



Exploring the complexities of coordinating electric vehicles with electricity grids : computation costs, information value, transaction costs and regulation

Diego Manuel Cebreros-Saettone

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Exploring the complexities of coordinating electric vehicles with electricity grids: computation costs, information value, transaction costs and regulation

*Explorer les complexités de la coordination des véhicules
électriques avec les réseaux électriques : coûts de calcul,
valeur de l'information, coût de transactions et régulation*

Thèse de doctorat de l'université Paris-Saclay

École doctorale n°573: matériaux, systèmes, usages (INTERFACES)

Spécialité de doctorat: Ingénierie économique

Graduate School : Science de l'ingénierie et des systèmes. Référent. CentraleSupélec

Thèse préparée dans l'unité de recherche **Laboratoire Génie Industriel** (Université Paris-Saclay, CentraleSupélec), sous la direction de **Pascal DA COSTA**, professeur, et le co-encadrement de **Yannick PEREZ**, professeur, et de **Jan LEPOUTRE**, professeur.

Thèse soutenue à Paris-Saclay, le 12 Mai 2025, par

Diego Manuel CEBREROS-SAETTONE

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Titre: Explorer les complexités de la coordination des véhicules électriques avec les réseaux électriques : coûts de calcul, valeur de l'information, Coût de transactions et régulation.

Mots clés: Véhicules électriques, Systèmes électriques, Science de la complexité, Vehicle-to-Grid, Recharge intelligente.

Résumé: Cette thèse examine un défi majeur : Comment les véhicules électriques (VE) devraient-ils être coordonnés avec les systèmes électriques pour devenir des outils de réduction des émissions de gaz à effet de serre (GES) ? Bien que les barrières techniques à la mise en œuvre de la technologie Vehicle-to-Grid (V2G) soient progressivement levées grâce à la standardisation et à l'introduction de véhicules compatibles V2G, la commercialisation de la V2G et de la recharge intelligente continue d'être freinée par des incertitudes liées aux modèles économiques, des obstacles à l'adoption par les utilisateurs et des perspectives fragmentées parmi les parties prenantes de l'industrie.

Ma recherche démontre que l'intégration des VE dans les systèmes électriques n'est pas seulement un défi technique, mais une interaction complexe entre le flux d'informations, les cadres de participation des utilisateurs et l'alignement des objectifs économiques et environnementaux. Le succès de la V2G et d'autres applications de réseaux intelligents dépend non seulement de la faisabilité technologique, mais aussi de la manière dont les utilisateurs de VE sont intégrés dans les opérations du

réseau et les mécanismes de marché. Les structures de gouvernance, les cadres réglementaires et les dynamiques de marché façonnent tous les incitatifs et les obstacles à la participation, influençant l'évolutivité et l'efficacité de la coordination des réseaux intelligents.

En cadrant le défi de la coordination comme un problème de complexité de l'information, de gouvernance et de conception systémique, cette thèse pose les bases d'une approche plus holistique pour intégrer la V2G et les énergies renouvelables dans la transition énergétique. De futures recherches devraient explorer comment les cadres réglementaires en évolution, les avancées technologiques et les structures de marché impactent la participation des consommateurs. En outre, l'étude de la transparence, de la standardisation, de l'automatisation et du pouvoir de marché fournira des aperçus cruciaux pour optimiser les modèles de gouvernance pour l'intégration des producteurs-consommateurs résidentiels et garantir que les systèmes de réseaux intelligents soutiennent à la fois l'efficacité économique et les objectifs de décarbonation.

Title: Exploring the Complexity of Coordinating Electric Vehicles with Electricity Grids: Computation Costs, Information Value, Transaction Costs and Regulation.

Keywords: Electric Vehicles, Electricity Systems, Complexity Science, Vehicle-to-Grid, Smart Charging

Abstract: This dissertation investigates a critical challenge: How should electric vehicles (EVs) be coordinated with electricity systems to become tools for mitigating greenhouse gas (GHG) emissions? While technical barriers in Vehicle-to-Grid (V2G) implementation are progressively addressed through standardization and the introduction of V2G-capable vehicles, the commercialization of V2G and smart charging continues to be hindered by business model uncertainties, user adoption barriers, and fragmented perspectives among industry stakeholders.

My research demonstrates that the integration of EVs into electricity systems is not only a technical challenge but a complex interaction of information flow, user participation frameworks, and the alignment of economic and environmental objectives. The success of V2G and other smart grid applications is contingent not only on technological feasibility but also on how effectively EV users

are integrated into grid operations and market mechanisms. Governance structures, regulatory frameworks, and market dynamics all shape the incentives and barriers to participation, influencing the scalability and effectiveness of smart grid coordination.

By framing the coordination challenge as one of information complexity, governance, and systemic design, this dissertation lays the groundwork for a more holistic approach to integrating V2G and renewable energy into the energy transition. Future research should explore how evolving regulatory frameworks, technological advancements, and market structures impact consumer participation. Additionally, examining transparency, standardization, automation, and market power will provide crucial insights into optimizing governance models for residential prosumer integration and ensuring that smart grid systems support both economic efficiency and decarbonization goals.

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Preface

"Think how hard physics will be if particles could think." - Murray Gell-Mann¹

This dissertation represents nearly three years of research in collaboration with my advisors and coauthors. My work focuses on implementing Vehicle-to-Grid (V2G) technology, which enables electric vehicles (EVs) to store and supply energy to the grid. V2G can address one of the key challenges in fully decarbonizing electricity systems: the need for large-scale energy storage. By mitigating the intermittency of renewable energy sources like wind and solar, V2G could reduce reliance on fossil fuels, ensuring electricity demand is met even when the sun isn't shining or the wind isn't blowing.

My journey toward this research began over sixteen years ago when I pursued a degree in Environmental Engineering, driven by a desire to understand how technology could address pressing environmental issues, from pollution in the mining industry to global warming. Initially, I was fascinated by applying physics, chemistry, and biology to solve ecological problems—managing polluted sites, identifying sources of greenhouse gas emissions, and developing sustainability strategies. However, I soon realized that the biggest challenge was not the absence of technological solutions but the difficulty of scaling them. While many argued that economic constraints were the primary barrier—believing sustainable technologies would only be adopted if financially viable—I sensed that a deeper, more structural issue was at play.

To better understand this challenge, I pursued a master's degree in theoretical economics, convinced it would provide the missing piece of knowledge. However, I soon found myself puzzled by the fundamental constructs used in economic modeling. Coming from an engineering background, I was accustomed to models representing universal physical laws governing predictable, quantifiable systems. In contrast, economics employed multiple models to explain the same phenomenon, often based on simplified assumptions about human behavior. Moreover, many economists seemed uninterested in integrating tools from other disciplines, even when it seemed obvious they could enhance economic analysis.

After seven years as a consultant in Energy Policy and Carbon Markets across Latin America, I moved to France with my wife. I enrolled in a second master's program—this time in network industries and digital economics

¹Nobel Prize in Physics for his work on the theory of elementary particles.

(Master IREN). Initially, I saw this as an opportunity to expand my professional network and establish a career in France. However, I quickly realized Master IREN was unlike my previous academic experiences. It integrated concepts closer to engineering with economics, management, and politics, offering a unique perspective on electricity systems, market structures, and emerging technologies like V2G. During the program, and through the recommendation of Eric Brousseau, the program director, I learned that Yannick Perez, the holder of the Chair Armand Peugeot, was looking for a master's student to pursue a PhD on V2G business models—the initial focus of this dissertation.

During my PhD, I benefited immensely from the unique platform provided by Chair Armand Peugeot, which fosters collaboration between academia and industry. This opportunity was further enriched because my PhD contract required me to work at Stellantis—the world's fourth-largest car manufacturer, with over 14 brands, including Jeep, Peugeot, Fiat, Citroën, DS, and Dodge. This dual perspective exposed a striking contrast: on one side, academics were developing sophisticated strategies to optimize EV charging and discharging to align with renewable energy production. On the other, my colleagues in the automotive industry struggled to grasp what V2G truly meant for EV usage, the challenges of developing the technology in practice, and, most importantly, the implications for customers buying their EVs. Additionally, my role as a member of the advisory board for a European project introduced me to industry stakeholders from various sectors and countries, each operating under different business models and regulatory environments.

Engaging with these diverse communities working on V2G led to a key realization: while nearly everyone agreed on its potential, there was no consensus on how to implement it. Each stakeholder had a vision of how V2G should function, highlighting the complexity of coordinating its deployment across industries and markets. Furthermore, much of the academic research on V2G remained fragmented. Engineers optimized V2G operations but often overlooked the real-world constraints that shape those optimizations. Economists focused on estimating the economic value of V2G, frequently disregarding the physical realities of electricity systems. In practice, the limitations and value of V2G varied significantly depending on the perspective—whether from regulators, car manufacturers, electricity providers, or end users.

This realization reignited some of the intellectual concerns I had encountered earlier in my academic journey. It became increasingly clear that the divisions between disciplines—particularly between engineers and economists, shaped how V2G was studied. By treating its technical and economic aspects separately, many studies failed to capture the full complexity of deploying

V2G at scale.

Determined to bridge these gaps, I sought a framework connecting the fundamental laws of optimization and electricity systems with the economic rationale of profit-maximizing agents. By chance, my search took an unexpected turn when Jan Lepoutre, another of my advisors and holder of the Chair Armand Peugeot, shared a video on information theory. The video illustrated how information theory could be used to determine the most likely word to solve a word puzzle based on conditional information from previous attempts and word length.

This discovery sparked an idea: what if information theory could be applied to V2G? My advisors and I began exploring how information flows within optimization algorithms, particularly in scenarios with varying degrees of uncertainty regarding EV behavior. Most optimization models in the literature made strong assumptions about how information was processed and shared—often overlooking the fact that EV users, electricity markets, and aggregators all operate with different levels of uncertainty. By incorporating an information-theoretic approach, we saw an opportunity to understand better how information constraints shape decision-making and, ultimately, the feasibility of V2G at scale.

As I delved deeper into the roots and implications of information theory, I realized that my broader intellectual curiosity aligned with questions in complexity science. This field studies how structured collective behavior emerges from the interaction of simple subsystems. As life emerges from molecular chemistry and societal laws evolve from human interactions, what mechanisms might drive the large-scale adoption of disruptive technologies like EVs to achieve their environmental promise?

Throughout this dissertation, I explore these questions, aiming to bridge the gap between theory and practice, economics and engineering, academia and industry. By examining coordination through fundamental concepts such as information, I aim to unveil the opportunities and risks of V2G complexity.

Diego Manuel Cebreros Saettone
Paris, March 2025

Acknowledgments

The great opportunity I've had to pursue my PhD is thanks to the support and help of many people who have crossed my path over the past three years. Here, I will briefly try to show my appreciation by mentioning them in reverse order of their involvement in this research project.

I would like to begin by thanking my jury, composed of seven distinguished members. They generously gave their time to read and listen to my research, offering valuable insights and comments that have improved this work. Among them, I must highlight the honor of having Willet Kempton on my jury. He authored the seminal paper and is the most cited researcher in the field of Vehicle-to-Grid (V2G). It was a particular privilege to include him, especially given his contributions not only to academic research but also to the industry, as a co-founder of one of the leading companies working on V2G.

If doing a PhD is meant to be the time when one learns the craft of research, then the PhD advisors are the mentors responsible for providing the tools and guidance to navigate the many trials and errors that come with that process. I was fortunate to have three advisors—each of whom I can now call a friend—with unique strengths, and together they were incredibly complementary.

First, I will always be grateful to Pascal. He taught me how to ask difficult questions without being impolite. His human qualities and calm demeanor were a source of reassurance; I knew that if I faced a problem or had a doubt, his advice would help me find clarity.

