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« The Economic Governance of Residential Prosumers in Smart Grids »

by

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The economic governance of residential prosumers in smart grids

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Abstract

As smart grids increasingly integrate decentralized energy resources (DERs), their success depends on managing residential prosumers—households that consume and produce electricity through assets such as electric vehicles and rooftop solar panels. However, integrating prosumers introduces new risks, including privacy concerns over prosumer data and the challenge of designing appropriate economic incentives. There are multiple, often fragmented, perspectives on how prosumers should be integrated, with many overlooking the risks they may face. This paper examines the various organizational structures proposed for prosumer integration through a unifying framework based on transaction cost theory (TCT). By focusing on two key dimensions that drive transaction costs—monitoring and switching costs—we identify four main governance models and analyze their impact on prosumer transaction costs and risks of opportunism. When applied to a comparative case study of business models in France, the United Kingdom, and California, our framework reveals a clear gap in organizations that could offer prosumers the lowest risk of third-party opportunism. This suggests untapped opportunities to develop business models to mitigate these risks and attract prosumers. Finally, our findings contribute to policy discussions on transparency, standardization, automation, and market power, offering insights to advance residential prosumer integration.

1 Introduction

Smart grids are widely regarded as the next generation of electricity grids, evolving from traditional systems designed for power transmission from large centralized generators to small distributed consumers into advanced networks that integrate small distributed energy resources (DERs) and demand control (Clastres, 2011; Tuballa & Abundo, 2016). These systems leverage advanced information and communication technology (ICT) to enable bidirectional data flow, facilitating decentralized optimization. This, in turn, enhances the flexibility of electricity systems, allowing them to manage network congestions and support the integration of defossilized energy resources (Ketter et al., 2018). Additionally, smart grids have the potential to generate new sources of profits for consumers, system operators, and generators (Coville et al., 2011).

Integrating residential prosumers is among the challenges that are particularly critical for smart grid success. These are broadly defined as households that are both consumers and producers, typically possessing DERs capable of controlling their consumption, self-producing, or storing electricity (Gautier et al., 2018; Parag & Sovacool, 2016). This importance arises for at least four key reasons. First, residential consumers represent an average of 26% of global electricity consumption (IEA, 2021), and they are well-positioned to participate in smart grids through the increasing adoption of DERs such as electric vehicles (EVs), photovoltaic solar panels, smart appliances, and heat pumps among other DERs. Second, households have been shown to express privacy concerns regarding sharing their

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data. For instance, during the roll-out of smart meters, McKenna et al. (2012) show empirical evidence that residential prosumers tend to be cautious about what data is collected and who collects it. Third, encouraging the transition of residential consumers to prosumers might require economic incentives (Cortade & Poudou, 2022; Kotilainen et al., 2019), because engaging prosumers in environmentally sustainable practices often demand additional investments, effort, or operational costs compared to remaining solely as consumers (Castellini et al., 2021; Golla et al., 2022). Finally, from a regulatory perspective, smart grids fundamentally reshape the position of prosumers in the organization of electricity systems (Parag & Sovacool, 2016). This shift may introduce new forms of opportunism, significantly affecting how the value created by smart grids is distributed between prosumers and the firms enabling their integration into electricity systems (Friedrichsen, 2015).

Prior research on prosumers in the context of smart grids has primarily focused on proposing and evaluating the impact of various mechanisms for integrating residential prosumers. This literature can be broadly classified into three categories based on the types of mechanisms: regulatory mechanisms, market mechanisms, and intermediation. Regulatory mechanisms primarily examine the impact of policies, such as adopting different metering approaches for selling electricity back to the grid (Gautier et al., 2018). Market mechanisms explore the design and evaluation of prosumer markets (Parag & Sovacool, 2016), which can vary depending on the market scope and the specific actor in the electricity system requiring the market. This category includes studies on markets for microgrids (Hu et al., 2018; Zafar et al., 2018), distribution systems (Mišljenović et al., 2023; Rodríguez-Molina et al., 2014), peer-to-peer energy transactions (Mišljenović et al., 2023; Rosen & Madlener, 2016), and wholesale markets. Finally, intermediation mechanisms consider scenarios where prosumers do not directly participate in the market but instead interact through intermediaries, such as an Aggregator, that buy and sell electricity on their behalf (Burger et al., 2017). Research within intermediation mainly differs based on the intermediary's identity, the information exchange, and the type of control required to control the DERs.

While prior research has highlighted several potential configurations for prosumer integration, it lacks a unifying framework that looks at how each organizational structure impacts the costs and risks that prosumers might endure to participate in electricity systems. This gap leaves important questions unanswered: When should prosumer integration rely on an intermediary, and when should it rely on direct market participation? Is the choice of intermediary inconsequential, or does it significantly influence the effectiveness of prosumer integration in specific contexts? Addressing these questions requires a deeper understanding of the benefits and costs of different configurations and the potential risks of opportunistic behavior that each configuration for prosumer integration might create. Therefore, our research question is: *How does the organization of prosumer integration impact prosumers' costs and risks of participating in smart grids?*

In this paper, we build on previous research that has applied transaction cost theory (TCT) to analyze organizational phenomena in electricity systems (Finon & Perez, 2007; Friedrichsen, 2015; Saussier, 2000; Signorini et al., 2015). TCT provides a framework for understanding how the costs associated with coordinating and enforcing exchanges, commonly referred to as transaction costs, shape organizational structures, such as markets, hierarchies (vertical integrated organization), or hybrid (a combination of hierarchies and markets) forms (Williamson, 1975, 2010). We propose a framework that compares organizational structures based on two key dimensions affecting prosumers' transaction costs: monitoring and switching costs. From these dimensions, we derive four archetypal governance models for prosumer integration. We apply our framework to a comparative case study of business models in California, the United Kingdom, and France to validate it.

This framework offers two key contributions. First, it provides theoretical insights into how different organizational structures shape prosumer integration and influence the risk of opportunism in smart grids. Second, when applied to a comparative case study of business models, it proves adaptable to different structures that might otherwise be difficult to distinguish from a governance perspective. Notably, our analysis of California, the UK, and France shows a clear gap in organizations that might potentially offer prosumers the lowest risk of third-party opportunism. This suggests untapped opportunities to develop business models to mitigate third-party opportunism and attract prosumers. Beyond these contributions, our framework provides a theoretical foundation for policy discussions underexplored by researchers and policymakers. Specifically, we highlight four critical factors—transparency, standardization, automation, and market power—that influence the emergence of specific governance structures, and we propose should be studied in future research.

This paper is organized into six sections. The next section outlines the TCT's main theoretical concepts. In the third section, we use TCT concepts as building blocks and propose a conceptual framework for exploring organizational choices for integrating prosumers. Section four applies this framework as an analytical tool to examine the organizational structures of business model archetypes found in previous research and the current implementation of business models that integrate prosumers. Then, we discuss the limitations of our framework and show the framework's potential to raise new questions that advance prosumer integration research and policy, followed by our concluding remarks.

2 Theoretical background

We review two key research streams that inform our conceptual framework. First, we review the main assumptions and concepts of TCT. Then, we review TCT research in electricity systems.

2.1 Theoretical Foundations of TCT

TCT is typically associated with 'make-or-buy' decisions (Williamson, 2010). This theory expands the understanding of economic relationships by considering that parties strive to maximize gains by "assigning transactions to governance structures in a discriminating way" (Williamson, 1985, p. 18). Transactions are discriminated to economize both transaction costs and production costs. The former is broadly defined as the private efforts of the parties on a transaction to align incentives and craft governance structures that are attuned to their exchange needs (Williamson, 2002). This considers the contract's negotiation, decision-making, risk-bearing, monitoring, and enforcement costs.

To analyze the different types of governance structures, TCT uses the lens of contracts rather than the lens of choice typically used in neoclassical economic theory (Buchanan, 1975). From this perspective, spot markets, firms, and hierarchies are comparable contractual arrangements (Williamson, 2002, 2005). TCT posits that when transaction costs are negligible, trading partners can maximize value through markets benefitting from the incentives and transparency of competition. However, as the transaction increases in complexity, requiring specific investments or accounting for specific risks, transaction costs might increase due to monitoring costs or sunk investments, thus potentially incentivizing actors involved in the transaction to shift from market arrangements into vertically integrated arrangements.

The discrimination process, from which parties in a transaction economize by choosing the economic governance, is mainly influenced by three main constructs of TCT: the behavioral assumptions of the parties involved in the transaction, the dimensions used to characterize a transaction, and the process of drafting contracts (Williamson, 1984).

