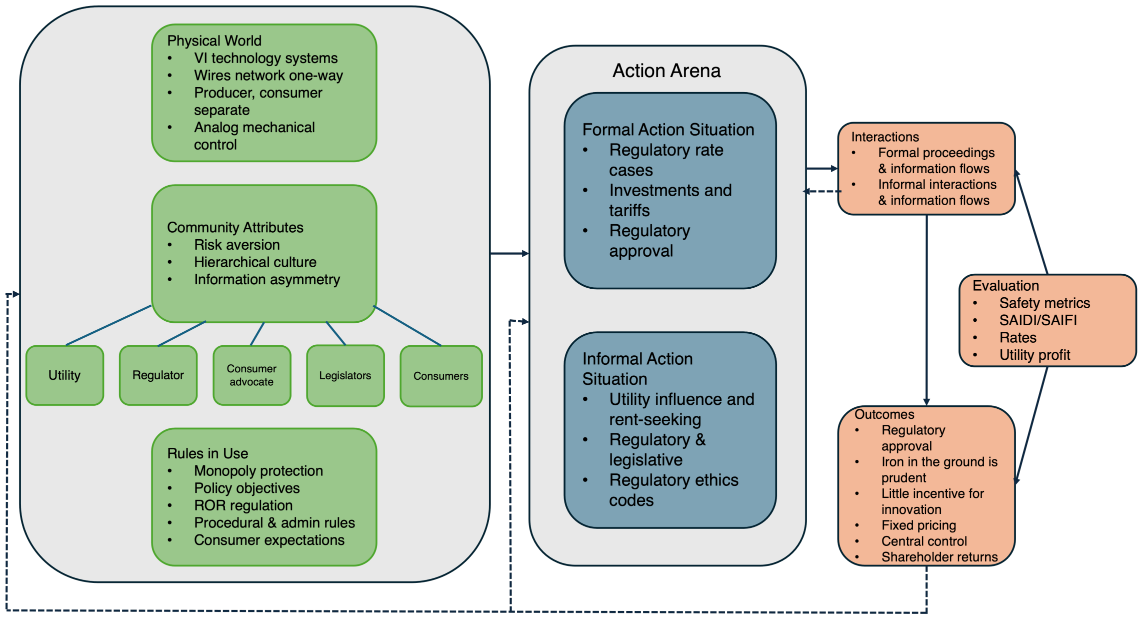


Figure 10: IAD Framework, Traditional Regulation

What institutional changes are compatible with enabling the economic and environmental value of this technology shock? In this mapping exercise I use the IAD framework to apply the technology shock to the benchmark model. I then identify institutional dimensions of the benchmark model that are less compatible with the new technologies than they were with the 20th century electro-mechanical system. As an exercise in comparative statics institutional analysis, I abstract from important details about grid operations.

For simplicity I also assume that actors and community attributes are unchanged, to focus on the association between changes in the physical world and in the rules in use, with two exceptions. First, while the utility remains vertically-integrated, in the TE setting the utility and its regulators have agreed to allow DER interconnection (e.g., rooftop solar, electric vehicles, batteries) around the edge of the utility's distribution network; while this is a change in rules in use, it also affects the community's shared understanding of the setting. Another exception is the inelastic demand of consumers arising from their payment of fixed, averaged rates. Facing the more dynamic pricing available in a transactive system reveals the underlying price elasticity of demand and is expressed as changing consumption (operationalized autonomously), so this change in ability to see and respond to changes in the system represents an important change in community attributes.

Identifying these institutional changes is necessarily speculative, as they are changes that have not occurred. Using the IAD framework this way allows me to identify specific elements of the institutional pacing problem in light of DER and digitalization and the potential for transactive energy. The effects of digitalization, DERs, and transactive energy have been discussed in electricity policy for over 15 years, so some proposed changes exist. I rely on proposals that have been discussed in the U.S. but not yet implemented, examples from other jurisdictions, and my experience working in electricity policy research and implementation to propose a set of institutional changes for consideration. To the extent possible the institutional changes highlighted in the model reflect actual proposals and changes that some states have proposed.