Second, I want to thank Jan, who exemplifies a person with a deep passion for thinking critically and caring about the academic profession. He has become a lasting reference point for me. He challenged me in the best way possible, showing me what research can aspire to be, while also reminding me that it is a gradual process. I have fond memories of our discussions on the philosophy of science, economics, sociology, and information theory. He truly instilled in me the importance of viewing academia through a sociological lens.

Third, I want to thank Yannick—not only because he understood my sense of humor (which is no small feat), but especially because he taught me to

focus on what truly matters, both in research and in life. He reminded me to set aside ego, stay open to new ideas, and never lose sight of the fact that personal aspirations in academia should not come at the expense of family or friends. In fact, he showed me that knowing your priorities and building strong partnerships—both within and beyond research—can lead to better, more meaningful outcomes in the long term. He was also incredibly generous with his resources, time, network, friends (who unsurprisingly also became my friends), his advice, and his stories.

In addition to working with my advisors, I had the opportunity to collaborate with several co-authors. I can say that one of the reasons I love doing research is the collaborative process. Discussing and sharing ideas with others has been a very enriching experience. I am deeply indebted to all of them: Carlos, Eric, Marc-Olivier, Arnaud, Francisco, Alejandro, Adrien, David, Olivier, and Emma.

I also want to thank my lab, LGI, and all the friends I met there. Even though I lived in Paris far from the Lab, I was always happy and excited to arrive at the office after getting off the bus. I think the atmosphere there is truly unique, with a strong spirit of collaboration—a special place to be.

I want to give a special mention to the Chaire Armand Peugeot and those who run it for many years: Yannick, Jan, and Marc, in collaboration with Stellantis. This chair gave me a unique opportunity to work with the industry and offered a platform for valuable collaboration. I will always be grateful to this institution.

Throughout these three years, I met many people within Stellantis and the broader industry who supported me and stood by me during this journey. Among them, I'd like to name a few: Pierre, Damien Pierre, Lorenzo, Olivier, Fabrice, Anne-Catherine, Clement, Solène, Alain, Nicolas, and the list continues.

In addition, I must mention two special people who either opened or held the door during the early steps of my academic path. Eric Brousseau, who directed the Master IREN, gave a compelling description of the academic profession that made me envision myself as a researcher. He was kind enough to invite me to work with him in the Chaire Governance and Regulation, where I also made many friends—and where I was introduced to Yannick (and, well, we already know how that went!).

I also want to thank Jose Carlos, my master's advisor in Peru. I remember clearly that after I failed my master's thesis in economics, he told me: "Esto

te va a servir algún día.” And it did. He was the first person who encouraged me to pursue interesting questions, rather than settle for simple answers.

Finally, I need to mention my friends and family, who have given me love and laughter throughout these three years—and long before that. My friends, through sports and endless conversations about huevadas, helped me build the ability to laugh in the face of adversity. Whether we were surfing scary waves, stuck on a mountain ledge, exhausted, hungry, or facing problems, they taught me to stay light-hearted and resilient. They’ve helped shape an optimistic attitude that I carry with me.

I also want to give a special mention to the five years of my life when I sailed competitively. During that time, my friend Alexander taught me to be curious and observant—to watch what the best sailors did and try to learn from them. That habit of observing, imitating, and obsessively trying to copy the best practices became a guiding principle throughout these three years of my PhD.

Finally, whenever I come home from work, whether the day was good or bad, I feel safe and loved. That feeling, I believe, has been essential in helping me recover and move forward after any setback. My sister, father, and mother have always supported me unconditionally, just as they did when they used to pick me up from school to take me to training, drive me to classes, or even sacrifice their own comforts so I could pursue my academic and athletic goals.

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1 - Introduction

1.1 . Background and motivation

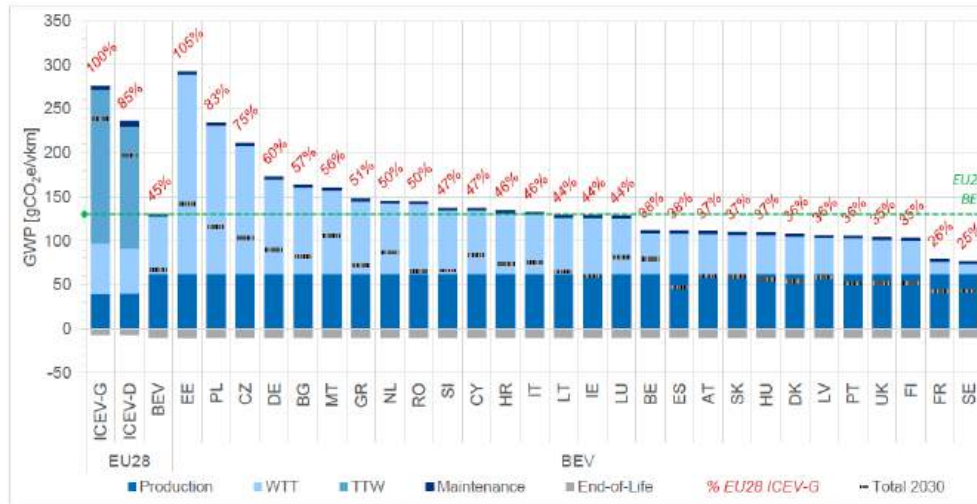
Nearly 1 in 5 cars sold in 2023 was a battery electric vehicle (EV) (IEA, 2024). Governments worldwide have provided over USD 128 billion in direct subsidies to support EV buyers between 2017 and 2022 (IEA, 2022; Statista, 2022). Several cities, like Paris, Oslo, London, and Brussels, and countries like Denmark, Iceland, and the Netherlands, among others, have plans to limit the sale and use of vehicles with internal combustion engines (ICE) and encourage EV use in the cities (Wappelhorst, 2020).

A key driver of the support that EVs have received for their adoption relies on the fact that most of the time, they are portrayed as a solution to critical environmental challenges, such as improving the air quality in the cities and mitigating global warming (Coffman et al., 2017). However, while it is well known that EVs produce no tailpipe emissions, meaning they generate less pollution through their driving than ICE vehicles, a system-wide evaluation of their impact is required to assess their environmental impacts in terms of greenhouse gasses (GHG) emissions. Such an evaluation is typically conducted through a life-cycle assessment (LCA), which examines the environmental impact of EVs across their entire lifecycle encompassing battery manufacturing, electricity production, and end-of-life vehicle management (Hawkins et al., 2013). The LCA approach accounts for various GHG emissions, including CO_2 and CH_4 , as well as local pollutants such as CO , SO_2 , and metal emissions, among others, which contribute to acidification and human toxicity. For a thorough review of LCA methodologies applied to EVs, see Hawkins et al. (2012) or Xia and Li (2022).

At the same time, and perhaps more importantly, the transition from ICE vehicles to EVs could introduce new challenges, potentially increasing global emissions. The electric power sector currently accounts for 36% of global GHG emissions, meaning electricity is not always a fully decarbonized energy source (Clarke et al., 2022). As a result, EVs may, in some specific cases even contribute to more GHG emissions than ICE vehicles. Figure 5.1 illustrates this by comparing the LCA of EV-related GHG emissions across the 27 EU member states and the UK. The findings reveal significant differences in the net impact of EVs depending on each country's electricity mix. For example, in Estonia (EE), the high-carbon electricity mix leads to EVs emit-

ting more GHGs during their use phase than ICE vehicles. This highlights the need to consider EV–electricity system interactions to ensure that EVs contribute effectively to climate change mitigation. In the power sector, this means achieving a 70% reduction in GHG emissions by 2030 (Clarke et al., 2022).

Figure 1.1: Regional Variations in Life Cycle Assessment of GHG Emissions from EVs. (Hill, Raugei, et al., 2023)



Notes: Production = production of raw materials, components manufacturing, and vehicle assembly. WTT = fuel/electricity production cycle; TTW = impacts due to emissions from the vehicle during operational use; Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from the collection, recycling, energy recovery, and disposal of vehicles and batteries. Other key input assumptions include a lifetime activity of 225 000 km over 15 years and battery technology from 2020 of 58 kWh, with a 300 km range.

1.2 . Previous research

In two seminal papers, Kempton and Tomić (2005a, 2005b) proposed a transformative system in which EVs could serve as a tool to defossilize electricity systems and mitigate GHG emissions. The concept, Vehicle-to-Grid (V2G), envisions that EVs can charge and discharge based on the availability of intermittent renewable energy sources such as solar and wind, which produce little to no GHG emissions. Specifically, EVs would be charged when renewable energy production is abundant and discharged back into the grid

when renewable generation is insufficient, reducing reliance on fossil-fuel-based power plants. They highlighted that given EVs remain parked approximately 96% of the time and typically have battery capacities exceeding daily driving needs, they could provide sufficient storage capacity to accommodate the variability of solar and wind energy. This hypothesis was later formalized by Xu et al. (2023), who demonstrated that, under projected EV adoption rates, EV batteries alone could satisfy global electricity storage needs by 2030.

Following the foundational work of Kempton and Tomić (2005a, 2005b), the V2G concept continued to evolve, leading to simpler and more advanced configurations to reduce GHG emissions. One such development was the introduction of V1G, also referred to as "smart charging", which offers a simpler, unidirectional approach that optimizes the timing and rate of EV charging (Noel, Zarazua de Rubens, et al., 2019a, 2019b). The core idea behind V1G is to coordinate EV charging to prevent peak consumption events, which could strain the electricity grid while maximizing the use of intermittent renewable energy. This approach leverages the flexibility of EV batteries, as their capacity typically exceeds the energy required for daily commutes.

Additionally, the concept has evolved into a broader framework known as Vehicle-to-Anything (V2X) (Thompson & Perez, 2020), which assigns specific names to different V2G applications depending on the recipient of the energy. For example, Vehicle-to-Home (V2H) refers to supplying energy to a household, Vehicle-to-Building (V2B) to a building, and so on. Furthermore, V2G has been integrated into the emerging paradigm of Connected, Autonomous, Shared, and Electric vehicles (CASE), which shifts the focus beyond privately owned EVs to shared mobility solutions. This has led to discussions on combining car-sharing models with V2G systems, exploring the potential for shared EV fleets (Ketter et al., 2023; Sperling, 2013).

1.3 . Main Research Problem

Web of Science¹ lists over 2,000 peer-reviewed articles on V2G and more than 15,000 on V1G or "smart charging". Additionally, over 151 pilot projects have been implemented (Gschwendtner et al., 2021; V2G Hub, 2025). However, they are only a few commercial implementations² and the progress in

¹A well-known scientific database.

²Examples of commercial V1G and V2G offerings have primarily been implemented in professional fleets. Some commercial options available to households include Mobilize's V2G offer in France, WeDriveSolar in the Netherlands, and PG&E's smart charging program

scaling these technologies for widespread adoption has been slower than initially anticipated. This stands in contrast to early expectations set by Kempton and Tomić (2005a, 2005b), who suggested that *"once fleets demonstrate viability and vehicle production volumes bring down costs, V2G revenues may stimulate (V2G) aggregator participation"* (Kempton & Tomić, 2005b, p.289).

Empirical studies on the barriers to V2G and V1G adoption remain limited but provide valuable insights. Goncaruc et al. (2024) surveyed 44 experts from various stakeholder groups within the European EV charging ecosystem, identifying key business-related obstacles such as profitability uncertainties and the absence of a viable business case. The study highlighted that potential users often lack a clear understanding of V2G's economic benefits, making it difficult for business models to scale.

Similarly, Libertson (2022) conducted interviews in Sweden to examine user flexibility in smart charging schemes. While users expressed a willingness to relinquish control over charging, their expectations regarding EV availability were significantly higher than their actual usage. Moreover, real-world charging behavior was influenced by time-specific factors such as work schedules, traffic conditions, and access to charging infrastructure.