2.1.1 Behavioral assumptions

There are mainly two assumptions that one needs to consider on the behavior of the parties involved in the transaction: bounded rationality (Simon, 1997) and opportunism (Williamson, 1993). The former implies that each party faces limitations and costs in collecting and analyzing information, which hinders their ability to behave rationally. Indeed, from the TCT perspective, the attention and computation of the parties involved in the transaction are also scarce. The latter refers to the self-interest-driven behavior of parties. Such assumptions considered that parties might withhold information, misrepresent facts, or fail to fulfill agreed-upon obligations (Holmstrom & Milgrom, 1991).

2.1.2 Characteristics of transactions

The principal dimensions from which TCT analyzes transactions are asset specificity, frequency, and uncertainty.

Asset specificity. A transaction is considered specific to an asset when the asset's value in a transaction with a different party is lower than in the present transaction (Cuypers et al., 2021). The greater the difference between the asset's value in its first-best and next-best use, the greater the degree of asset specificity. Overall, five types of asset specificity are widely recognized: site specificity, where an asset's value is tied to its physical location (P. L. Joskow, 1985); physical assets, involving specialized machinery or infrastructure (Klein et al., 1978); human-capital assets, related to skills or expertise developed for a specific transaction (Becker, 1962); dedicated assets, which represent investments made to meet the needs of a particular transaction (Williamson, 1984); and intangible assets, such as proprietary knowledge or intellectual property (Caves et al., 1983). High levels of asset specificity, regardless of type, often lead trading parties to favor increased vertical coordination or long-term contracts to safeguard the value of their investments in the transaction (Williamson, 1975, 1979).

Frequency: A transaction can be on-time, occasional, or recurrent. The more frequent a transaction, the more it justifies investments in specialized governance structures. For example, frequent interactions can facilitate trust and learning between parties, increasing incentives for creating long arrangements and specialized contracts. In contrast, infrequent exchanges may require more safeguards to mitigate risks of opportunism (Williamson, 1985).

Uncertainty: Refers to the unanticipated circumstances that can surround a transaction. Uncertainty can be environmental or behavioral. The former relates to difficulties predicting technological performance, demand volume, or meteorological conditions (Jurado et al., 2015). The latter includes the risk of information asymmetry amongst the parties (Akerlof, 1978). The degree of uncertainty in a transaction makes it more imperative that the parties have organizations that allow mechanisms to adapt and "work things out" ex-post (Williamson, 1975, 1979). The higher the uncertainty, the more risk-bearing mechanisms the parties within the contract might want to implement. Depending on the type of safeguards for uncertainty, whether behavioral or environmental, the impact on economic governance will not be the same. In most cases, behavioral uncertainty is related to vertical integration, while environmental uncertainty depends strongly on the asset-specificity of the transaction (Williamson, 1984).

2.1.3 Process of drafting contracts

Considering that parties have bounded rationality, TCT posits that contracts are inherently incomplete, as it is costly to anticipate all potential contingencies in complex transactions (Hart, 1989). Moreover, contracts are seen as mere promises rather than self-enforcing mechanisms, and resolving conflicts through court orders might be costly and sometimes ineffective. Consequently, property rights—defined as the authority of an individual to select any use for specific goods within a non-prohibited class—play a crucial role in shaping contractual agreements (Allen, 1991). Since any contract is built upon the initial rights of each party and the associated enforcement costs, property rights become a key institutional factor in selecting the economic governance for a transaction (Coase, 1960; Williamson, 2002). Finally, TCT suggests that the drafting process is influenced by market competition. When only a single party is available, monopolistic terms prevail, whereas competitive terms emerge when multiple parties compete (Williamson, 1984).

2.2 TCT and Electricity Systems

TCT in electricity systems research has been used to explain the diversity of contractual arrangements as parties aim to minimize energy-related and transaction costs. Contributions in this area range from analyzing why coal producers and electricity generators adopt specific types of long-term, price-adaptive contracts (P. L. Joskow, 1988) to demonstrating that utilities' bounded rationality contributes to contract incompleteness, especially when uncertainty and asset specificity surrounding coal purchases are high (Saussier, 2000). Moreover, research has highlighted the lack of investment safeguards in policies promoting renewable energy within the European Union (EU) (Finon & Perez, 2007), and shown that higher asset specificity in utilities' investments correlates with longer contract durations across Californian electric utilities (Onofri, 2008). These contributions, among others (Perez & Ramos-Real, 2009; Signorini et al., 2015), have advanced our understanding of organizational phenomena in electric systems. While this research has provided valuable insights, it has predominantly focused on the supply side of large-centralized plants, often overlooking specific considerations related to electricity consumers.

The research on electricity consumers has mostly focused on analyzing the tension in liberalized retail markets between dynamic versus fixed electricity tariffs and spot markets versus long-term contracts (Bae et al., 2014; Defeuilley, 2009; P. Joskow & Tirole, 2006; Littlechild, 2021; Mulder & Willems, 2019). If transaction costs are negligible, neoclassical economic theory suggests dynamic tariffs are more beneficial than static ones because dynamic tariffs allow prosumers to adjust consumption and generation in response to price fluctuations, leading to more efficient energy use. Similarly, spot market arrangements outperform long-term contracts without transaction costs by aligning electricity prices with real-time market conditions, fostering optimal decisions. However, to this day, most consumers have opted for fixed or near-fixed electricity tariffs rather than switching to dynamic pricing despite the potential for overall cost saving (ACER-CEER, 2024). P. Joskow and Tirole (2006) has suggested this might be because transaction costs are high. Long-term contracts with fixed tariffs become more cost-effective for electricity consumers. Yet, they have also indicated that this might change as digital technologies are more integrated into electric equipment. Furthermore, Littlechild (2009) has also suggested switching costs from searching for new electricity providers and the diversity of offers as important additional transaction costs that might take time to decrease as the offer of electricity products develops.

From the perspective of prosumers and smart grids, the work from Friedrichsen (2015) has provided an important initial exploration, using TCT to offer theoretical arguments favoring the unbundling of DSO from retail and generation responsibilities. This work emphasizes that smart grid organizations must guarantee non-discrimination and transparency for two reasons. First, the scope and necessity of controlling DERs increase significantly compared to centralized energy resources. Second, granting control of DERs to a third party introduces the potential for opportunistic behavior, where these resources could be used for the third party's benefit, potentially disadvantaging the prosumer.

Compared to previous research, adopting TCT as the primary analytical lens to study the organization of prosumer integration in smart grids requires considering notable differences across many of TCT's dimensions. First, the bounded rationality of prosumers is likely more constrained than that of professional firms and electricity consumers. Prosumers often lack the expertise and resources needed to navigate the complexities of energy markets, which may become even more intricate in smart grids than in typical electricity systems. Second, the nature of asset specificity in these transactions shifts from physical constraints—such as fuel quality or power plant technology—to digital interactions. Several types of data collection, mining, optimization, and risk management activities are performed by digitally connected equipment, enabling smart grids to be smart. Finally, the importance of property rights over data and the competitive dynamics of prosumer integration are amplified due to the novelty of the technology. This is relevant both in the ex-ante evaluation phase and during implementation. Therefore, in the next section, we aim to advance our knowledge of prosumer integration by developing a framework that applies the TCT lens to the governance of prosumers.

3 Conceptual Framework

This section presents our conceptual framework, offering a structured approach to link organizational structures for prosumer integration with different governance models influencing prosumers' transaction costs. The section is organized into two parts. The first part describes the nature of the main transaction costs faced by prosumers, focusing on the interaction between behavioral assumptions and the specific characteristics of smart grid transactions. The second part operationalizes the framework by breaking down transaction costs into two primary dimensions: asset specificity and oversight costs. Using these dimensions, we propose and characterize governance models that 'economize' on transaction costs.

3.1 Nature of prosumer transactions costs in smart grids

The transition from traditional electricity systems to smart grids has significant implications for the transaction costs incurred by prosumers. In conventional systems, transaction costs primarily arise from consumers' efforts to optimize energy consumption, such as switching costs when transitioning from fixed to dynamic tariffs (Littlechild, 2009) or the costs associated with monitoring dynamic prices (P. Joskow & Tirole, 2006). These costs are largely driven by bounded rationality and the limited availability of consumer technological support. While these 'types' of transaction costs (monitoring and switching costs) persist in smart grids, the automation and digital technologies that underpin their operation introduce new sources of transaction costs, including *(i) the use of prosumer data*, which involves sharing or selling critical information for grid optimization; *(ii) control arrangements*, which define how third parties interact with prosumer-owned energy assets (Friedrichsen, 2015); and *(iii) technological complexity*, which pertains to the need for prosumers to internalize new concepts and responsibilities to participate effectively in smart grids.

3.1.1 Prosumer data

Prosumer data is crucial to the efficiency of smart grids, encompassing not just consumption patterns but also detailed insights, such as appliance usage or EV charging behavior. This data plays a key role in enhancing system coordination, enabling the design of tariffs tailored to prosumer preferences (Schreiber et al., 2015; Valogianni et al., 2020), optimizing DERs' utilization through direct control (Iria & Soares, 2019; Lu et al., 2020), and improving risk management through demand and supply forecasting to mitigate power imbalances (Deng et al., 2020; Winzer et al., 2024). However, the value of this data also brings with it the challenge of governance and ownership, which is central to the debate surrounding its role in smart grid systems.