In the analysis that follows I have mapped the technological changes and their direct implications into the benchmark IAD model and represent those changes in blue. The dimensions in which existing institutions are ill-suited to the new technologies and their potential are represented in red, as suggested institutional changes that would be compatible with the technology shocks.

3.3.1 Physical World in the TE Setting

The technology shocks of digitalization and DER indicated in the TE setting have the largest impact on the IAD model in the physical world. The new technologies mean that the TE setting represents physical changes in many parts of the electric system. The existing vertically-integrated system of power plants, wires networks, and meters still exists, but the digital and DER technologies create more monitoring, sensing, and automated response capabilities both within the grid itself (improving grid operations) and around the edge of the distribution network. Accommodating this technology shock changes the architecture of the distribution grid by connecting devices for production, consumption, and storage digitally around the grid edge, or "behind the meter" from the utility's perspective. That change decentralizes the grid and makes it accessible to smaller-scale DER, changing the nature of supply in general away from large-scale generation to a more heterogeneous portfolio of generation resources at different scales and many more locations.

In the traditional grid architecture, producers and consumers were distinct agents on the grid because only utilities with large-scale power plants could supply, and end-use consumers only consumed. Digitally-connected DERs change the human aspect of the grid by changing the roles that individuals can fulfill. A PV or battery or EV owner can be a producer, not just a consumer, and in the TE setting they produce not only for self-supply, but also for consumption by others through participation in a local energy market. Consumers with PV, EVs, batteries are prosumers.

In the TE setting the grid continues to operate as a large-scale wires network at two different voltage levels. The primary change that occurs in the TE setting is that the distribution grid is capable of two-way current flow, which is necessary to accommodate the use of DERs and their participation in a TE system.[6]

The final physical dimensions in the IAD model also would change significantly. The benchmark "iron in the ground" infrastructure assets have long useful lives, typically 30-40 years, and one of the requirements of regulatory prudence is that a utility must employ its assets as long as they are "used and useful". Digital and DER assets, on the other hand, have shorter useful lives, and are frequently made obsolete by technological change even if they are still "used and useful".[7] This difference means that infrastructure assets will be a mix of longer and shorter useful lives. While not physically difficult to manage, this distinction will have implications for the regulatory treatment of depreciation, whether or not utilities owning digital assets are allowed to replace them when obsolete but still "used and useful", and larger questions of system reliability and resource adequacy that are beyond the scope of this analysis. Finally, the change in the distribution system that makes the TE setting possible is the move from analog controls and metering of consumption to digital metering, controls, and automation, all capable of acting on smaller time scales and more quickly than the analog system. Figure 11 displays the physical world dimensions from the traditional utility setting on the left and the technology shock effects on the physical world on the right, with changes indicated in blue.

3.3.2 Rules in Use in the TE Setting

One contribution of this analysis is identifying the dimensions of the rules in use in the electric system that are affected by a technology shock to an existing vertically-integrated, regulated utility setting. Rules in use are a combination of formal regulatory rules and informal norms, both of which can be affected by a technology shock. In the

[6]The utility expenditure to enable two-way flow is likely to be considerable and is the topic of current debate nationally and in many states.

[7]As a concrete example, consider your own decisions of updating your mobile phone while it is still "used and useful".

IAD domain	*Traditional VI ROR regulation*	*VI utility using TE*
Physical World	Vertically integrated technology systems of power plants, wires networks, meters	Vertically integrated technology systems but with DER consumption/production/storage resources
	Large scale generation for supply	Heterogeneity of scale and location for supply
	Producers and consumers are distinct agents in the system	Consumers with PV, EVs, batteries are prosumers
	Large scale wires networks at two different levels	Large scale wires networks at two different levels
	Wires network architecture is one-way flow	Wires network architecture is two-way flow
	Infrastructure assets have long useful lives (30-40 years)	Infrastructure assets are a mix of longer and shorter useful lives
	Analog controls and metering	Digital controls, metering, automation

Figure 11: IAD Framework, Physical World with Transactive Energy

TE setting the technological changes modify what is physically possible, so some of the rules in use change as a direct consequence, but others require more deliberate institutional change (denoted in red).