A broader investigation by Kester et al. (2018) and Noel, de Rubens, et al. (2019) performed 227 semi-structured interviews with transportation and electricity experts from 201 institutions across 17 Nordic cities. Their findings highlighted a disconnect between academic research and industry stakeholders, which has hindered V2G commercialization. The study also noted that pilot projects remain scarce across the Nordic region, with Denmark being a rare exception. Reinforcing these observations, Kester et al. (2018) identified a widespread lack of awareness and understanding of V2G within the transport and electricity sectors. This gap is reflected in the limited number of proposed policy mechanisms and the frequent conflation of V2G with smart charging.

These studies suggest that beyond technical challenges that are in the process of being solved through standardization and the offer of V2G capable vehicles³, the commercialization of V2G and smart charging is primarily hindered by business model uncertainties, user adoption barriers, and a fragmented perspectives of the technology among industry stakeholders, including regulators. This raises a critical question: ***How should EVs be coordi-***

in California.

³The following EVs are reported to have V2G capabilities: Audi Q4 e-tron, Cupra Tavascan, Kia EV9, Nissan Leaf, Polestar 3, Renault 5 EV, Skoda Enyaq, and VW ID.

nated with electricity systems to become a tool to mitigate GHG emissions?

While it is possible to intuitively understand *coordination*—whether in the synchronized movement of a choreographed dance or the orderly flow of people exiting a metro station—not all forms of coordination are identical, nor are they equally effective. For instance, traffic coordination at intersections often leads to delays, as vehicles must slow down or stop to allow others to proceed. In contrast, an orchestra performing a symphony achieves a seamless interplay of instruments, producing a unified sound greater than the individual sum of its parts. This comparison raises two fundamental questions that build on our main research question: *What is "good coordination" for EV-power system coordination?* and *What is required to achieve it?*

Given the previous context, answering the first question seems simple, as "good coordination", given our motivation, is the one in which EVs and power systems minimize total GHG. However, responding to the second question is challenging given the many interdependencies that one needs to consider on electricity systems and their emission factor, kg CO₂ emitted per kWh consumed, to which EVs are charged. Emissions in electricity systems depend simultaneously on total demand, time of consumption, and locational factors. Total demand impacts the type of coordination required because supply and demand must always be balanced in alternating current systems to maintain a stable frequency. If EV charging demand is uncoordinated, it might create new consumption peaks, and fossil fuel power sources may need to be activated to cover the peak demand. Conversely, an oversupply of renewable energy may require curtailment to prevent grid imbalances. Moreover, time plays a key role, as the electricity generation mix fluctuates based on the availability of intermittent energy resources such as solar and wind electricity-generated power. Locational factors further complicate the coordination, as electricity is transmitted through interconnected networks that can experience congestion, limiting power flow across regions.

However, despite the unique characteristics of electricity systems, achieving 'good coordination' is a research problem that extends beyond the operational or strategic challenge of determining when and how much to charge, issues that could be addressed through game theory or optimization theory. It also includes organizational, regulatory, and technological factors, which may either constrain or support different types of coordination. For example, organizational challenges include the selection of communication standards that industrial actors must agree upon to facilitate the deployment of V2G and V1G (Neaimeh & Andersen, 2020). On the regulatory side, Borne et al. (2018) identify potential legal and policy barriers hindering V2G participation. Technologically, challenges arise in measuring and accounting for the

additional costs of battery cycling (Thompson, 2018). These factors play a critical role in determining how EVs should be coordinated.

Therefore, through this dissertation, I aim to address the coordination problem in collaboration with my co-authors through four research papers. Each paper uses a unified theoretical paradigm to tackle different aspects of the broad coordination challenge. This approach views the interdependencies between strategies, organizational, regulatory, and technological choices as a complex system. The following section reviews the key approaches used to study EV-electricity coordination and outlines the foundational pillars for studying coordination as a complex system.

1.4 . Shifting paradigms to study EV-Power Systems Coordination

A "paradigm," as defined by Kuhn (1962), refers to the established set of models and theories employed by various scientific disciplines to address a research problem. In this section, I argue that the current paradigm for studying the coordination of EVs with power systems has been largely disciplinary, meaning the problem has been tackled through the lenses of specific academic fields (e.g., electrical engineering, economics, computer science, communication engineering). While this approach has provided valuable insights, it has overlooked critical interdisciplinary aspects of coordination, such as computation costs, information value, and path-dependencies. Therefore, rather than examining the issue from a singular disciplinary perspective, we propose viewing the coordination of EVs and power markets as a complex system (Simon, 1962). In the following subsection, we review and characterize existing studies on EV-power electricity coordination. Then, in the subsequent subsection, we discuss how complexity science offers a more suitable paradigm to address the research questions.

1.4.1 . Current paradigm: A disciplinary perspective

Previous research on V1G and V2G, which has tried to address EV-electricity system coordination, can be classified as having studied two main coordination components. The first stream has focused on the *interoperability* and adopted a "communication perspective." This strand explores the interactions between physical components, emphasizing bandwidth, coverage area, data rate, frequency range, latency, communication, and security protocols required for data exchange that subsequently addresses coordination (Bao et al., 2018; Shom et al., 2022; Ustun et al., 2013; Zhang et al., 2017). For in-

stance, Neaimeh and Andersen, 2020 examined the communication protocols necessary for V2G applications. Or W. Han and Xiao (2016) who proposes a communication protocol that guarantees privacy preservation on the EV - EV-electric system coordination. For a literature review on the papers that have expanded our understanding of the communication process between EVs and the electric system, I recommend the reader to look into Vadi et al., 2019.

The second stream has adopted an *algorithmic and optimization perspective*, mainly using optimization and game theory, to design algorithms and strategies for charging and discharging the EVs tailored for V1G, V2G, or V2G-car sharing applications. Notable examples include demand-side management algorithms (Moghaddam et al., 2017; Sadeghian et al., 2022), adaptive tariff algorithms (Erden et al., 2018; Valogianni et al., 2020), and dispatch algorithms for decentralized loads (Bai & Qiao, 2015; Mastoi et al., 2023). This research highlights the potential applications of V1G and V2G and develops a practical strategy to decide how much should be charged or discharged for each EV. It often relies on two types of organizational paradigms: centralized and decentralized. A single actor performs most computations in centralized organizations, while decentralized organizations distribute computation among multiple decision-making entities (El-Hendawi et al., 2022). For a review of the different algorithms that exist for coordinating EVs for V1G or V2G, the reader might refer to Mukherjee and Gupta (2014) or Nimalisiri et al. (2019)

While this research has contributed to our understanding of specific aspects of coordination, it has yet to provide clear answers to the above—questions that are crucial for assessing the effectiveness of EVs as tools for defossilizing electricity systems. Each of the strands of research offers a fragmented perspective on coordination. For instance, the communication perspective fails to explore how different communication standards might impact coordination performance. Instead, it largely extends practices from the automotive and electricity industries into V2G systems, offering limited insight into how varying standards might affect the value of EVs-electricity system coordination. In contrast, the algorithmic perspective is more explorative, proposing fragmented strategies for optimizing EV charging and discharging. However, this perspective often assumes that all necessary information is readily available. In reality, it may require actors to coordinate beyond the traditional scope of V2G interactions to ensure that the information needed for optimization is accessible in the first place.

1.4.2 . A new paradigm: A complexity science perspective

Under the premise that a broader definition of coordination is more likely to explain what I can define as good coordination and what is required to achieve in the context of EV-electricity system coordination. I formalize our definition of coordination as: "*managing interdependencies between activities*" (Malone & Crowston, 1994, p.1994), this includes broadly the management of processes (Crowston, 1997; Van de Ven et al., 1976), technologies (Kanda, Deshmukh, et al., 2008; Papadopoulos & Arbab, 1998), and organizations (Farrell & Saloner, 1988; Williamson, 1975). This definition of coordination takes a complexity science standpoint, which has been proposed as an ideal paradigm for analyzing the impact and tensions created by new technologies (Arthur, 1989). Some examples of coordination problems from this perspective include the management of shared resources, producer-consumer relations, vehicle traffic, and standardization processes, among others.

Complexity science is a paradigm for studying phenomena encompassing machines, organisms, and organizations with purpose or function (Simon, 1977). These process information entities adapt to their environment (Gell-Mann & Lloyd, 1996; Rosenblueth et al., 1943). Thus, complexity science is a paradigm that unifies and connects natural sciences, social sciences, and engineering concepts. Its objective is to provide effective theories to inquire how and why "more is different" (Anderson, 1972), which means that a reductionist approach is insufficient for understanding the collective behavior of a complex system - a system that comprises numerous elements (functional or material), with many no-simple inter-dependencies among themselves (Simon, 1962) - simply by extrapolating the properties of individual components (Anderson, 1972).

Weaver (1948) defines three types of scientific problems that are useful to distinguish complex system research problems from 'non-complex problems': problems of simplicity, problems of disorganized complexity, and problems of organized complexity. Problems of simplicity pertain to closed systems that can be predicted by knowing initial conditions and the forces affecting the system; such problems include those that can be solved using classical trajectory models from physics, such as determining the trajectory of a projectile. Problems of disorganized complexity, on the other hand, involve systems with many interacting elements, such as gas molecules in a container colliding with each other. Predicting the trajectory of each molecule would be computationally impractical; instead, statistical methods allow us to describe the system's average behavior. The predictive power of statistical mechanics holds as long as the distribution of molecules remains random—what Weaver (1948) describes as "disorganized." However, if the molecules were arranged

in an ordered fashion—all aligned in rows and set into motion along perfectly parallel paths—this system of molecules would no longer have a random distribution, and the fundamental theorem of statistical mechanics (ergodicity) would not apply. Such a scenario exemplifies problems of organized complexity, which encapsulate the idea of complex systems that complexity science aims to study.

The central challenge in complexity science is linking fundamental theories (e.g., physics, electromagnetism, theory of evolution) to macroscopic features of the system (stability, predictability, reliability) through an effective theory (Anderson, 1972; Krakauer, 2024). Emergence is a key concept in this context, as it describes how certain properties arise and evolve due to the system's complexity to allow comparisons between seemingly unrelated phenomena, such as how a mind arises from a brain or how market prices emerge from individual transactions. From a complexity science perspective, these phenomena share a common characteristic: both require a contingent set of effective theories that relate the parts (neurons or individuals) to the whole (the mind or market). Complexity science might look beyond even when the effective theories differ; for example, neuroscience explains the brain-mind relationship, while economics may describe the link between individuals and market prices. Complexity science aims to explore how such effective theories can be compared. In other words, it seeks to understand what economics and neuroscience share in their explanations of emergence.

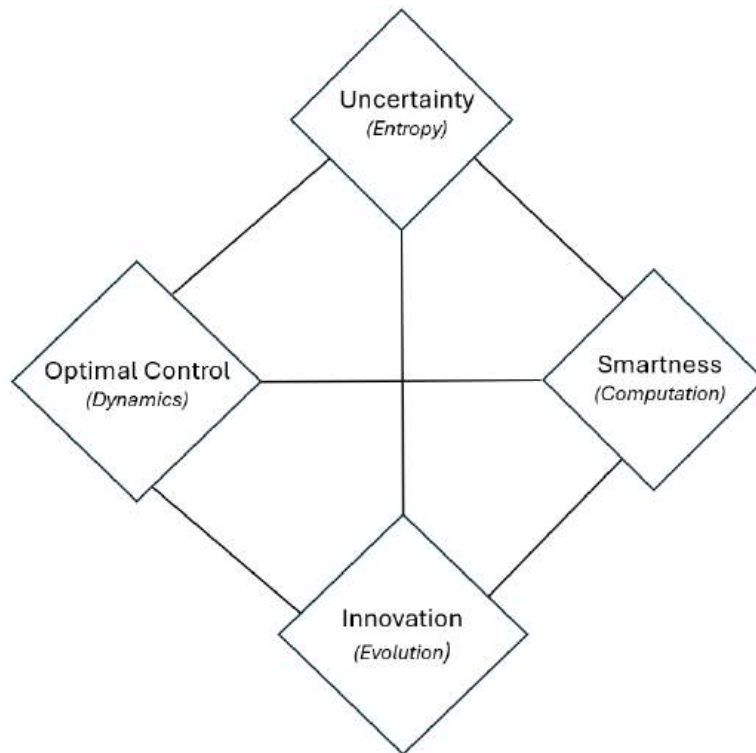
According to complexity science, the coordination between EVs and electricity systems arises from the emergence of the different actors involved in the coordination trying to address the complex system in which they are participating on. This paradigm suggests that such coordination rather than focusing on the material differences between components, should be analyzed using the same principles applied to other complex systems, such as biological cells, brains, markets, factories, or ecosystems to understand their functional role within the system's overall complexity.