Because data is often described as a non-rivalrous good—one that can be consumed by multiple actors simultaneously—its widespread use can generate significant benefits (Jones & Tonetti, 2020; Varian, 2000) and, therefore, for some, it is even viewed as a public good (Stiglitz, 2002). However, the risks associated with privacy breaches and unauthorized data use by third parties raise concerns for data subjects -the individuals the data concerns- about sharing their data. As a result, governments and scholars have advocated for granting individuals ownership over their data, allowing each data subject to determine how much they value their privacy (Acquisti et al., 2013; Bélanger & Crossler, 2011; Schwartz, 2012).

In smart grids, the exchange of data and associated privacy concerns can lead to significant monitoring costs—a transaction cost that consumers must bear to enforce their data rights. These monitoring costs arise when data users exploit personal data without proper consent or fair compensation. Therefore, in smart grids, one might argue that the easier it is to enforce data property rights for prosumers, the lower the risk of opportunistic behavior (Stigler, 1980), the lower the monitoring costs, and the greater the incentives for data owners for data sharing.

Moreover, interoperability on data exchange between DERs can also become a source of transaction costs due to asset specificity. If the data is collected using closed systems or stored in specific formats, prosumers face barriers when switching between service providers, as data transferability becomes limited (Kerber & Schweitzer, 2017). This creates lock-in effects, where prosumers may struggle to migrate to alternative providers without incurring high costs, as they might require a change of equipment or incur additional investments. These interoperability challenges often result in high switching costs and may lead to monopolistic control over the data, further diminishing competition.

3.1.2 Control arrangements

Control arrangements define how prosumers' DERs are managed. Through direct or indirect control[1], prosumers may delegate operational authority to third parties so they can manage their energy assets. Under direct control, prosumers relinquish decision-making autonomy by signing an agreement with a DER controller. In contrast, under indirect control, they retain significant authority over their DERs while establishing predefined automation parameters that enable their assets to respond to market signals and grid needs.

Direct control imposes significantly higher monitoring costs on prosumers, who may struggle to verify information or understand the decision logic used by third parties when managing their energy assets. From a TCT perspective, direct control implies a hierarchical structure (Williamson, 1979, 1985) in which a third party holds decision-making authority over the prosumer's DERs. As a result, proving whether third parties act in the prosumer's best interest can be particularly challenging (Friedrichsen, 2015). A third party may simultaneously control multiple assets, employing portfolio strategies that prioritize certain assets at the expense of others. Furthermore, it may leverage superior knowledge of the decision-making process to capture additional profits from prosumers.

In contrast, indirect control can significantly reduce monitoring costs, as control operates through a feedback mechanism between the third-party controller and the prosumer. Rather than a top-down hierarchy, indirect control relies on incentives (Williamson, 1979, 1985) that guide prosumers to act in a certain way. In this framework, ownership of the DER remains with the prosumer, while the third-party operator facilitates decision-making without exerting full authority. Instead of relinquishing control, prosumers receive relevant market signals and retain the ability to adjust automation parameters to optimize or modify the energy management of their assets.

In addition, the control capabilities of energy resources can be limited by design or contractual arrangements, resulting in switching costs. Asset-specificity by design often stems from interoperability challenges. For instance, prosumers may face difficulties integrating their assets with alternative control mechanisms if an energy asset—such as a smart battery or EV charger—is designed exclusively for a particular aggregator, utility, or demand response program. Furthermore, asset-specificity could occur when a DER's exclusive or restricted use ties its operation to warranties or service agreements, limiting third-party access or control.

3.1.3 Technology complexity

The combination of data access and control arrangements introduces novel challenges for consumers transitioning into the role of prosumers, particularly during the ex-ante (screening) and ex-post (contract enforcement) stages of committing to an economic governance framework. For example, in the case of prosumer data usage, even when safeguards are implemented to reduce monitoring and switching costs, prosumers might be limited in understanding the contractual clauses related to data access, transfer rights, or any other liability. Furthermore, in the case of control arrangements, the complexity of smart grid technology—characterized by automation and real-time data exchange between multiple devices- can exacerbate these challenges by making it difficult for prosumers to fully understand the implications of their choices. Without widespread knowledge from prosumers and standard contract agreements governing data usage and control arrangements, technology complexity can also become a source of monitoring and switching costs.

Table 1 summarizes the main transaction costs previously mentioned.

3.2 A Governance Framework for Prosumers

To build our governance framework, we refine the two main transaction costs identified in the previous section (monitoring and switching costs) into two dimensions: the complexity of oversight and DER specificity. The complexity of oversight refers to the monitoring and enforcement costs that prosumers

[1] In direct control the DER asset is obliged to follow the command of a third party; on indirect control the DER asset follows a price signal.

Table 1: Comparison of Transaction Costs in Non-Smart Grids and Smart Grids

Transaction Cost Type	Change to Dynamic tariffs (Non-Smart Grids)	Use of Prosumer Data (Smart Grids)	Control Arrangements (Smart Grids)	Technology Complexity (Smart Grids)
Monitoring Costs	Consumers have limited means to monitor real-time electricity pricing and process information, making it difficult to anticipate cost fluctuations and act on dynamic tariffs.	Costs arise from verifying how prosumer data is used and ensuring compliance with privacy agreements. There is a risk that third parties use data without fair compensation or transparency.	Costs stem from monitoring third-party control over energy assets to ensure they are managed optimally and according to agreements. Poor management can reduce efficiency and financial benefits.	Enforcement of data property rights might be too complex and burdensome for most prosumers unless the process is standardized and becomes common knowledge.
Switching Costs	Consumers hesitate to switch from fixed to dynamic tariffs due to uncertainty about price volatility and administrative burdens.	Proprietary data formats and interoperability issues make transferring data to new service providers or platforms costly for prosumers.	The control of energy assets may be subject to contractual conditions—such as warranties, software locks, or exclusive agreements—limiting interoperability between providers and restricting consumer choices.	Contracts can create barriers due to unclear data rights and liabilities, increasing switching costs from simple electricity contracts to more complex ones.

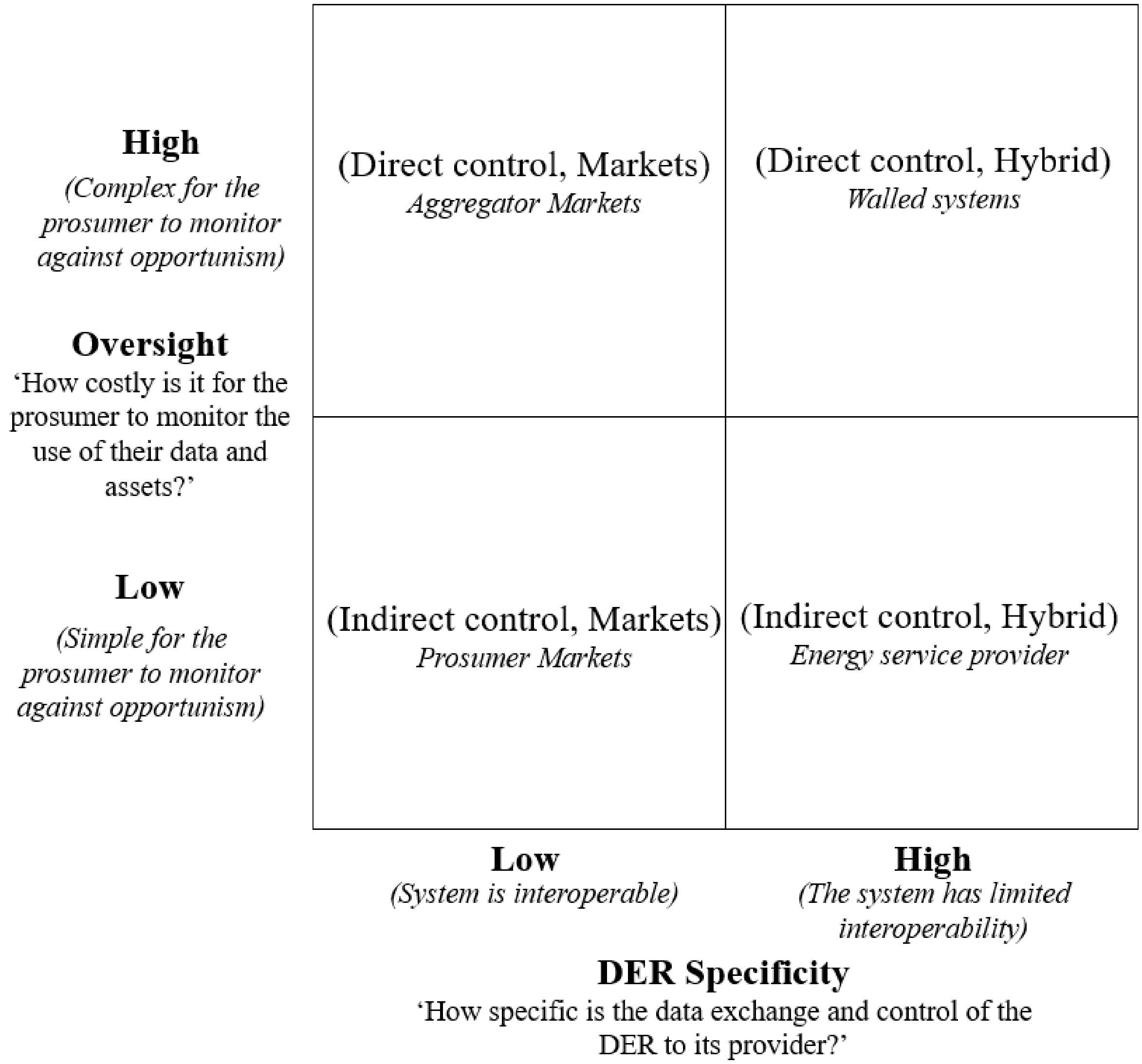
incur to protect against opportunistic behavior by third parties. It captures prosumers' difficulties in monitoring, controlling, and potentially monetizing their DERs while mitigating third-party opportunism. In contrast, DER specificity relates to the costs associated with switching intermediaries and engaging with different actors in the smart grid.