In this institutional comparative statics mapping, the utility business model and the regulatory model stay the same, so many of the rules in use are unchanged in this specific setting (although for other settings like microgrids or allowing retail competition, more of these rules in use would have to change). While the regulatory model stays broadly the same in the sense that the state government grants the commission the authority to regulate utilities to achieve the state's policy objectives, the specific rules in use at the commission are the focus of this analysis. In particular, the foundational dimensions of regulation remain unchanged in the TE setting. A regulatory process determines the utility's revenue requirement, and a rate-setting process turns that revenue requirement into a rate structure. The specifics of that rate structure change, though, to include the TE option.

Other rules in use that remain in this setting are utility long-term planning, regulatory prudence review, administrative and procedural rules, the federal-state jurisdiction split, and the extent to which regulators do not see their roles as policymakers. As a rule in use around consumer expectations, they continue to see demand for electricity as a derived demand from the value it has in use.

One important change in a rule in use is associated with technological change, but is a more general evolution of policy objectives to be implemented in utility regulation. The benchmark setting's policy objectives of safety, reliability, and affordability remain high priority. A growing focus on climate change mitigation and adaptation over the past two decades, as well as an impetus to incorporate distributional effects of energy infrastructure into regulatory policy, have added resilience, decarbonization, and energy justice to the set of policy objectives. States are adopting these policy objectives to different degrees and in different ways, but in general they are influencing how regulators evaluate utility proposals, and therefore they are influencing the investments that utilities propose.

The technology shock has a direct impact on two of the rules in use related to the nature of the electricity transaction and how consumers expect to interact with the system. In the analog-mechanical benchmark setting, electric service is characterized and sold as a uniform commodity service, and consumers expect to engage in consumption at a fixed, averaged rate and receive a bill at the end of the month, at which time they learn how much they consumed and what they paid. In a digitalized grid, though, information can be communicated more quickly and more specifically both to and from consumers. Electricity, the production cost of which can vary dramatically both hourly and seasonally, can be more easily sold to consumers not as a uniform commodity, but as a differentiated product.[8] In particular, since the TE setting involves customer device participation in a local energy market, they experience time-differentiated dynamic pricing rather than fixed, average rates, and that dynamic pricing emerges from the interaction of buyers and sellers and thus reflects distributed knowledge in the system and leads to price discovery. Thus in the TE setting consumers choose their willingness to pay/willingness to offer buy/sell trigger price settings, embodied in their devices and their home energy management system through the algorithmic response they choose. This change also creates a change in how consumers interact with the system; digital measurement and controls make it possible for people to choose to observe and interact with their energy choices much more than was feasible before, and they also have digital automation tools to manage how actively they interact with their energy choices. Figure 12 presents the technology-induced changes in rules in use (in blue), unchanged rules in use (in black), and institutional mismatch dimensions (in red).

Several rules in use from the traditional setting are not a good fit with the TE setting, denoted in red in Figure 12. The three proposed institutional changes all relate to how traditional regulatory instituitons influence utility incentives for size of expenditure and type of technology.

Taking advantage of both the economic and environmental opportunities of these new technologies requires changing the utility's franchise agreement to allow intercon-

[8] Large industrial customers who require extremely precise voltage and frequency characteristics for their production ("power quality") have been able to contract with the utility for electricity as a differentiated product for decades, and that capability required specific measurement and metering. With digitalization, contracting over power quality becomes more feasible at the margin for more, and more types, of customers.