Considering a review of seminal works in complexity science, Krakauer (2024) propose that this analysis should be structured around four key research pillars. The first pillar, entropy, refers to the application of thermodynamic laws to all system elements, emphasizing the principles of order and disorder in the production of mechanical work and its application to measure uncertainty (Clausius, 1879; Maxwell, 2012). The second, evolution, highlights the historical shaping of system elements and configurations through competition, leading to an adaptive fit between the system and its environment. The third, dynamics, pertains to the system's adaptive and self-regulating nature, which requires agents to internalize and process knowledge

about their environment (Crutchfield, 1994). Finally, computation refers to transforming information inputs into desired outputs through simple systems capable of performing local logical operations that support computational functions (Kolmogorov, 1968; Shannon, 1948).

To clarify how each paper relates to the complexity science paradigm and our broader effort to analyze coordination from a larger perspective, I will use Figure 1.2 as a guiding framework. This figure will appear at the start of each chapter, positioning each paper according to the main pillars of complexity science it focuses on most. Additionally, we have adapted the names of the pillars to reflect better their relevance to the specific coordination challenges addressed in this research.

Figure 1.2: The four pillars of complexity. Adapted from (Krakauer, 2024)



Note: Complexity science recognizes that in any complex system, all fundamental theories contribute to emergent behaviors, though certain aspects may be more emphasized than others. This framework is based on Krakauer (2024), who presents a similar figure highlighting the authors who were the first to establish connections between these frameworks.

1.5 . Research questions

This section presents four research questions, each constituting an independent paper. Across all of them, the problem treated plays a central role in shaping the coordination among EVs and electricity systems. However, the specificities of the problem vary across the papers, each emphasizing different pillars of complexity science to varying degrees. Moreover, we draw a clear distinction among the papers based on the primary community they contribute to. The first two research questions are strongly linked to evaluating information flows that enable coordination through their computation costs or ability to manage uncertainty. As such, the first two subsections contribute to the Information Systems (IS) community, a multidisciplinary field that integrates engineering and economics in information systems management. In contrast, the third and fourth of research questions focus more on specific institutional arrangements within electricity systems, closely tied to the regulatory history of market reforms in electricity. Therefore, the third and fourth research questions target the energy economics community.

1.5.1 . Problem 1: Optimization and Control

As the transition towards more sustainable energy systems progresses, renewable energy sources are increasingly integrated into the electricity mix. However, introducing these renewable sources presents challenges for SOs in maintaining grid stability, particularly because their ability to balance supply and demand is traditionally based on controlling the power supply alone (Tuballa & Abundo, 2016). The intermittent nature of many defossilised electricity sources, such as solar and wind power, complicates this task. SOs can not control when the sun is shining or the wind is blowing; thus, the power supply is less controllable.

As electricity supply becomes more unpredictable and less controllable, electricity systems must be redesigned to accommodate controllable demand commonly known as demand response—along with the necessary information flows to support grid control and optimization (Ancillotti et al., 2013; Clastres, 2011; Farhangi, 2010; Joskow, 2012; Potter et al., 2009; Yu & Xue, 2016). In traditional, uni-directional electricity systems, SOs typically collect data on consumption and production, with minimal information flowing back from SOs to the consumers. To address these challenges, solutions have emerged under the concept of "Smart Grids," which leverage advanced information and communication technologies (ICT) to enable bi-directional data exchange and decentralized optimization.

Over the past decade, research on smart grids has examined a variety of optimization solutions, covering a wide array of applications (e.g., rooftop solar panels, heat pumps, load curtailment, and electric vehicles) and levels of analysis (e.g., individual households, microgrids, fleets, buildings, distribution systems, and transmission networks). These studies have highlighted the potential of smart grids to reduce energy costs and emissions by optimizing and automating the timing of energy consumption and supply (Ketter et al., 2018; Yu & Xue, 2016). However, much of this research has overlooked the additional operational aspects of smart grids associated with the information flows necessary to make smart grids functional. As a result, several critical questions remain unanswered from an operational perspective, such as: What if the energy required to process the information for optimization exceeds the energy savings achieved by the optimal strategy? What if there are constraints on the information flow? How would such constraints influence the selection of the most effective optimization algorithm?

Indeed, in some smart grid applications, several actors might be required to exchange information, and perhaps the best-performing applications in a pilot may not work at scale. Given the slow diffusion of such smart grid systems as V2G, it is important to understand and assess the impact of information flows at scale on their potential. Our first research question, therefore, deals with the following research question: ***What is the impact of information flow design on Smart Grid computation costs at scale?***

1.5.2 . Problem 2: Uncertainty and Control

It is mostly assumed that successfully integrating V2G services into existing electricity systems requires an essential intermediary: an "Aggregator"(Amamra & Marco, 2019; S. Han et al., 2010) who connects EV users and power markets, purchasing renewable energy for EV charging and selling surplus energy back to the grid through sequential electricity markets. Most power markets operate on schedules that require bidding or trading hours in advance—typically before EV users have finalized their travel plans. The Aggregator’s fundamental value is to predict when EVs will be available for charging or discharging, managing uncertainties on both the supply and demand sides (Burger et al., 2017).

Over- or under-procurement of power can destabilize the grid and negatively impact electricity system operation, which requires maintaining a real-time grid balance between power supply and demand, potentially leading to costly penalties for the Aggregator, which could make their business model unprofitable (Codani et al., 2016). To avoid these penalties, the industry and

governments in the USA and Europe, has agreed to implement communication protocols that make mandatory a minimum inter-organizational information system (IOIS) that can enable different brands of EVs and any charging point operator to exchange mobility information with a V2G Aggregator (e.g., Neaimeh and Andersen (2020), Noel, Zarazua de Rubens, et al. (2019b), and Tseng (2012)). Such protocols can be on the 'front-end' between the EV and the charging stations (e.g., ISO 15118-20 in Europe or DIN 70121 for California), formally referred to as electric vehicle supply equipment (EVSE), or the 'back-end' between the EVSE and the Aggregator (e.g., OCPP 2.0 in Europe, IEEE 2030.5 in California).

However, despite the existence of communication standards, prior research and pilot trials on V2G have revealed a wide range of perspectives on the type of IOIS aggregators that might need to facilitate the information exchange required to deal with the uncertainties on mobility behavior (Gschwendtner et al., 2021; Kester et al., 2018). Nevertheless, there is a gap in our understanding of the value of going beyond current communication standards as a form of IOIS. Against this gap, the potential of V2G services might be limited by hindering collaboration between the potential actors that could contribute to providing data to the aggregators, and rather than fostering data sharing to enhance the value of V2G services, lead to the creation of data silos or closed systems. Thus, to address these gaps, our second research question is: ***What type of IOIS optimizes the necessary data flow to enable V2G aggregators to play their role in smart grids?***

1.5.3 . Problem 3: Control and Innovation

V2G relies on the integration of residential prosumers—households that both consume and produce electricity. However, their integration might present several challenges, regarding the type of interactions that they will have with their traditional energy providers. Most of these challenges, pertain to the specific characteristics of data, and include privacy concerns, monitoring costs, and misuse of this assets.

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 considers regulatory mechanisms, market mechanisms, and intermediation. While this 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 pro-

sumer 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 third research question is: ***How do integration arrangements of prosumers into grids impact their costs and risks?***

1.5.4 . Problem 4: Innovation and Uncertainty

The fourth paper addresses the role of regulatory governance in aligning environmental and economic objectives, to promote renewable energy adoption and the challenges that such alignment might impose in the context of competitive electricity markets. In particular, it focuses on the governance of National Regulatory Authorities (NRAs) in the European Union (EU) and their influence on renewable energy integration. It examines how the governance of regulation affects the pace and extent of renewable energy adoption. Institutional theory (Acemoglu & Robinson, 2006; Acemoglu et al., 2001) will suggest that given that the legal mandate of NRAs is to manage competitive electricity markets and not to promote green objectives, those NRAs that are independent might resist rapid renewable energy growth due to concerns about market competition and system efficiency. Therefore, our fourth research question is ***Is the governance regime of NRAs in tension with the growth of renewable energy in the EU?***.

1.6 . Main results and Contributions

This section presents a summary of the key findings and contributions of the four papers included in this dissertation, each addressing the research questions outlined in the previous section.

1.6.1 . Addressing problem 1: Measuring how computation costs increases with scale.

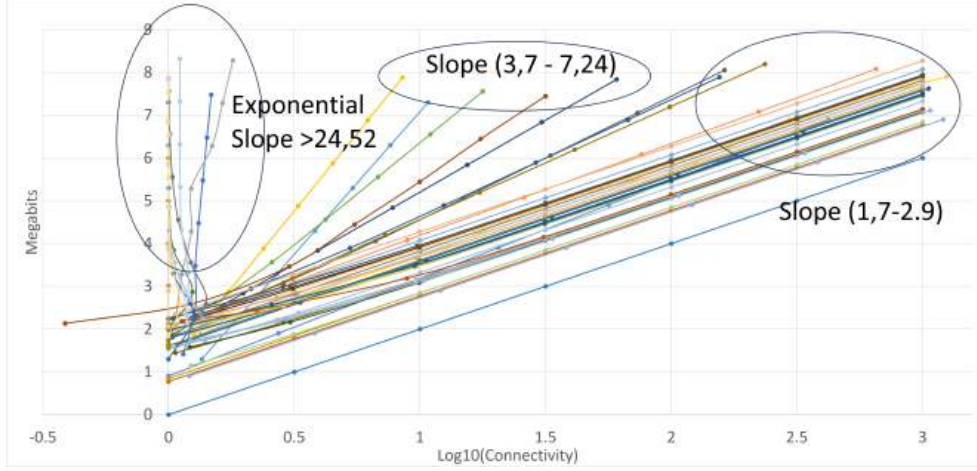
In chapter 2 given the lack of empirical data on information flows of V2G systems, we chose to address our research question by relying on extant V2G designs in the technical literature and derive the information needed from them. We conduct a literature review to identify and model different designs of the information flow required for the V2G system and subsequently as-

sess how scaling these designs impacts their information flows. For these assessments, we use two measures to analyze the information flow networks: connectivity and algorithmic complexity (Borgatti, 2005; Chaitin, 1966; Kolmogorov, 1965; Strogatz, 2001; West et al., 1997).

Figure 2.7 shows the relationship between the algorithmic complexity and connectivity measures. Each point on the observed lines represents a tenfold increase in scale (in terms of aggregated EVs). Overall, as we have seen before in 2.5, almost all the information flows reach a similar level of computation costs, with a lower bound of 8 megabits. The second main remark is that the information flows can be grouped by the ratio of algorithmic complexity to connectivity, or in other words, by how centralized or decentralized the network becomes once the system scales. The ratio analysis between these two measures allows us to divide the information flows into three main clusters visually identified on figure 2.7. Furthermore, each cluster can be identified quantitatively by comparing and grouping the information flows by minimizing the difference in the slope within this archetype.