Figure 1 presents our framework as a two-by-two matrix, distinguishing between two levels of transaction costs for each dimension. These magnitudes are represented relative to high or low transaction costs. For instance, high DER specificity increases switching costs by making it more difficult and expensive for prosumers to adapt their energy resources to new systems or market participants. Similarly, greater complexity of oversight raises monitoring costs, making the risks of opportunism higher in the use of data and DERs.

An organizational structure can characterize each quadrant in the framework. Looking at the horizontal axis, which differentiates between high and low DER specificity, we can distinguish between market-based organizations and hybrid (characterized by a combination of markets with hierarchies (Williamson, 1993)) governance models. On the left, where DER specificity is low, interoperability enables prosumers to switch between intermediaries or service providers with relatively low switching costs, fostering competition. High DER specificity on the right constrains prosumers to long-term relationships with specific providers, forming long-term relationships between prosumers and third parties with limited opportunities to change suppliers without incurring costs. On the vertical axis, organizations are differentiated by their control mechanisms, ranging from direct to indirect control. Under direct control, monitoring costs are high because prosumers face difficulties tracking how their data and energy assets are managed, as decision-making processes are external to them. In contrast, indirect control assumes prosumers retain decision-making authority, meaning they receive relevant market information and can set parameters to optimize their assets. Indirect control simplifies asset oversight and reduces the need for extensive data exchange, lowering monitoring costs.

We have developed archetypes of each organization to characterize each quadrant and illustrate how different organizational models has different economic governance. As shown in Figure 1, these governance models include Aggregator Markets, Prosumer Markets, Walled Systems, and Energy Service Providers. In the following section, we provide a detailed explanation of each governance model, focusing on the key transactions in which prosumers are involved.

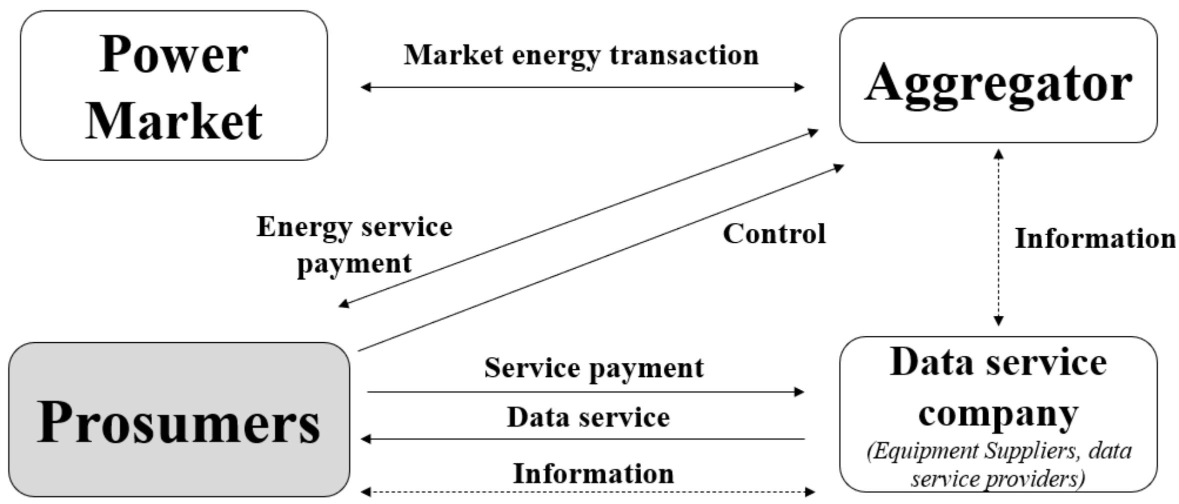
Figure 1: Prosumers framework for economic governance



3.2.1 Aggregator Markets

In Figure 2, we illustrate the Aggregator Market governance model from the perspective of key transactions. It is very important to have a clear definition of aggregator in this context; that, for us, represents the fundamental aggregator described by Burger et al. (2017), which refers to an actor whose added value is to manage the uncertainty of DERs for electricity markets while managing risk for the prosumer. Under the organization of this model, prosumers face a complex oversight of their data and energy assets because they lack direct visibility into the aggregator's strategy and how their data or energy assets contribute to value creation through portfolio strategies -assuming the aggregator is controlling several DERs simultaneously- in power markets. Instead, they only observe their energy service payments. In addition, since their energy resources are interoperable with other systems, the flexibility to switch between aggregators is somewhat limited; thus, prosumers can hire a data service provider to manage and redirect their energy-related data to an aggregator.

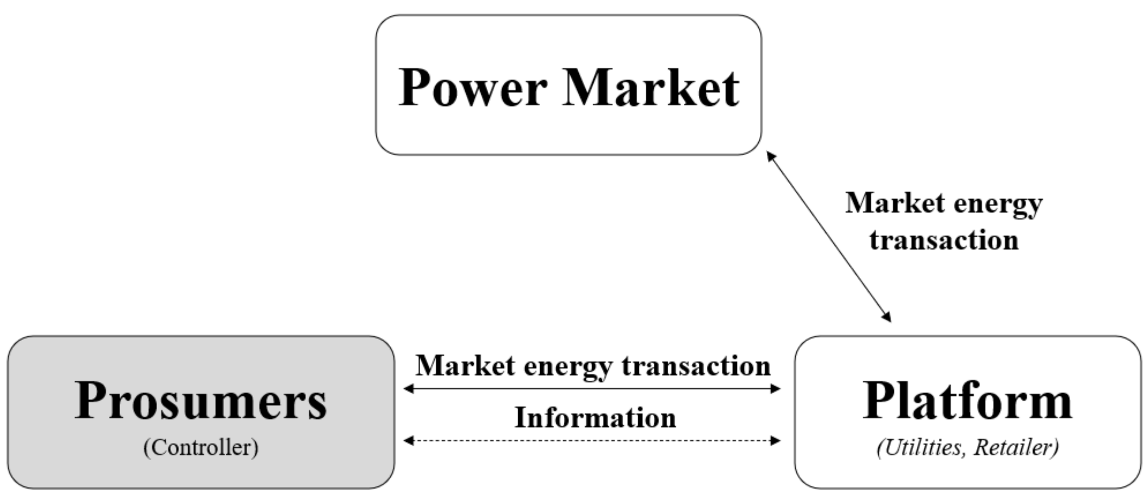
Figure 2: Transactions of Aggregator Markets



3.2.2 Prosumer Markets

Figure 3 illustrates the Prosumer Markets governance model. This model assumes an open platform where prosumers must adhere to platform rules to interact directly with the market. Prosumers decide on the bids they offer and have visibility into how the platform processes these bids to grant them market access. Additionally, they retain control over their energy resources, allowing them to monitor their assets. Since prosumers define their market strategy, they only need to provide the minimum necessary data to the platform without compromising data privacy.