Rules in use	Monopoly firm with legal entry barrier protection	Monopoly firms with legal entry barrier protection but now allows DER
	Policy objectives: Safe, affordable, reliable	Policy objectives: safe, affordable, reliable, resilient, decarbonized, just
	Electricity framed as a commodity transaction	Electricity can be a differentiated product
	Cost-recovery-based rate-of-return regulation	Performance-based regulation or price cap regulation
	Revenue depends on capital base and volume sold	Revenue depends on achievement of performance metrics aligned with policy objectives
	Regulatory process determines revenue requirement	Regulatory process determines revenue requirement
	A rate-setting process turns the revenue requirement into a rate structure	A rate-setting process turns the revenue requirement into a rate structure
	Utility performs long-term planning to invest to achieve policy objectives	Utility performs long-term planning to invest to achieve policy objectives
	Regulators exercise authority over prudent investment to achieve policy objectives	Regulators exercise authority over prudent investment to achieve policy objectives
	Utility and regulators prefer status quo scope of investment, "iron in the ground"	Contingent on incentive compatibility of regulatory institutions utility may be technology agnostic
	Regulators do not see their role as policymakers	Regulators do not see their role as policymakers
	Administrative procedures for public notice and participation	Administrative procedures for public notice and participation
	Procedural rules for regulator transparency (e.g., ex parte)	Procedural rules for regulator transparency (e.g., ex parte)
	Federal-state jurisdiction split (except for Texas)	Federal-state jurisdiction split (except for Texas) polycentricity
	Consumer value proposition: "Cold beer and warm showers"	Consumer value proposition: "Cold beer and warm showers"
	Consumer interaction with system: "I flip the switch and the light goes on" dependability	Consumer interaction with system: Convenience and dependability through automation

Figure 12: IAD Framework, Rules in Use with Transactive Energy

nection of DER, or in the case of a utility opposed to such interconnection, requiring the utility to allow DER interconnection.

Similarly, the incentives inherent in ROR regulation can induce the utility to object to DER interconnection and flexible coordination through a TE platform when it reduces their ability to make larger capital investments, given that their revenue model is predicated on earning a rate of return on their rate base. As a generation owner, the utility may also oppose DER interconnection because it would reduce demand for their generation. Other forms of regulation are more likely to be well-suited to aligning investment incentives in the digitalization and grid modernization that enables TE while also reducing the size of the utility's generation assets. These other forms of regulation would reduce the extent to which the utility's revenue relies on its capital base and the volume sold, and would shift its revenue generation toward achievement of performance metrics that are aligned with the (now larger) stipulated policy objectives.

Institutional change away from ROR regulation can change utility incentives and make them more performance-oriented, taking into consideration new technologies and expanded policy objectives. But one rule in use is likely to persist because it builds on the fundamental community attribute of risk aversion. Both utility and regulators have favored "iron in the ground" conventional technologies that are well-known, well-understood, and for which the grid architecture was designed. Reducing the barriers to innovation and new technology adoption could result in both the utility and regulators becoming more technology agnostic, but that change is likely to be slow given how deeply embedded the risk aversion attribute is in both primary actors.

This mapping suggests that the fundamental dimensions of institutional change for enabling a future utility-based TE setting are allowing and improving ease of DER interconnection to the distribution grid and making utility regulation performance-based rather than capital-based.

3.3.3 Action Situations in the TE Setting

As long as the vertically-integrated regulated utility structure remains, the procedural aspects of the action situations are likely to remain the same. Both the formal regulatory proceedings and the informal influence situation are still relevant, even if the institutional changes identified above occur.

3.3.4 Interactions, Outcomes, and Evaluation in the TE Setting

As technology and institutions change, the resulting interactions and outcomes will differ, as will the means of evaluating the outcomes. Given the limited changes in the action situations, the interaction that changes the most in the utility-based TE setting is the expansion of formal regulatory interactions to involve more stakeholder interactions and information gathering in non-adversarial regulatory proceedings.

The combination of technological and institutional changes that would bring about a utility-based TE setting yield considerable changes in outcomes compared to the traditional setting. These outcomes are contingent on the extent of institutional change and the nature of the changes, and this discussion indicates those contingencies.

Two outcomes change directly due to the technological changes in the TE setting. The nature of a TE system means that some of the customer's devices will respond autonomously to dynamic price signals, depending on the device bids and offers that reflect the owner-operator's preferences. This TE design feature necessitates a change from charging fixed, averaged rates. It also necessitates a shift in investment decisions away from an "iron in the ground" focus toward more digital and communications investments, to enable two-way flow and decentralized monitoring and automation in the distribution grid.