The largest group of information flows has a slope very close to “2,” representing the most dominant design of V2G information flow. Still, also, they are the more centralized information flow, which increases the difficulty of distributing the computation costs among the network. Furthermore, the fact that one design dominates is surprising, as it shows that some underlying design principles might exist regarding the information flows used for V2G optimization. In the second archetype, which is the information flow with a “2.7 to 3.9 slope,” the network is almost by a half less centralized, which suggests that they are at least two times more likely than the first cluster to be able to decentralize the computation costs among the network nodes. Furthermore, we have a third archetype, which is defined as “Exponential slope”, where the information flows, the system connectivity decreases or remains constant, which means that the network scale with several nodes of connection is equally important, increasing the potential to distribute amongst computation costs. Finally, in the fourth archetype, “Hierarchical,” information flow is unidirectional. In this particular case, the level of information shared is not with the EV level but with the fleet operator level. This implies an assumption that EV owners are not participating in the information process directly, as all the information exchanges are known from the interaction of the EV with the EVSE. This archetype presents the least amount of examples.

Figure 1.3: Algorithmic complexity and Connectivity .



Our research has two main contributions. First, we identify four types of V2G information flow design archetypes in the literature that vary in the distribution and level of computation costs responses to scaling: “Hierarchical design”, “Exponential”, “3.2-7.4” and “1.7-2.7”. Second, we use these archetypes to develop insights for practitioners and Smart Grid researchers who aim to design V2G applications. Our perspective explains why some smart grid applications might evolve successfully while others do not, especially considering how the distribution of the computation costs might increase with scale.

1.6.2 . Addressing problem 2: Measuring the value of information to manage EV uncertainty

In chapter 3, we developed a simulation framework to measure the value of information that we use to evaluate how different IOIS impact the profits and GHG emissions of a V2G aggregator that buys and sells power in day-ahead and intraday power markets. The simulation allows us to distinguish between a ‘real environment’ and the ‘Aggregator expectations’, which is based on historical data on EV mobility, where we model an IOIS as a discovery process in which the Aggregator gets to inform itself about the ‘real environment’ of the EV owner behavior. Table 3.5 summarizes the IOIS scenarios that we evaluate.

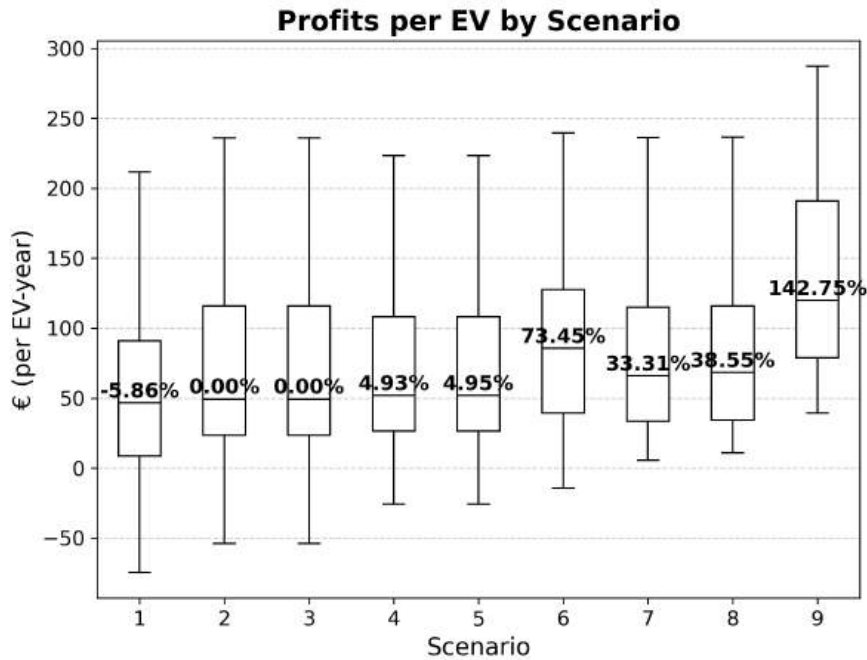
Table 1.1: IOIS scenarios

Id - IO;IS	Channel	Information received				
		$driving_{t,n}$	$evse_{t,n}$	$soc_{t,n}$	$\beta_{t,n}$	$\alpha_{t,n}$
(1)- No industrial standard	None	-	-	-	-	-
(2)- ISO 15118	Power Line Communication (PLC)	-	Yes	Yes	-	-
(3)- ISO 15118 + Original Equipment Manufacturer (OEM)	PLC + Over the Air Communication (OAC)	-	Yes	Yes	-	-
(4)- ISO 15118 + Nav.App	PLC + OAC	Yes	Yes	Yes	-	-
(5)- ISO 15118 + OEM + Nav.App	PLC + OAC	Yes	Yes	Yes	-	-
(6)- ISO 15118 + CPO	PLC	-	Yes	Yes	Yes	-
(7)- ISO 15118 + OEM + CPO + Nav.App	PLC + OAC	-	Yes	Yes	Yes	-
(8)- ISO 15118 + Mobility Service Provider (MSP)	PLC + OAC	Yes	Yes	Yes	Yes	Yes
(9)- ISO 15118 + MSP (+1day)	PLC + OAC	Yes	Yes (1 day before)	Yes	Yes (1 day before)	Yes (1 day before)

Figure 3.12 presents the distribution of annual profits that the Aggregator would gain from each EV owner, combining V1G and V2G profits. Furthermore, it shows the difference in the median profit for each scenario in respect of Scenario 2, which is the current industry standard of IOIS for Aggregators. The first remark is that the median of the profits ranges from €50 in Scenario 1 to €125 in the most favorable case. However, from the aggregator's business model perspective, analyzing the differences across distributions provides more valuable insights.

Notably, in Scenario 2 (ISO 15118), a significant portion of the EV user distribution remains above the €20 profit mark, with fewer substantial losses. Furthermore, the figure highlights that the anomalous median profit observed in Scenario 6 for V1G (Figure 3.10) remains elevated. However, in Scenario 6, the variance of the distribution is also noticeably higher compared to Scenarios 7 and 8, suggesting that there must be some EV drivers in this scenario that might have better performance with this scenario, but many others that do not.

Figure 1.4: Distribution of total profits per Scenario.

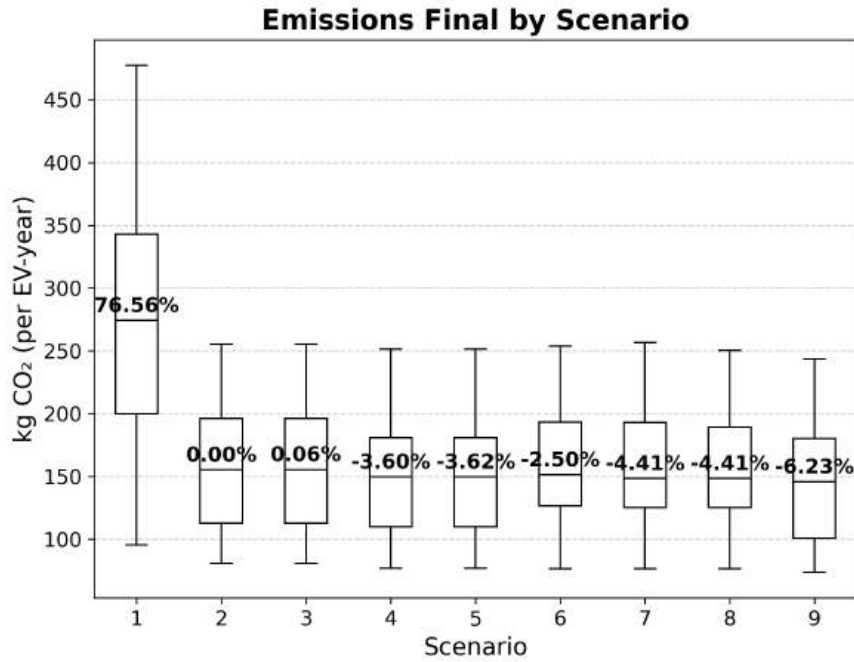


Scenarios:(1)- No industrial standard, (2)- ISO 15118, (3)- ISO 15118 + OEM, (4)- ISO 15118 + Nav.App, (5)- ISO 15118 + OEM + Nav.App, (6)- ISO 15118 + CPO, (7)- ISO 15118 + OEM + CPO + Nav.App, (8)- ISO 15118 + MSP, (9)- ISO 15118 + MSP (+1day)

Finally, Figure 3.13 serves as a useful proxy for system imbalances, as these are reflected in the additional emissions resulting from dispatching in each scenario. It is important to recall that the aggregator's optimization is driven by economic objectives rather than environmental considerations. The results show that while the difference in profits between Scenarios 1 and 2 was not particularly significant, the disparity in emissions is much more pronounced. This can be attributed to the imbalances caused by the lack of information and the relatively low cost of these imbalances. Furthermore, as

expected, greater information availability leads to lower GHG emissions from EVs. However, the differences between having access to information one day ahead appear to be less significant, as the emission factor remains constant regardless of whether the aggregator bids in the day-ahead or intraday market.

Figure 1.5: Distribution of emissions per Scenario.



Scenarios: (1)- No industrial standard, (2)- ISO 15118, (3)- ISO 15118 + OEM, (4)- ISO 15118 + Nav.App, (5)- ISO 15118 + OEM + Nav.App, (6)- ISO 15118 + CPO, (7)- ISO 15118 + OEM + CPO + Nav.App, (8)- ISO 15118 + MSP, (9)- ISO 15118 + MSP (+1day)

The study's contributions, are twofold. First, we propose a novel simulation framework that allows us to measure the value of information and can be extended to other electricity and mobility systems applications. Second, our findings show that increasing the information on departure times and future mobility needs can enhance profitability by up to +150% while simultaneously reducing CO₂ emissions by −6% compared to simply adhering to the industrial standard ISO 15-118.

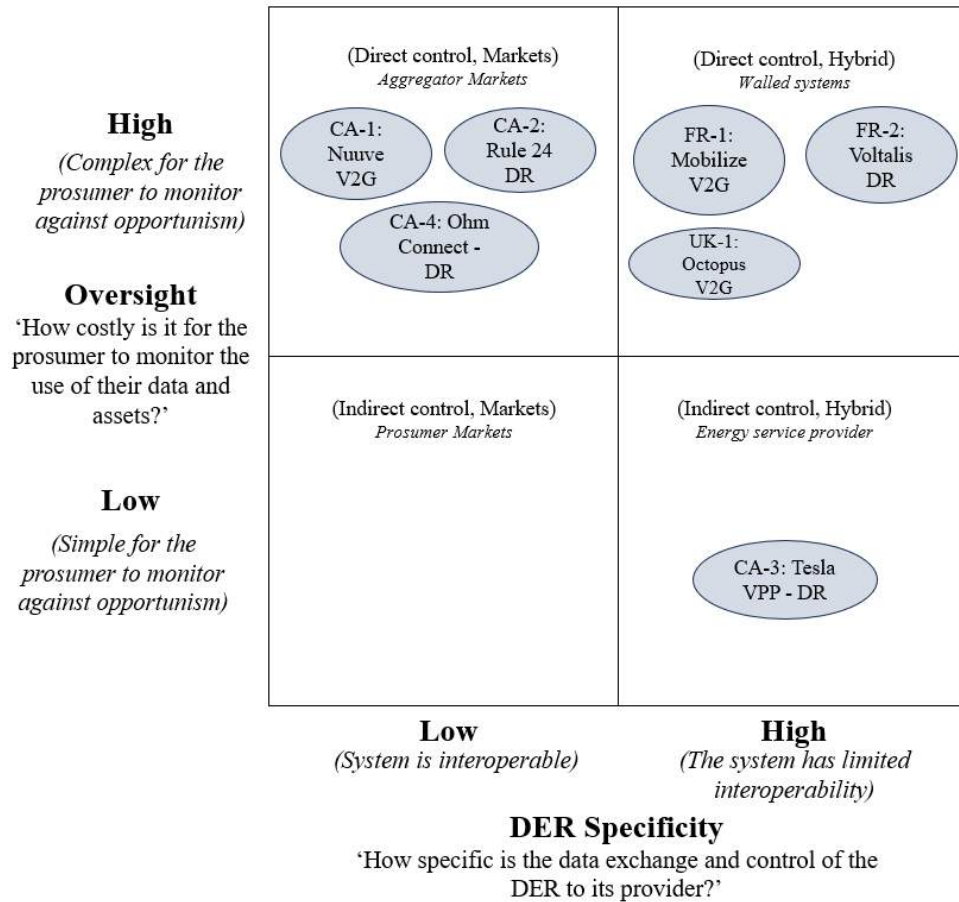
1.6.3 . Addressing problem 3: Identifying the impact of the arrangements to integrate EV users into smart grids

In chapter 4 we propose a framework based on transaction cost theory (TCT), which helps analyze the contractual structures that govern prosumer integration. By comparing different governance models, we evaluate how factors like monitoring and switching costs might pose theoretical problems for prosumers' participation. The framework is applied to case studies in California, the UK, and France to assess various business models.