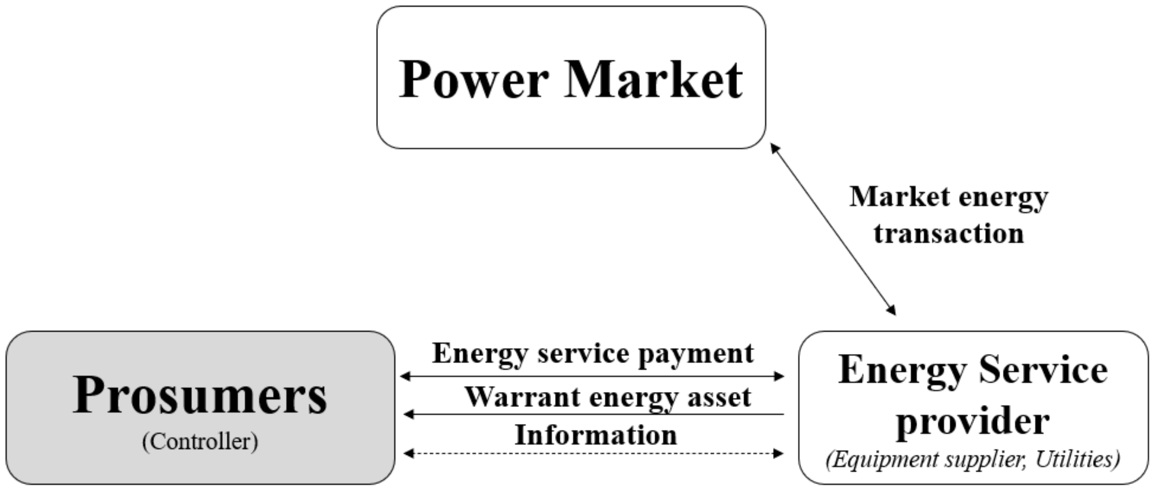
Figure 3: Transactions of Prosumer Markets



3.2.3 Energy service providers

In Figure 4, prosumers acquire energy services directly from an energy service provider, who may also be responsible for maintaining and ensuring the proper functioning of the energy asset. However, the prosumer retains full control over how and when the asset is used for energy provision. Since control is indirect, the complexity of oversight is reduced, as prosumers ultimately decide when their energy resource is utilized. However, switching costs remain high, as changing providers often require either replacing the energy asset or purchasing it from the current service provider to transition to a different intermediary or governance model.

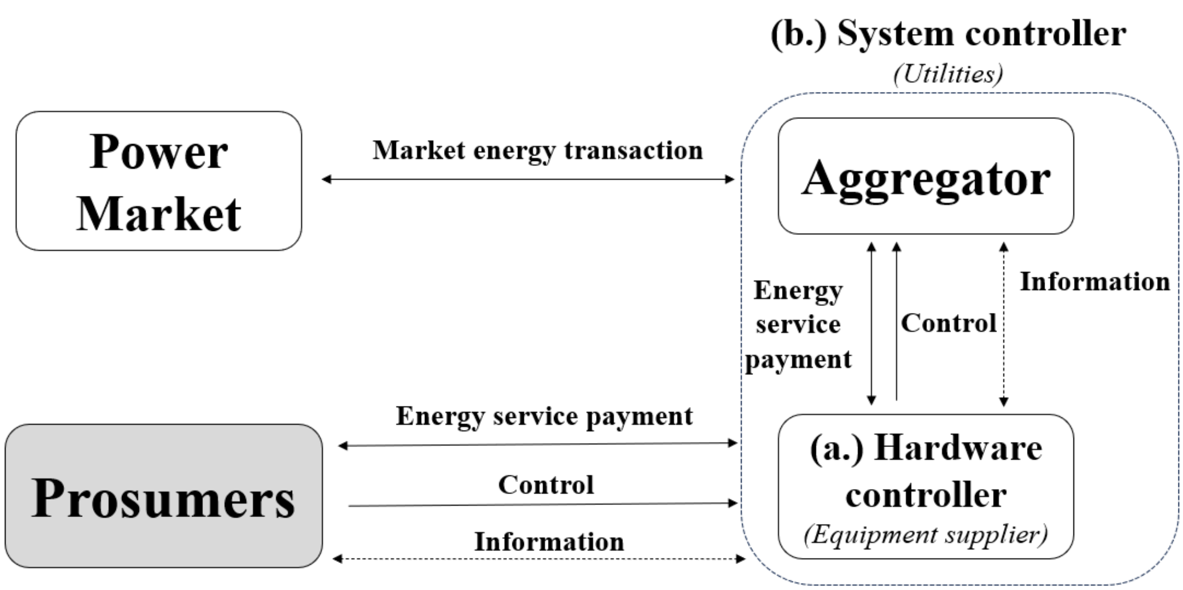
Figure 4: Transactions of Energy service providers



3.2.4 Walled Systems

In Figure 5, prosumers interact with two types of actors: either a system controller that integrates and performs the tasks of an aggregator or a hardware controller that transfers power market responsibilities to an aggregator. Walled systems are highly structured and restrictive models in which prosumers are confined to specific energy systems or platforms. The key difference compared to energy service companies is that prosumers relinquish control over using their energy assets.

Figure 5: Transactions of Walled Systems

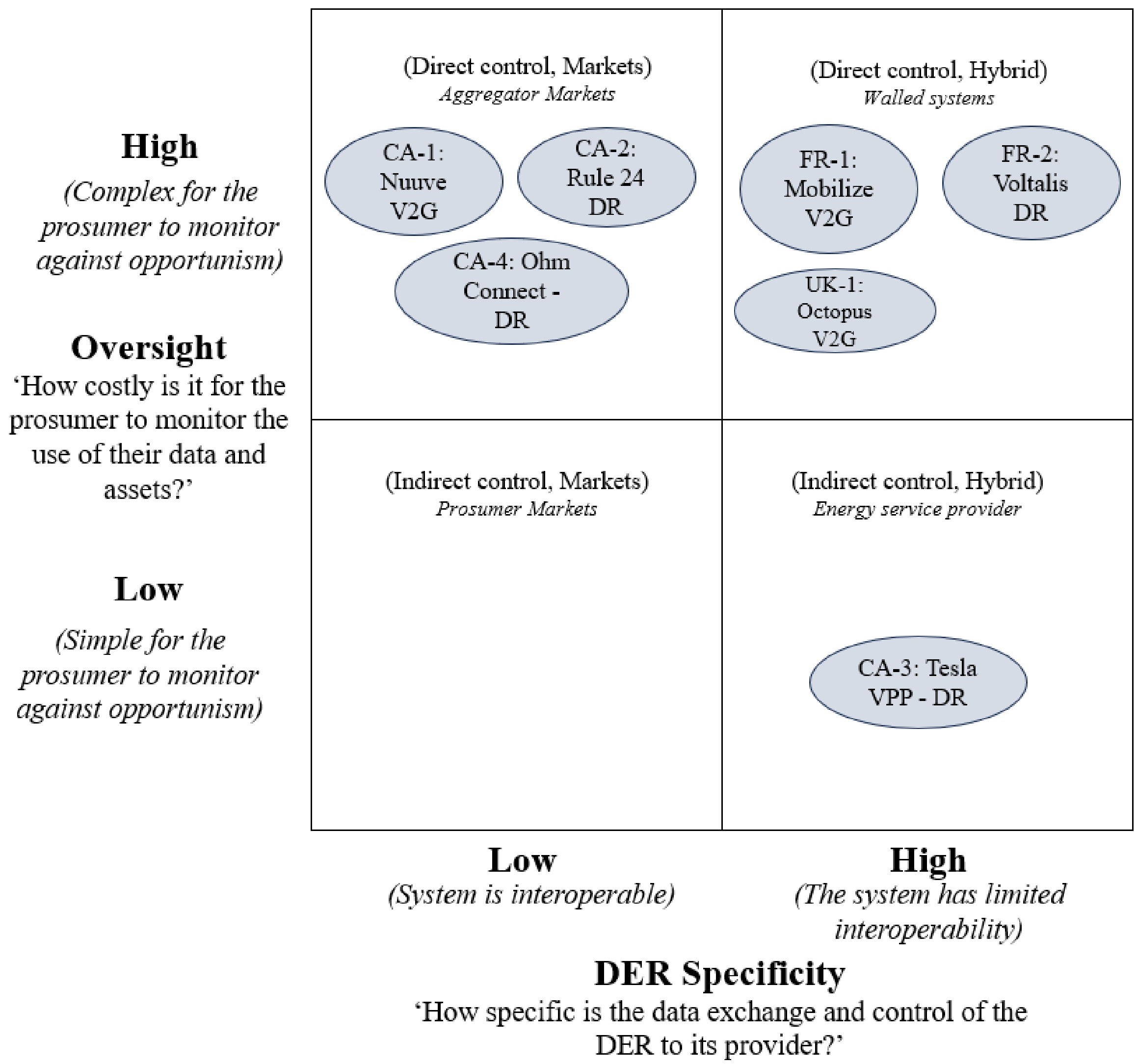


4 A comparative analysis using the framework

This section applies our conceptual framework to analyze business early business models in California (CA), the United States of America (USA), France (FR), and the United Kingdom (UK).