The autonomous decentralized coordination of devices using emergent market prices also creates a change in the system's control architecture, moving from an environment in which central distribution control room operators perform all system control to one in which decentralized market prices coordinate resources and reduce (but do not eliminate) the need for centralized control actions.

One change in outcomes arises from changing policy objectives, which expand from safety, reliability, and affordability to include resilience, decarbonization, and energy justice. In the traditional setting, cautious technology choices were historically consistent with the affordability of achieving safe and reliable outcomes. In the utility-based TE setting, technology choices must be compatible with balancing this broader set of policy objectives. To the extent that the TE setting enables flexibility, customer choice, and greater DER interconnection, it is more likely to be compatible with this broader set of policy objectives than continuing the traditional setting.

Other outcome changes are more contingent on institutional changes. In the traditional setting regulators generally approve utility investments. That decision represents a confluence of utilities making proposals they think will be approved, regulators operating under incomplete information, and utility influence of outcomes that can arise from regulatory capture. All three of those factors continue to influence regulatory approval decisions, but the expansion of the policy objectives and the greater heterogeneity of the technology landscape may, or may not, lead to less certain approval or more negotiation and iteration in utility rate cases. If the regulatory institutions involve performance-based metrics or a move to price cap regulation, that change may align utility incentive compatibility with the policy objectives that regulators are required to implement.

The technology choice outcomes are contingent on the combination of regulatory institutions and the shared community attributes of caution and risk aversion. In the traditional setting, caution characterized investment decisions for both utility and regulators, which led to utilities having little incentive to propose investments in qualitatively different technologies. An institutional (formal and cultural/mental model) change that the utility-based TE setting will require is a shift to wires-focused investments, creating an integrated power/communications smart grid. Regulators apply a prudence requirement, and part of the changing mental models will include characterizing such investments as prudent, which would change the incentives of the utility to propose digital wires-based investments.

Evaluation of these outcomes would retain the metrics for safety, reliability, and affordability, and would add metrics for the three additional policy objectives. Figure 13 compares the traditional setting to the TE setting.

Patterns of interactions	Formal rate case regulatory proceedings with highly structured participation	Formal rate cases and other forms of formal participation
	Information flows through party filings, proceeding testimony, and published decisions	Information flows through party filings, proceeding testimony, and published decisions
	Informal interactions through other professional events	Informal interactions through other professional events
	Utility information, event sponsorship etc. to influence information set of regulators	Utility information, event sponsorship etc. to influence information set of regulators
	which yield:	**which yield:**
Outcomes	Regulator generally approves utility investments (asymmetric information and/or capture)	Contingent on incentive compatibility utility may propose investments that regulator approves
	Investment decisions, typically "iron in the ground"	Investment decisions are more digital, communications, enabling decentralized coordination
	Technology choices are cautious, seen as prudent	Prudent technology choices shift from generation to wires (power and communications) technologies
	Little incentive to propose technological change	Contingent on incentive compatibility may have incentives to propose technological change
	Cautious technology choices have historically been consistent with affordability	Technology choices must be compatible with balancing a broader set of policy objectives
	Pricing is generally flat, averaged rates	Consumer chooses mix of fixed and dynamic pricing; consumers participate through automated bids
	Reliability	Reliability
	Distribution control room operators perform system control	Emergent market prices coordinate resources and reduce need for control actions
	Utility ROR and shareholder returns	Utility ROR and shareholder returns
Evaulation	Safety metrics	Safety metrics
	Reliability as measured by SAIDI/SAIFI	Reliability as measured by SAIDI/SAIFI
	Utility ROR and shareholder returns	Utility ROR and shareholder returns
	Rates	Rates
		Resilience metrics
		Decarbonization rates
		Energy justice metrics

Figure 13: IAD Framework, Outcomes and Evaluation with Transactive Energy

Figure 14 modifies the traditional utility setting IAD model (Figure 10) and indicates the technological and institutional changes and their implications in italics.