To build our governance framework, we refine the two main transaction costs that have been suggested as central for electricity consumers (monitoring and switching costs) into two dimensions that are adapted to prosumers in smart grids: the complexity of oversight and DER specificity. The complexity of oversight refers to the monitoring and enforcement costs that prosumers 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 4.7 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. Furthermore, it compares the eight existing business models that we analyzed in the conceptual framework showing its applicability to analyze the risks and opportunities faced by prosumers.

Figure 1.6: Comparison of business models



This framework offers at least three important contributions. First, it provides theoretical insights into how different organizational structures shape prosumer integration and the risk of opportunism in smart grids. Second, it serves as a comparative tool for assessing the implications of alternative systems. More importantly, it provides a theoretical foundation for policy discussions under-explored in research and regulatory agendas. Specifically, we highlight four critical factors that might drive the emergence of a particular type of economic governance: Transparency, standardization, automation, and market power.

1.6.4 . Addressing problem 4: Identifying a tension between economic and environmental objectives in electricity systems.

In chapter 5, we conduct an empirical analysis using panel data to measure the impact of NRAs' governance on the share of renewable energy (and electricity tariffs) in EU member states. However, measuring governance is challenging, as publicly available indicators are not comparable over time. Therefore, we utilize a novel governance regime dataset provided by Brousseau and Gonzalez-Regalado (2022), which processes OECD regulatory governance surveys (Organisation for Economic Co-operation and Development, 2016).

Table 5.2 shows the parameter estimates for the effects of the governance regime on the share of renewable energies. Models (1) and (5) show a negative relationship between *independence* and the share of renewable energy after controlling for the rest of the dimensions. This estimate indicates that independent regulators are associated with a lower share of renewable electricity produced. The rest of the dimensions do not seem to have a crucial influence on renewable generation. Our results indicate that between 2013 and 2018, NRAs endowed with legal power (*independence*) were negatively associated with the share of renewable energy sources (RES) in total energy consumption.

Our contribution from this results is twofold. First, prior research analyzing the institutional context of policymakers (Alesina et al., 2005; Anderton et al., 2020; Égert, 2018) has primarily focused on the effects of reforms (policy output) on economic performance (investments, factor productivity, and labor markets). We contribute to the empirical literature on the effects of the liberalization of utilities by distinguishing between the impacts of regulation per se and the impacts of governance arrangements that implement it. Second, we contribute to the literature on the drivers of decarbonization by discussing the policy implications that our results hold for NRAs and environmental objectives. We highlight an ongoing tension between the desire to support renewable energy development and operate electricity systems at affordable prices through competition. Furthermore, we contextualize our results by discussing the policy implications of the ambitious targets to decarbonize electricity systems in the EU by 2050.

Table 1.2: Fixed Effects: Impact of governance on renewable energies shares

	(1)	(2)	(3)	(4)	(5)
Independence	-0.817** (0.334)				-0.968* (0.531)
Discretion		-0.203 (0.317)			
Transparency			-0.371 (0.496)		0.098 (0.504)
Market				0.167 (0.682)	0.53 (0.683)
Liberalization	1.456** (0.616)	2.306** (0.864)	1.725* (0.902)	2.091** (0.787)	1.452** (0.583)
Inst. Stability	0.038*** (0.006)	0.041*** (0.008)	0.039*** (0.008)	0.040*** (0.008)	0.039*** (0.006)
Non-renew power	-1.039** (0.312)	-1.328** (0.351)	-1.148** (0.358)	-1.297** (0.371)	-1.084** (0.312)
Demand (GDP)	2.049** (0.861)	1.739* (0.843)	2.133** (0.977)	1.887** (0.910)	1.978** (0.852)
Wealth	-2.136** (0.921)	-1.926** (0.918)	-2.271** (1.029)	-2.067** (0.971)	-2.051** (0.934)
Trade balance	0.107 (0.105)	0.095 (0.118)	0.101 (0.113)	0.094 (0.115)	0.104 (0.113)
Years ren. laws	0.262*** (0.058)	0.319*** (0.085)	0.274*** (0.092)	0.309*** (0.087)	0.255*** (0.073)
Patenthundred	0.134** (0.056)	0.125* (0.067)	0.125* (0.067)	0.123* (0.070)	0.127** (0.053)
Individual effects	yes	yes	yes	yes	yes
Time effects	yes	yes	yes	yes	yes
adj. R ²	0.87	0.842	0.846	0.841	0.868
AIC	-141.4	-132.3	-133.5	-131.8	-139.5
Observations	48	48	48	48	48
F-statistic	33.137	18.331	23.049	24.334	36.048

Controls: *mkt access* level of market reform implementation related to granting new incumbents access to the natural monopoly segment of the industry, *inst. Stability*: freedom House political rights score. Extent to which political institutions are stable. *non-renew mkt power*: Proxy of lobbying power of non-renewable generators in the industry, *demand(GDP)*: measured in PPP USD of 2010, *wealth, income per capita*: In PPP USD 2010 per are set in logs., *patenthundred*: ratio of patents and the number of people in a country.. Discretion is excluded in model (5) due to multicollinearity with the other gov. dimensions. Heteroskedasticity robust standard errors in parentheses * p < 0.1, ** p < 0.05, *** p < 0.01.

1.7 . Dissertation structure

This dissertation is structured into nine chapters. This chapter provides the background and context of the study, defining the research questions, objectives, and the role of V2G technology in leveraging EVs to defossilize electricity systems. As outlined in the previous section, Chapters 3 to 5 present the four core papers of this dissertation, each with its own introduction and conclusion. Chapter 6 then synthesizes the key findings, explores their implications for coordinating EVs as a decarbonization tool for electricity systems, and proposes future research directions in V2G and smart grid systems.

Beyond the four main papers, during my three years of PhD research, I had the opportunity to collaborate with fellow PhD researchers on additional projects. These collaborations resulted in two additional papers, which are included in Chapter 7.

Chapter 8 contains the annexes, aggregating all relevant data, code, supplementary tables, and additional information from previous chapters. Lastly, Chapter 9 consists of the appendices, providing complementary details on the dissertation process, including a list of presentations for each core paper and my CV.

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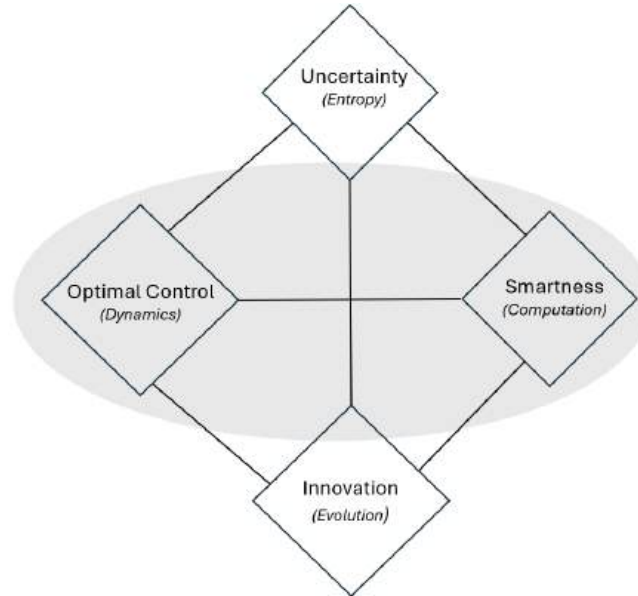
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2 - Measuring the computation costs of scaling V2G

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Figure 2.1: The four pillars of complexity applied to Chapter 2. Adapted from (Krakauer, 2024)



The gray area in the figure highlights the two key pillars that this work directly addresses: Optimal Control and Computation. Optimal control is examined through optimization algorithms that rely on information to determine when and how much EVs should charge or discharge. Smartness or computation, in this context, is measured by analyzing the length of the input required for the optimization algorithm. A key focus of this work is that, as optimization algorithms scale with more EVs controlled by the same entity, the input size may increase exponentially, impacting the overall computation costs of V2G. This represents an initial step in understanding how the complexity of electricity systems may evolve, considering that the benefits of optimization could reach an energetic threshold beyond which computation costs outweigh the gains.

¹The original title of the paper is: *Evaluating The Design of Smart Grid Information Flows: The Impact of Scale and Complexity in Vehicle-to-Grid (V2G) Applications.*

Abstract: The integration of intermittent renewable energy sources challenges system operators (SOs) in balancing supply and demand. Smart grids, enabled by advanced information and communication technologies (ICT), promise to enhance grid stability by facilitating bi-directional data exchange and decentralized optimization. However, much-existing research has focused either on algorithmic optimization or communication standards, overlooking the operational constraints introduced by the information flows that make smart grids "smart". This paper addresses this gap by integrating scaling and information theory to assess the impact of information flow design on computational costs in smart grid applications—particularly in Vehicle-to-Grid (V2G) systems. We identify and model four archetypes of V2G information flow design and analyze their scalability using information and connectivity measures. Our findings highlight how computational demands increase with system scale, offering insights into why some V2G optimization algorithm designs might succeed while others struggle.

2.1 . Introduction

As the transition towards more sustainable energy systems progresses, renewable energy sources are increasingly integrated into the electricity mix. However, introducing these renewable sources presents challenges for system operators (SOs) in maintaining grid stability, particularly because their ability to balance supply and demand is traditionally based on controlling the power supply alone (Tuballa & Abundo, 2016). The operation of electricity systems requires an SO to manage the grid according to Kirchhoff's laws of current, which stipulate that power supply, demand, and losses must be balanced in real time to prevent damage to the distribution system and connected appliances or machinery from voltage fluctuations (Sorokin et al., 2012). The intermittent nature of many defossilised electricity sources, such as solar and wind power, complicates this task. SOs can not control when the sun is shining or the wind is blowing; thus, the power supply is less controllable.

As electricity supply becomes more unpredictable and less controllable, electricity systems must be redesigned to accommodate controllable demand—commonly known as demand response—along with the necessary information flows to support grid control and optimization (Ancillotti et al., 2013a; Clastres, 2011a; Farhangi, 2010; Joskow, 2012; Potter et al., 2009; Yu & Xue, 2016). In traditional, uni-directional electricity systems, SOs typically collect data on consumption and production, with minimal information flowing back from SOs to the consumers. To address these challenges, solutions have emerged under the concept of "Smart Grids," which leverage advanced information and communication technologies (ICT) to enable bi-directional data exchange and decentralized optimization. These systems integrate a wide range of defossilized energy resources, allowing for better control of demand and decentralized energy production and storage (Joskow, 2012; Ketter et al., 2018).