Figure 6 compares the eight existing business models we found in the comparative analysis of the conceptual framework we proposed in the previous section. In what follows, we provide details on how we arrive at such a classification.

Figure 6: Comparison of business models



4.1 Strategy for comparative analysis

We selected France, the United Kingdom, and California for our analysis because these regions are among the countries that have advanced the most in deploying DERs and simultaneously have distinct yet comparable regulatory landscapes. While the UK and California operate under different legal traditions—common law in the UK and a mix of common, civil, and federal law in California—France follows a civil law system. Despite these differences, all three regions share a liberalized electricity market where competition plays a crucial regulatory role. Additionally, our ability to work fluently in English and French allows us to analyze the latest developments in these markets.

We begin each country study with an overview of the regulatory frameworks governing data property rights and interoperability, providing context for the business models under review. Indeed, TCT suggests the influence of property rights and the institutional framework on transaction costs (Coase, 1960; Williamson, 1973). We collect secondary data directly from service providers' websites and focus on business models related to Demand Response (DR) and Vehicle-to-Grid (V2G) services.

DR allows consumers to adjust their electricity consumption to balance electricity systems, mostly curtailing energy usage during peak demand or grid stress. V2G leverages energy stored in EV batteries to support grid stability. By discharging power during periods of low renewable generation or excess demand, V2G helps integrate EVs to maximize the consumption of intermittent renewable energy and the energy system while providing electricity flows. Considering these two business models for integrating prosumers, we are covering many offers in smart grids.

4.2 California

Data property rights in California: Data property rights in the USA are primarily governed by federal laws defining individuals' rights over their data. The *California Consumer Privacy Act* (CCPA), enacted in 2018, provides Californians with several key rights, including the ability to know what personal information is collected about them, the option to delete that information, and the right to opt out of its sale or sharing (California, 2018). Personal information, as defined by the CCPA, encompasses any data that identifies, relates to, or can reasonably be linked, directly or indirectly, to an individual or their household. The CCPA is responsible for enforcing these rights, ensuring that businesses using personal data offer at least two methods for individuals to submit their requests for information about their data. These methods must include at least one toll-free phone number and, if the business operates a website, a way for individuals to submit requests online. An email should be sufficient for companies that operate exclusively online to inform the data user about the data being collected. However, we have not found any documentation regarding the difficulties in enforcing or the time of response of the business collecting the data.

Mandated interoperability in California: California Rule 21 defines a framework for DER integration with utilities, including interconnection, operation, and metering requirements. It requires utilities to provide the interoperability needed to incorporate DER to support grid stability (allowing the control of DERs to give energy and power services). The interoperability is guaranteed among the IEEE 2030.5 standard (also known as Smart Energy Profile 2.0) as the default communications protocol (C. E. Commission, 2024). However, implementing the standard at its full level of operation still remains on implementation (C. E. Commission, 2020; C. P. U. Commission, 2025). Furthermore, for the integration of EVs in the form of V2G services, Rule 21 makes mandatory the application of SAE241 J-3072 and IEEE242 1547 communication standards to exchange information with the utility operator (C. P. U. Commission, 2025; Martinot, 2019).

Case CA-1: Nuvve - V2G
Nuvve is a company that sells EVSE preconfigured with a Grid Integrated Platform (GIVe™), offering solutions for V2G implementation. The platform allows a parked EV to charge its battery and discharge stored energy back to the grid in response to real-time signals from a third party. Nuvve's, GIVe™ can also provide the services of management of the EV; for example, they offer to provide battery warranty management services (Corp., 2025).

Evaluation of Nuvve business model: Nuvve's business model for integrating prosumer considers mainly its dual role as hardware and service provider; on one hand, they provide the EVSE and the service of managing the energy process. From the service management perspective, their energy business model considers direct control in an interoperable environment, as nothing impedes a prosumer from changing from Nuvve to another aggregator. Thus, this business model aligns with the **Aggregator market** governance model.

Case CA-2: Rule 24 DR programs
Pacific Gas and Electric Company (PG&E), San Diego Gas & Electric (SDGE) and Southern California

Edison (SCE) are vertically integrated utilities. Through Electric Rule 24 they are all required to enable prosumers to participate in DR programs managed by third-party DR providers. These programs allow market mechanisms to incentivize reducing electricity consumption during peak demand periods. A critical aspect of Rule 24 is its facilitation of data sharing between the utilities and DR providers, and the participation rules that allow DR providers to aggregate and bid electricity reductions into the wholesale market operated by the California Independent System Operator (CAISO). From a data and interoperability standpoint, Rule 24 establishes a framework for customers to authorize PG&E, SDGE, and SEC to share their electricity usage data and relevant account information with selected DR providers. This data-sharing mechanism allows DR providers access to real-time or historical consumption patterns necessary for demand aggregation and market bidding. Customers can manage their data-sharing authorizations through PG&E's and SEC online portal. The ShareMyData tool allows users to review existing authorizations and verify data-sharing agreements with DRPs (Pacific Gas and Electric Company, 2025).

EnergyHub, OhmConnect, Olivine, Enel X, Tesla, and Leapfrog Power are some third parties authorized to participate according to Rule 24 in PG&E, SDGE, and SEC DR programs (CPUC, 2025). One of the main services that they can provide is the Emergency Load Reduction Program (ELRP), that incentivizes prosumers—households or businesses with battery storage or solar panels—to support grid stability during peak demand periods. Through the program, PV and energy storage owners can discharge stored energy to the grid and earn $2 per kWh for their contribution (SCE, 2025).

Evaluation of Rule 24 organization: Rule 24 mandates that the utilities enables interoperability and direct control of prosumers DERs. Furthermore, prosumers can select which aggregator to use and share their data with. Thus, organizational model that PG&E's and SCE must follow to comply with Rule 24, aligns with the **Aggregator Market** governance model.

Case CA-3: Tesla Virtual Power Plant - DR

Tesla's Virtual Power Plant (VPP) enables Powerwall owners to participate in grid support programs offered by PG&E (Tesla, 2025a) and SCE (Tesla, 2025b) through the Emergency Load Reduction Program (ELRP). By subscribing to the program, power wall users can contribute to supplying energy during peak demand periods by opting in, helping maintain grid stability while earning USD 2 per kWh exported. Participants retain control over their energy reserves by setting a Backup Reserve level, ensuring they always have power for outages. Events typically occur between May and October from 4–9 p.m., lasting one to five hours, with an annual cap of 60 hours.

Participation is flexible and voluntary, allowing users to opt out of individual events via the Tesla app or suspend their involvement entirely without penalties. Compensation is provided as bill credits for direct enrollees, while third-party aggregators handle incentives for other participants. Eligibility requires a residential service account with PG&E or SCE, a certified interconnection agreement, and no enrollment in conflicting DR programs.

Evaluation of Tesla VPP business model: Tesla VPP is only compatible with powerwalls. Furthermore, the type of control of ELRP allows only indirect control, as the prosumer can opt out and define the backup reserve level to provide the service. Though Tesla is not directly providing the hardware as part of the service, it is providing a fixed curtailment service; thus, while the system is not identical to the governance model of **Energy Service Provider**, it is surely aligned in the same quadrant.

Case CA-4: OhmConnect - DR

OhmConnect partners with utilities like PG&E and SCE in California to offer demand response programs, allowing prosumers to reduce energy consumption during peak times in exchange for discounts on their electricity bills. This is achieved through the control of smart home devices such as thermostats (e.g., Google Nest, ecobee, Sensi, Honeywell, and Wiser), all of which integrate with OhmConnect's platform to manage energy use efficiently (OhmConnect, 2025).

Evaluation of Ohm Connect - DR: According to the type of service of OhmConnect, the control is conceded to Ohm directly through the smart appliances of certain loads. Furthermore, the system is interoperable with various kinds of hardware that can be aggregated. Thus, the OhmConnect business model aligns more with **Aggregator Market**.

Others

We have not found additional V2G commercial services for residential prosumers. However, we have discovered several V2G pilot projects with private fleets and examples of them. Furthermore, among the aggregators that can participate in the Rule 24 program, a large share does not offer services directed to prosumers; for instance, Energy Hub, Olivine, Enel X, and Leap-frog are mostly a business-to-business model, and their objective is to unify and optimize energy resources for equipment manufacturers, or utilities, managing multiple DER classes in one integrated platform.

4.3 France

Data property rights in France: Data property rights in France are primarily governed by the General Data Protection Regulation (GDPR) and the *Loi Informatique et Libertés* (French Data Protection Act). These regulations give individuals control over their data, including the right to access, rectify inaccuracies, object to processing, and even erase their data (CNIL, 2025). The *Commission Nationale de l'Informatique et des Libertés* (CNIL) is the regulatory authority responsible for enforcing these rights and ensuring compliance across various sectors. To our knowledge, the regulation is silent on the times for enforcing data subject rights.