4 Analysis and Discussion

INCOMPLETE

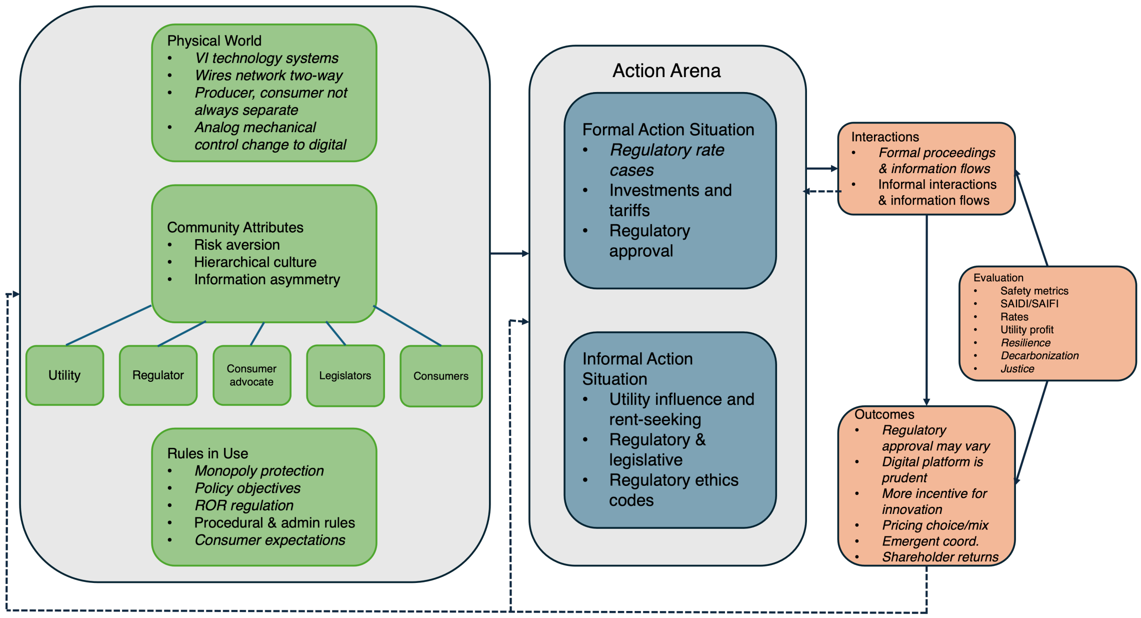


Figure 14: IAD Framework, Transactive Energy (changes in *italics*)

Evidence that some of this is already happening. But this process only happens slowly, if at all. Public participation, regulation as a principal-agent problem

5 Conclusion

INCOMPLETE

This paper creates a representation of the co-determined technologies and regulatory institutions in the electricity industry, and then uses transactive energy as a case study in the potential value creation from the combination of DER with digitalization in a utility setting. Unleashing that value creation requres not only technological change, but also institutional change. DER and digitalization enable electric systems that are qualitatively different from those of the 20th century, different in ways that are better suited to achieving the updated set of policy objectives including decarbonization, resilience, and energy justice. But system-level change is challenging, technologically, institutionally, and culturally.

The analysis identifies the dimensions of existing regulatory institutions that are misaligned with the changing landscape of technologies and policy objectives of the energy transition. I used Ostrom's IAD framework to analyze the historical representation of technologies and institutions, and to characterize the digitalized transactive energy setting. I then used this IAD model to identify changes brought about by technological change, and sets of institutional changes that would be more compatible with that setting than the existing regulatory institutions. The institutional environment includes both regulation and policy objectives, which are formalized in state statutes that provide regulatory agencies with guidance on their mission and scope. This application of the IAD framework has two interacting action situations: the formal regulatory situation and the informal influence situation.

Ostrom's body of work indicates that for good outcomes, rules have to fit their socio-ecological-technological environment. When technology changes, rules can and should change.

Further work: develop the model for a changing utility business model, in which the utility becomes a wires only DSO platform; discuss the political economy of that happening, status quo influence and regulatory capture buffeted by Schumpeter's perennial gale of creative destruction

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