Over the past decade, research on smart grids has examined a variety of optimization solutions, covering a wide array of applications (e.g., rooftop solar panels, heat pumps, load curtailment, and electric vehicles) and levels of analysis (e.g., individual households, microgrids, fleets, buildings, distribution systems, and transmission networks). These studies have highlighted the potential of smart grids to reduce energy costs and emissions by optimizing and automating the timing of energy consumption and supply (Ketter et al., 2018; Yu & Xue, 2016). However, much of this research has overlooked the additional operational aspects of smart grids associated with the information flows necessary to make smart grids functional. As a result, several critical questions remain unanswered from an operational perspective, such as: What if the energy required to process the information for optimization exceeds the energy savings achieved by the optimal strategy? What if there are constraints on the information flow? How would such constraints influence the selection of the most effective optimization algorithm?

To address these critical questions, we explore the trade-offs introduced by information flow design in smart grid applications by integrating scaling and information theory into our analysis. Scaling theory suggests that, as a system expands, its management costs and inefficiencies can increase exponentially (West & Brown, 2005). In complement, information theory highlights that the minimum computation cost of an algorithm is determined by the length of the shortest bit-string containing the input required by the algorithm (Chaitin, 1990; A. Kolmogorov, 1968). By combining these theories, we can evaluate complex information flows and provide a basis to measure if the computational demands of managing the information flow may increase significantly as the system scales. This could inform about situations where an optimization algorithm, which appeared efficient in pilot projects, becomes inefficient at larger scales.

Understanding and quantifying the computational costs associated with optimization algorithms—such as those employed in Vehicle-to-Grid (V2G) applications that use Electric Vehicle (EV) batteries both as an energy sink (balancing the grid during excess energy production) and as an energy source (for transportation in mobile mode and electricity supply to the grid in stationary mode) (Kempton & Tomić, 2005b; Thompson & Perez, 2020)—is crucial for assessing the technology’s potential for two main reasons. First, V2G systems might likely experience rapid scaling, with the rapid uptake of EVs and the potential that the collective capacity of EV batteries has to provide sufficient energy storage to support the transition to a defossilized electricity system (C. Xu et al., 2023). However, V2G technology is still in its early stages, and the effects of scale have been largely overlooked, with most empirical analysis limited to pilot projects and lab experiments (V2G Data Hub, 2023). Second, there is no clear consensus on how key stakeholders—such as EV owners, car manufacturers, charging operators (CPOs), energy retailers, and grid operators—can effectively collaborate to scale V2G (Gschwendtner et al., 2021; Sovacool et al., 2020). This issue highlights the need to address both the organizational and information flow challenges of V2G while also considering the computational costs associated with scaling

these systems. Consequently, our research seeks to answer the following question: *What is the impact of information flow design on V2G computation costs at scale?*

Given the lack of empirical data on information flows of V2G systems, we chose to address our research question by relying on extant V2G designs in the technical literature and derive the information needed from them. We conduct a literature review to identify and model different designs of the information flow required for the V2G system and subsequently assess how scaling these designs impacts their information flows. For these assessments, we use two widely accepted to analyze flow network's: connectivity and algorithmic complexity (Borgatti, 2005; Chaitin, 1966; A. N. Kolmogorov, 1965; Strogatz, 2001; West et al., 1997).

Our research two main contributions. First, we identify four types of V2G information flow design archetypes in the literature that vary in the distribution and level of computation costs responses to scaling: "Hierarchical design", "Exponential", "3.2-7.4" and "1.7-2.7". Second, we use these archetypes to develop insights for practitioners and Smart Grid researchers who aim to design V2G applications. Our perspective explains why some smart grid applications evolve successfully while others do not, especially considering how their computation costs and system interdependencies increase with scale.

The paper is divided into six sections. In the next section, we provide an overview of related research and present the main theoretical concepts use in this paper, including the two measures we use to assess the computation costs of the information flow. In section three, we present our methods to review the literature, identify information flows and compute the information flow measurements. Finally, in sections five and six, we present our discussions and conclusions, respectively.

2.2 . Theoretical background

We review three key research streams that inform our work. First, we examine studies that conceptualize the core research on Smart Grids. Second, we present scaling theory as a lens for understanding how systems change with increasing scale. Finally, we introduce information theory to measure computation costs from information flows.

2.2.1 . Smart Grids

While there is no universally accepted definition of smart grids, it is generally considered to be a second iteration of electricity grids, moving from a traditional grid designed to only transmit and distribute power to one that "integrates information technology into the existing power grid to optimize energy efficiency through a two-way exchange of electricity information between suppliers and consumers in real-

time” (Tuballa & Abundo, 2016, p.712). The integration of information systems in grid management is particularly important to “intelligently integrate the actions of all users connected to it – generators, consumers and those that do both” (ibid), requiring bi-directional information and optimization (Ancillotti et al., 2013b; Clastres, 2011b; Farhangi, 2010; Joskow, 2012; Potter et al., 2009; Yu & Xue, 2016).

Based on the work of Tuballa and Abundo (2016), Table 2.1 compares the main differences between the Traditional Electric Grid and a Smart Grid. Indeed, leveraging the potential of distributed energy resources (DER) – as opposed to large-scale centralized energy sources in traditional grids – requires considering that DER might have a dual role: self-consumption (e.g., for private use, behind the meter) and grid services production (e.g., selling services to the electric system in front of the meter). Therefore, bi-directional information and optimization allow the use of decentralized energy resources where it is more efficient to use them (for private or grid use). For example, demand response services, where users curtail their consumption, require knowing the willingness of consumers to shift their consumption (Strueker & Dinther, 2012). Similarly, V2G, where EVs can supply electricity to the system acting as energy storage, requires knowing the EV owner’s mobility needs (Parsons et al., 2014). These two examples show how smart grids optimize when consumers receive the energy needed and when they can turn into producers by taking advantage of excess energy stored in their EV batteries.

Table 2.1: Comparison of Traditional Grid and Smart Grid adapted from Tuballa and Abundo (2016)

Traditional Grid	Smart Grid
Mechanization	Digitization
One-way communication	Two-way real-time communication
Centralized power generation	Distributed power generation
Radial network	Dispersed network
Less data involved	Large volumes of data involved
Small number of sensors	Many sensors and monitors
Less or no automatic monitoring	Great automatic monitoring
Manual control and recovery	Automatic control and recovery
Less security and privacy concerns	Prone to security and privacy issues
Human attention to system disruptions	Adaptive protection
Limited control	Extensive control systems
Slow response to emergencies	Fast response to emergencies
Fewer user choices	Vast user choices

A large amount of research on Smart Grids has focused on developing an “Algorithmic view” of Smart Grids, focusing mostly on designing algorithms for specific smart grid applications. Examples of such research include applications for demand-side management algorithms (Bae & Kwasinski, 2012; Gottwalt et al., 2011; Khan & Khan, 2017), adaptive tariff algorithms (Erden et al., 2018b; Valogianni et al., 2020),

and dispatch algorithms for decentralized loads (Kirihaara et al., 2019; Li et al., 2021), amongst others. This research has provided significant practical and theoretical value, showing not only the potential of Smart grids across applications, but also developing the algorithms that can be used in practice. Furthermore, this stream of literature can be sub-classified into the consideration of two types of algorithms, that vary in terms of the type of control assumed over the grid assets that are optimized (control layer). Indeed, control can be either direct – a central actor implements the algorithms to centralize the operations of energy assets, or indirect – when an actor centralizes the information to send a signal (typically an adaptive price signal) to the energy assets (He et al., 2021), which independent consumers or prosumers on the smart grid can then use for their own decentralized decision-making (Valogianni et al., 2020).

We argue that the “Algorithmic View” has largely overlooked the operational aspects of smart grids related to the information layer essential for their functionality. However, the control and optimization of Smart grids is only one of four main layers of Smart Grids. Indeed, Ketter et al. (2018) has proposed that a Smart Grid, in essence, consists of four layers: an information system (IS) layer that enables a network of information exchanges amongst the actors within a Smart Grid application, a physical layer (e.g., electricity and communication networks), a monitoring layer (e.g., a network of sensors), and a control layer in which grid operators can directly control and optimize customer energy demand. Therefore, while the “Algorithmic View” is essential for Smart Grid, it often neglects how the information layer influences algorithmic performance and how information is made available for computation.

Existing research on this information layer primarily examines the characteristics and interoperability of communication infrastructure. This line of work focuses on operational constraints in information exchange between grid components—defining parameters such as bandwidth, coverage area, data rate, frequency range, latency, and security protocols (Ghorbanian et al., 2019). For instance, Neaimeh and Andersen (2020) analyzed communication protocols required for V2G interactions. While such studies provide valuable technical insights, they offer limited guidance on the effectiveness of optimization algorithms or the broader organization of smart grid applications.

To our knowledge, only two studies have focused on the information layer going beyond the communication standard. Liang et al. (2014) reviewed the literature to assess how different smart grid IS architectures impact system-wide efficiency, while Naus et al. (2014) analyzed how different designs of the information layer in smart grids impact household behavior, based on interviews with households participating in a smart grid pilot project in the Netherlands. Although these studies incorporate a broader range of variables in smart grid IS design, neither examines how system efficiency evolves with increasing network size.

To improve our understanding of the efficiency and constraints of smart grid ap-

plications that could be implemented on a large scale, such as V2G, we must move beyond the current dichotomy of focusing solely on either algorithms or communication standards. Instead, a broader perspective is needed. The following sections demonstrate how scaling and information theories offer new insights into this issue.

2.2.2 . Scaling theory

Scaling theory teaches us that certain networks exhibit fractal behavior. This means that as networks grow, the network geometry creates a pattern repeating itself over and over (Mandelbrot, 1967). These patterns have been extensively studied in biological systems, where the most famous example is their application of power-laws to the study of metabolic rates from a diversity of biological systems, which shows that among all of them, energy consumption increases at a scale of a fourth by a unit increase of the system body mass (West et al., 1997).

Such power laws are mathematically characterized by a power function that describes how a variable of interest, like computation costs, varies with a state variable, which can be the mass of the system, time, or number of EVs in the system. Equation 2.1 shows a general version of a power law.

$$Y = Y_0 \cdot X^b \quad (2.1)$$

where:

- Y is the dependent variable,
- Y_0 is a normalization constant,
- X is the independent variable, and
- b is the power law.

Taking the logarithm on both sides of Equation 2.1, we obtain a linear form in equation 2.5, which allows for easier scaling law interpretation, as the exponent b , is the power-law.

$$\log Y = \log Y_0 + b \log X \quad (2.2)$$

However, unlike metabolic systems, which scale over constant laws, the so-called power laws, not all networks behave similarly (Broido & Clauset, 2019). Instead, Albert et al. (2000) has shown that the connectivity distribution of a network, where connectivity is broadly defined by the number of connections a node has on the network,

influences how the network will scale. Thus, networks can be classified roughly into two groups: scale-free networks, when the scaling law is constant, and thus a constant power-law exists, or exponential networks, when the scaling law changes over time.

Scale-free networks are characterized by being inhomogeneous in their connectivity, meaning that most nodes have one or two links, but a few nodes have many links (Barabási & Bonabeau, 2003). In contrast, exponential networks are those in which the network is homogeneously distributed, meaning that each node has approximately the same number of links. Table 2.2 summarizes the key differences between these two network types and puts them in context on the context of our research question, showing the different implications from a computational perspective. Thus, considering the distribution of connectivity to distinguish between scale-free or exponential networks in the analysis of V2G can provide insights into how the computation burden on a given information flow might be distributed among several nodes or concentrated over one. In what follows, we introduce a connectivity measure, which has been suggested for analyzing the scaling behavior of networks.