Another important regulation influencing France's institutional framework at the EU level is Regulation (EU) 2022/868, known as the Data Governance Act (DGA), which defines requirements to support data sharing and reusability while maintaining privacy and confidentiality. The DGA aims to create common European data spaces across diverse sectors, including energy, health, and mobility, focusing on digital market fairness, trust, and security. Additionally, the Data Act (EU) 2023/2854 mandates that users have access to data generated by connected devices, providing fair access to third-party entities authorized by users. However, to our knowledge, the regulation is being implemented by member states, and there is currently no possibility of sharing prosumers' data through EU data spaces.

Mandated interoperability in France: While there is currently no mandatory level of interoperability among DERs or EVs across Europe, significant steps are being proposed to ensure interoperability in the future. The Third Energy Package and the recast Electricity Directive further emphasize the need for consumer access to consumption data, including metering and switching data (European Commission, 2019). Regulation (EU) 2023/1162 in 2023 outlines requirements that all data systems in electricity systems be capable of seamless interaction, facilitating efficient data exchange across the EU. In the specific case of EV, the European Alternative Fuels Infrastructure Regulation (AFIR) proposes that starting January 1, 2027, all new and refurbished public charging points and new private charging points must support the same communication protocol in their front-end and back-end (ISO 15118-20 and OCPP). Additionally, public charging points offering automated services like plug-and-charge must support both ISO 15118-2 and ISO 15118-20 (European Commission, 2019, 2025).

Case FR-1: Mobilize - V2G
In collaboration with The Mobility House, Mobilize, the energy company of Renault Group, has launched a V2G project in France, enabling Renault R5 EVs to feed energy back into the grid. Furthermore, EVs can be automated to charge when electricity demand is low. However, prosumers get remunerated by their "V2G Hours", the number of hours that the EV is connected under a "V2G schedule" - the times Mobilize considers that V2G might happen. This revenue from "V2G hours" is deducted from the user's monthly electricity bill. To participate in this program, customers must meet three key conditions: First, they must own a Renault R5 or Renault R4. Second, they need the Mobilize Powerbox Verso, a bidirectional charging station compatible with the V2G system, which must be ordered through Renault dealerships. Finally, users must subscribe to an electricity contract with Mobilize Power, operated by The Mobility House (Renault, 2025).

Evaluation of Mobilize business model: Interoperability is limited because of the three conditions related to hardware costs; the service does not allow for other EV brands. Furthermore, Mobilize has direct control of the EV, with the prosumer being remunerated by "V2G hours" rather than power or energy, which are market transactions. Thus, the Mobilize Power system aligns more with a **Walled system** governance model.

Case FR-2: Voltalis - DR

Voltalis installs connected thermostats in homes. These thermostats allow Voltalis to temporarily reduce energy consumption during peak times or when renewable energy production drops, helping to balance the grid and avoid using costly, polluting fossil fuel power plants. In return, Voltalis receives compensation from the electricity system for stabilizing the grid while users save on discounts on their electricity bills.

Evaluation of Voltalis: There is limited interoperability of the system, as Voltalis operates only the hardware installed by them (the thermostat). Furthermore, the control is direct, as Voltalis decides when the curtailment happens without the decision of the prosumer. Thus, this aligns with the **Walled system** governance model.

Others
In France, residential DR remains underdeveloped, with most flexibility programs targeting commercial and industrial consumers rather than individual households. Existing residential initiatives primarily rely on time-of-use tariffs and indirect incentives rather than automated, asset-controlled demand responses. For instance, EDF's Tempo tariff encourages consumers to shift electricity consumption away from peak periods by offering lower rates on designated "blue" days and significantly higher rates on "red" days. Similarly, TotalEnergies' 'Super Valley' prices provide discounted electricity prices during off-peak hours, particularly for EV charging. However, these models depend on consumer behavior rather than real-time automated demand control.

Regarding V2G, France has seen pilot projects such as the Renault-led "Smart Island" initiative in Belle-Île-en-Mer and the Dreev V2G service, a joint venture between EDF and Nuvve, which offers bidirectional charging solutions for businesses and fleets. While Dreev has positioned itself as a key player in V2G technology, its services are not yet widely available to individual residential customers.

4.4 United Kingdom

Data property rights: In the UK, data property rights are regulated under the UK General Data Protection Regulation (UK GDPR), which, after Brexit, replaced the EU GDPR but retained its core principles Government, 2021. The UK GDPR grants individuals significant control over their data, including rights to access, rectify, and delete information. The Data Protection Act 2018 further supplements the UK GDPR, ensuring compliance and introducing provisions for data security and enforcement Parliament, 2018.

Mandated interoperability: UK Grid Code Compliance requires that system operator support DER integration (National Grid, 2023). Grid interoperability also involves the ability of EV chargers and other DERs to communicate with grid operators for load management and balancing. UK Smart Charging Regulations (2023) ensure that all new home and workplace EV chargers are compatible with smart charging standards like Open Charge Point Protocol (OCPP) and ISO 15118 (for Transport, 2023).

Case UK-1: Octopus Energy Agile - V2G
Octopus Energy Agile program allows EVs to contribute to grid balancing using a Wallbox Quasar 1 charger, a compatible EV, and a smart meter. Participants also need a G99 certificate to export energy to the grid. The program requires about 12 hours of charging every few days, with a monthly limit of 333 kWh (1,084 miles). Current compatible vehicles include the Nissan Leaf, Nissan e-NV200, and Mitsubishi Outlander PHEV, with more integrations underway.

Evaluation of UK-1 Octopus : Octopus interoperability is limited to a single EVSE. However, we do not know why they do not accept other EVSES even though they accept several brands of EVs. Furthermore, it is considered a direct control of the EV. Thus, this business model is aligned with a **Walled Garden** governance model.

Others
In the UK, residential Demand Side Response (DSR) is still in its early stages, with most existing programs targeting businesses rather than individual households. The few residential offerings primarily rely on time-of-use tariffs, encouraging behavioral changes rather than automated, asset-controlled demand response. For example, Octopus Energy's Intelligent Octopus and Octopus Go tariffs incentivize

EV owners to charge during off-peak hours. OVO Energy's Charge Anytime offers similar benefits by integrating smart charging with dynamic pricing. However, these models depend on consumer participation rather than direct asset control. Additionally, while there have been past pilot projects exploring V2G capabilities, such as the OVO-Kaluza trials, we know no large-scale V2G programs are currently available to residential customers.

5 Discussions

Our research was motivated by prior studies that proposed various organizational structures for integrating prosumers into smart grids. However, no unified perspective has explored the potential consequences for prosumers when choosing between different governance regimes. Existing literature has largely assumed that the governance challenges faced by electricity consumers apply identically to prosumers in smart grids. However, according to TCT, different organizational arrangements expose prosumers to varying risks of opportunism (Friedrichsen, 2015). To address this gap, our research updates and refines the definition of transaction costs for prosumers, presenting a theoretically grounded framework that offers theoretical and managerial contributions. Additionally, it establishes a foundation for future research on how technological and market contexts may influence the dominance of one organizational structure over another.

5.1 Contributions

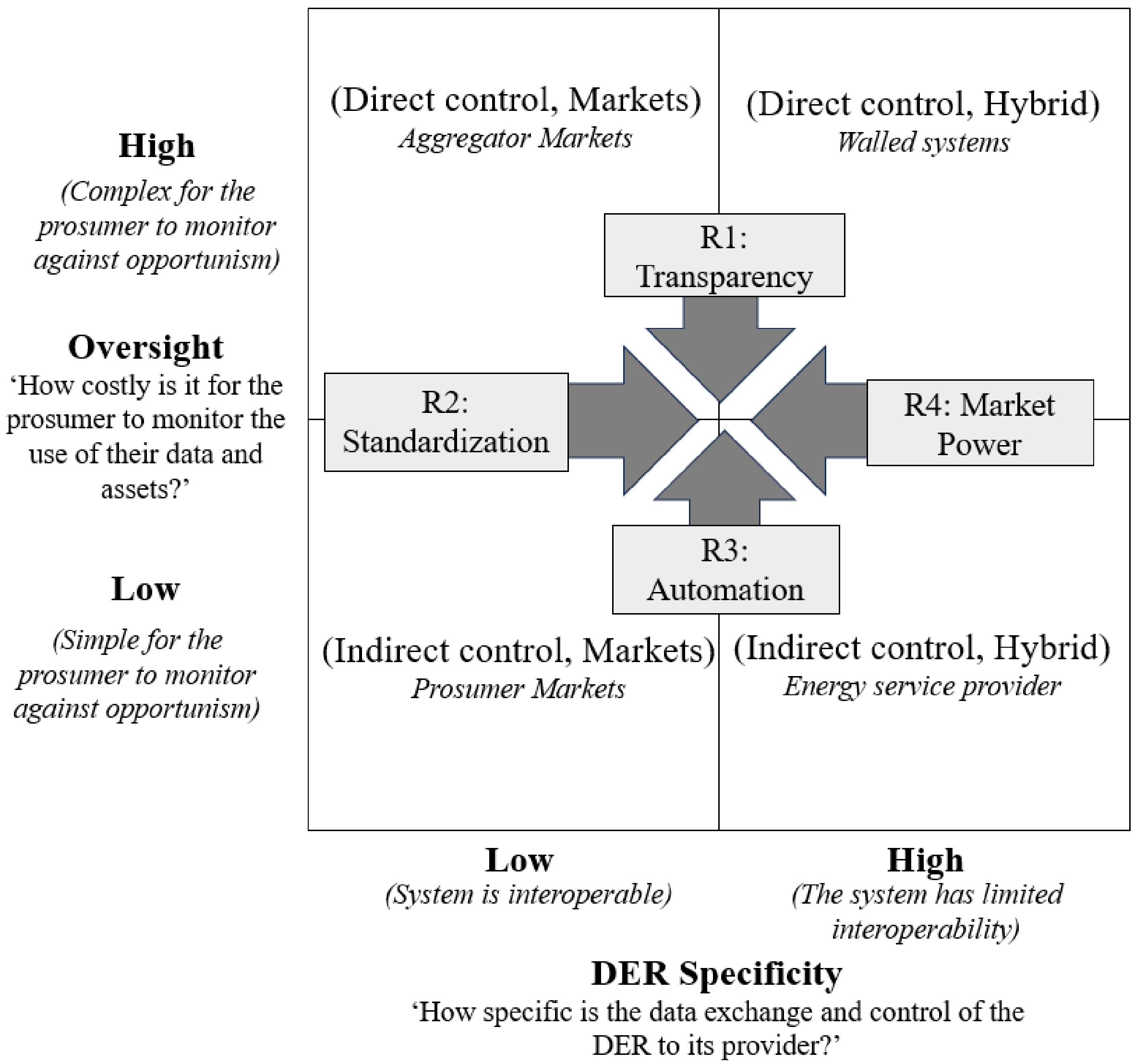
Our theoretical contribution is identifying two key organizational characteristics in prosumer contracts that distinguish existing business models in our comparative analysis. We categorize them based on direct vs. indirect control, which relates to oversight costs as the first dimension, and market vs. hybrid forms, which help differentiate switching costs as the second dimension. This framework fills a gap in the study of prosumer integration. As we previously emphasized, the question of which governance framework should dominate to advance smart grids has largely been a secondary concern for researchers. It is often treated as a trivial decision or assumed to mirror traditional consumer governance models. However, our framework provides theoretically grounded reasoning to challenge this assumption, demonstrating that the choice of governance structure is far from trivial.

Our managerial contribution is that our comparative analysis reveals a clear gap in organizations that simultaneously apply indirect control and market-based governance despite these arrangements potentially offering prosumers the lowest risk of opportunism. High DER specificity increases switching costs by making it more difficult and expensive for prosumers to adapt their energy resources to new systems or market participants. Likewise, greater oversight complexity raises monitoring costs, heightening the risks of opportunism in using data and DERs. This finding raises important managerial questions about why business models in the analyzed contexts have not yet leveraged this opportunity as a strategy to attract prosumers. In the next subsection, we will further explore the potential of our framework as a foundation for future research directions.

5.2 Future research questions

In Figure 7, we present our conceptual framework, where four key driving factors shape the boundaries of organizational structures for prosumer integration. First, **Transparency** may encourage more organizations with direct control by reducing the need for costly oversight. Second, **Standardization** can facilitate the development of interoperable systems, making integration more seamless across different stakeholders. Third, **Automation** may lead to the emergence of indirect forms of control, where decision-making processes become increasingly decentralized. Finally, **Market Power** can drive the dominance of proprietary systems, potentially limiting competition and interoperability. These factors collectively influence how prosumers engage with smart grids, determining whether they rely on intermediaries or participate directly in the market. In what follows, we formalize these factors as research questions, providing a foundation for future research.

Figure 7: Research questions



5.2.1 Transparency

What mechanisms can be implemented to enhance transparency in prosumer-driven energy systems, and how do these mechanisms influence governance structures?
Transparency is critical in reducing information asymmetries and mitigating the risks of opportunistic behavior of third parties seeking direct control over prosumer DERs. Insufficient transparency can lead to suboptimal decision-making, higher oversight costs, and diminished trust in intermediaries, ultimately affecting the efficiency and effectiveness of prosumer participation. However, enhancing transparency might present a trade-off between adequate visibility into the control of DERs and managing compliance costs. Understanding how regulation and governance models manage this trade-off is important for future research.

5.2.2 Standardization

How can determining what should be standardized versus what can remain flexible in energy systems impact interoperability and governance of prosumer participation?
Standardization is the main driver that guarantees interoperability in smart grids and expands the range of market opportunities available to prosumers. Standardization can lower entry barriers and enhance system efficiency by facilitating seamless integration across different platforms and technologies. However, excessive standardization may inadvertently constrain innovation, limiting the development of novel business models and technological solutions. Achieving interoperability requires significant upfront investments and stakeholder coordination, often introducing additional governance costs and institutional complexities. A central challenge in standardization efforts is reconciling the competing interests of industry actors, regulators, and technology providers, each of whom may have divergent priorities. An important avenue for future research is to examine the impact of industry-led versus government-led standardization initiatives on system design and market structure. Additionally, understanding the extent to which flexibility should be preserved to accommodate proprietary business models without undermining interoperability is a critical policy question with implications for market competition, consumer choice, and long-term system resilience.

5.2.3 Automation

What key activities should be automated in prosumer-driven energy systems, and how can learning from prosumer behavior be optimized while minimizing the need for human intervention?
Automation might be a key driver in reducing prosumers' attention and operational costs in systems governed by indirect control. By leveraging automated decision-making, prosumers can set predefined limits on using their DERs or establish price thresholds that align with their consumption patterns or preferences. However, a fundamental challenge in automation lies in determining the appropriate balance between automated processes and active prosumer involvement. Overly automated or opaque systems risk alienating users, potentially reducing engagement and trust in the system. Moreover, reliance on algorithmic decision-making raises concerns related to cybersecurity, regulatory compliance, and overall system resilience. Future research should explore which aspects of prosumer participation under indirect control—such as bidding strategies, energy trading, or demand response—benefit most from automation and to what extent over-reliance on automated systems introduces vulnerabilities. Understanding how to design automation frameworks that optimize efficiency while maintaining prosumer agency and trust is a critical avenue for further investigation.

5.2.4 Market Power

How do different forms of market power influence interoperability in prosumer-driven energy systems, and what strategies can be used to manage these power dynamics?
Market power plays a crucial role in shaping the competitive dynamics of prosumer-driven energy markets, as dominant players may reinforce closed systems to strengthen their monopolistic position,

ultimately limiting consumer choice and market competition. Early entrants that successfully establish proprietary platforms can leverage their advantage to create barriers to entry for smaller actors, reducing market diversity and innovation. A key challenge lies in understanding how existing market structures reinforce or mitigate these effects, particularly concerning high switching costs that can lock prosumers into specific ecosystems. Investigating the strategies dominant players employ to entrench their market position and the regulatory and policy mechanisms that can counteract these effects is an essential avenue for future research. This includes exploring interventions such as interoperability mandates, platform neutrality requirements, and market-based incentives designed to foster competition while ensuring a level playing field for all market participants.

6 Conclusions

This study contributes to ongoing research on smart grids by examining residential prosumer integration and developing a conceptual framework based on TCT. We identify four governance models that shape prosumer participation by analyzing monitoring and switching costs. Our comparative case studies demonstrate how this framework offers valuable theoretical insights into the trade-offs inherent in different governance structures, particularly control mechanisms and interoperability.

Our theoretical contribution is identifying two key organizational characteristics in prosumer contracts that distinguish existing business models and fill a gap in the study of prosumer integration, as governance structures have often been a secondary concern in smart grid research. Our framework provides a theoretically grounded argument that these decisions are far from trivial. Furthermore, through our comparative analysis, we reveal a clear gap in organizations that simultaneously apply indirect control and market-based governance, despite these arrangements potentially offering prosumers the lowest risk of opportunism.

Future research should investigate how evolving regulatory frameworks, technological advancements, and market structures influence prosumer participation. Additionally, exploring the role of transparency, standardization, automation, and market power can provide deeper insights into optimizing governance models for residential prosumer integration. Ultimately, the successful integration of prosumers into smart grids requires well-designed governance structures that align economic incentives, technological capabilities, and policy objectives. This study lays the foundation for future research and policy discussions by enhancing our understanding of these dynamics.

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