Table 2.2: Types of networks by scaling behavior

Types of Network	Scaling behavior	Connectivity Distribution	Impact on computation
Scale-free	Constant	Concentrated: A few nodes are very connected; all the others are equally connected.	In scale-free networks, where a few highly connected nodes (hubs) are dominant in the information flow of the system, computation can become a bottleneck because a single point handles a disproportionate share of the workload. As the system scales, these nodes may become overwhelmed, leading to non-linear increases in computational costs.
Exponential	Changes over time	Homogeneous: All nodes are similarly connected.	As all nodes have the same connectivity, computational load can be evenly distributed.

Measuring network connectivity

In a flow network, nodes represent the system components, while the directed edges represent the exchanges between the components, including their flow direction and volume (Ahlsweide et al., 2000). Within this network and directed edges model, system connectivity can be measured using the weighted geometric mean of the network

nodes, as shown in Equation ?? below (Zorach & Ulanowicz, 2003). This measure is computed by considering the relative node-outflow (i.e., how much information flow goes out from a node relative to the total system information flow) and the relative node-inflow connectivity (i.e., how much a given outflow of a node represents relative to all the flows that the receiving node receives from other nodes).

More formally, to determine our measure, we need an adjacency matrix denoting as $A(i, j)$ where the rows, i , define the node from which the flow originated and the columns, j , the actor receiving the flow. Furthermore, $a(i, j)$, denotes the elements in the matrix space, representing the flow from node i to node j .

$$C = \prod_{i,j} \left(\frac{a_{ij}^2}{a_{i.} a_{.j}} \right)^{-\frac{1}{2} \frac{a_{ij}}{A_{..}}} \quad (2.3)$$

Where:

$$\begin{aligned} a_{ij} &= \text{flow from node } i \text{ to node } j, \\ a_{i.} &= \sum_j a_{ij}, \quad \text{total node } i \text{ outflow,} \\ a_{.j} &= \sum_i a_{ij}, \quad \text{total node } j \text{ inflow,} \\ A_{..} &= \sum_{i,j} a_{ij}, \quad \text{total node flow in the system.} \end{aligned}$$

If optimization algorithms on V2G applications require a network of actors exchanging information to gather the data needed for their optimization, scaling theory teaches us that depending on the system connectivity, the computation costs of the network might increase exponentially with scale (Dobson et al., 2007; Krause et al., 2015; Maslov & Sneppen, 2002; Watson & Stallins, 2016) or might increase at a constant rate over scale, following a power-law. However, until now, we have remained agnostic on what is being exchanged on the network, and we have not yet explained in detail how we can measure computation costs. Therefore, in the next subsection, we introduce information theory to transform information flows into computation costs.

2.2.3 . Information theory

Information theory provides a statistical interpretation of uncertainty and information that has been used as a fundamental measure of semantic communication processes. In his seminal paper Shannon (1948) proposed a measure of uncertainty, as shown in Equation 2.4. Such measure is nonnegative², symmetric³, accumulative

² $I(A) \geq 0$

³ $I(A, B) = I(B, A)$

⁴, and convex ⁵ (Gell-Mann & Lloyd, 1996).

$$I(x) = -K \sum_x p_x \log p_x \quad (2.4)$$

where:

K = an arbitrary positive constant,

p_x = the probability that a given message r occurs over a set of alternative X ,

X = set of potential messages.

In digital communication processes, where uncertainty and information are quantified in bits, K is set to 1, and the logarithm is taken in base 2, $\log_2$. Shannon (1948) measure is a function of the ensemble $\{x \in X, p_r\}$. For example, if one considers communication through a telegrapher, the ensemble X is the common information that the sender and receiver have to code the messages: $(., .)$ for rain, $(., -)$ for sun, $(-, .)$ for clouds, and $(-, -)$ for fog. Before receiving the message, the receiver knows that it will receive either of four messages and thus have two bits of uncertainty $I = -\sum 0.25 \log_2 0.25 = 2$; thus, if we consider that the receiver sends the first part of the message $(-)$; then the receiver will have received 1 bit of information and have 1 bit of uncertainty as now it knows that the weather can be either sunny or foggy.

However, the ensemble can take different forms and describe analog applications (Gell-Mann & Lloyd, 1996). Such an approach has been used to determine the algorithmic information content of a message, which is a lower bound of the computation costs of any algorithm. The following subsection details how information theory is applied to measure the computation from an optimization algorithm.

Measuring algorithmic complexity

A. N. Kolmogorov (1965) and Chaitin (1966) applied information theory to analyze algorithms. They provide us with a measure, of how difficult it is to use an object x , which could be a bit-string, representing an informational input that receives an optimization agent, to gain information from y , which could be the optimal strategy to charge or discharge EVs. However, rather than comparing the computation process based on the operations of the calculation itself, they defined it in terms of the input uncertainty of the algorithm. Their key insight was that a minimum computation threshold can be found if the set X of possible messages is known by both the sender and receiver (as in digital communication). This led to the definition of

⁴ $I(A, B) \geq I(A)$

⁵ $I(A) + I(B) \geq I(A, B)$

Kolmogorov-Chaitin complexity $K(x)$ of object x , which is defined as the length (in bits) of the shortest program required to produce an output y . This measure, also called "algorithm complexity," has been suggested as a powerful approach to assess the complexity of information processing to obtain a given output y (Crutchfield, 1994).

More formally, in what follows we provide a summary of A. N. Kolmogorov (1965) theorem, let $I_A(x : y)$ be the information conveyed by the information flow, x , about the best charging strategy of the EVs y , where A is a given program to transform x into y . Furthermore, consider the set of possible messages $X = x$, with a finite sequence $n(x)$ of zeros and ones, where the length of the sequence $n(x)$ is $l(x)$. Under this definition, if one would consider to measure the total length of x and y together, such correspondence has a key property that it's less than the length of y plus some constant, C_x that depends only on x ; $l(x, y) \leq C_x + l(y)$.

Thus, A. N. Kolmogorov (1965) shows that if we consider the length of the program $l(p)$, where p is the shortest "program" that produces y from x , we can formalize the computation process as $\varphi_x(p, x) = y$, where φ_x is a function that depends only on p and x . Thus, for any such function, one can define:

$$K_\varphi(y | x) = \min_{\varphi(p, x)=y} l(p) \quad \text{or} \quad \infty \quad \text{if there is no } p \text{ such that } \varphi(p, x) = y$$

as the length of the shortest program that computes y from x .

From these premises, A. N. Kolmogorov (1965) states in his theorem of computational irreducibility that there exists a partially recursive function $A(p, x)$ such that for any other partially recursive function $\varphi(p, x)$, the following inequality holds:

$$K_A(y | x) \leq K_\varphi(y | x) + C_\varphi$$

where the constant C_φ does not depend on x or y . For a detailed proof of the theorem, one can refer to A. N. Kolmogorov (1965, p.973). Furthermore, it is noteworthy that Chaitin (1990) provided a similar theorem, demonstrating that while additional instructions (e.g., an algorithm interpreting the bit-string input) may be necessary, the computational cost of processing the input scales proportionally to the size increase of the bit-string.

A remarkable aspect of A. N. Kolmogorov (1965)'s theorem of computational irreducibility is that when considering an information input x that grows increasingly large, and a recursive program p , the minimum number of computations required is primarily influenced by the size of x rather than by the program p . In the context of our research, $K(x)$ can be interpreted as a lower bound on the number of computations an optimizing agent must perform to execute its algorithm. Thus, if incorporating more EVs into the operation of the algorithm increases the length of

x , then, according to A. Kolmogorov (1968) and Chaitin (1966), the computational steps of the algorithm will scale with the size of the input string.

Given this theoretical background, we set out to analyze the design of the information layer through both, the lens of scaling and information theory, utilizing the measures presented in this section. Our goal is to identify how the design of the information layer may exhibit specific computation costs from which we can derive insights that contribute to implementing this technology as a solution for defossilizing electricity systems.

2.3 . Methods

We adopted the following steps to assess the computational costs associated with the information layer in V2G applications as this system scales. First, we systematically reviewed peer-reviewed V2G articles to identify the main perspectives on V2G information flows. Second, we analyzed each article, focusing on task-actor relationships to identify the messages exchanged and the actors involved in the information flow. Finally, we transformed these information flows into an adjacency matrix, modeling a network where the flow is quantified based on the algorithmic complexity $K(x)$ of each information exchange x between actors in the V2G system. We then analyzed how the total algorithmic complexity of the information flow and the system's connectivity scale as more EVs are integrated into the network.

2.3.1 . Systematic literature review

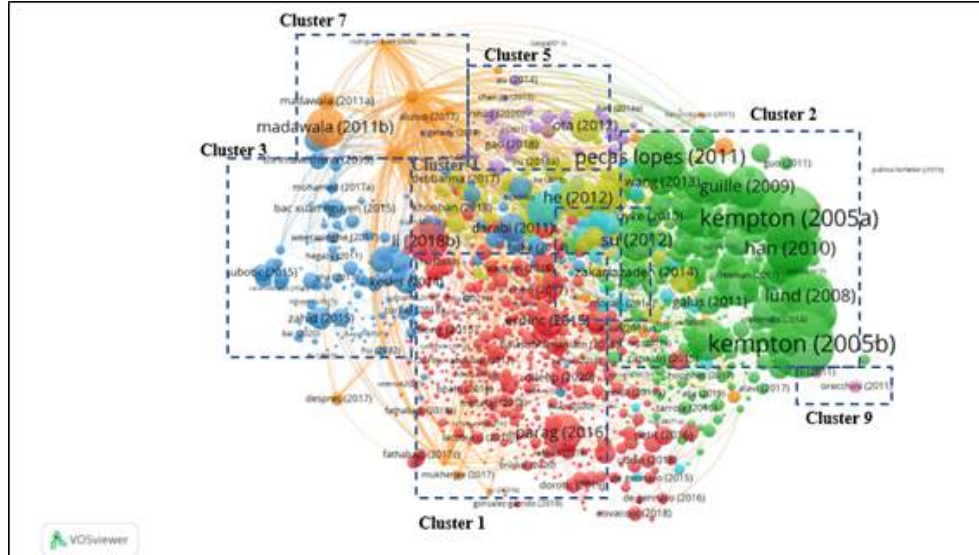
We used a systematic approach for our literature review (Asadi et al., 2017) to find different perspectives on V2G, in line with the PRISMA guidelines (Moher et al., 2009). We use the Web of Science as our source of scientific publications to identify research on V2G that was published between 2005, when the seminal paper on V2G was first published (Kempton & Tomić, 2005b), and 2023. We used “Vehicle-to-Grid” and “Grid integrated vehicle” as keywords for the search, which returned 1,273 publications.

We used a bibliographic coupling algorithm to classify the articles into clusters of articles according to their shared references (Cobo et al., 2011; Kessler, 1963; Mas-Tur et al., 2021). The algorithm compares two indicators—the number of links, which defines the number of referenced publications two articles have in common, and —the total weight of links, which adds all the familiar references an article has within its links. The benefit of bibliographic clustering is that it allows us to identify the different perspectives and fields within the V2G literature.

Figure 2.2 visually represents the connections between the articles found in the Web of Science search and the nine clusters identified by the algorithm, each with a

different color.

Figure 2.2: Bibliographic clustering.



Note: Each node represents an article. The node's color indicates the cluster it belongs to, while its size reflects the number of citations the article has received. Links between nodes represent connections between articles that share at least one reference. The width of each link signifies the strength of the connection, measured by the number of shared references between the linked articles.

Subsequently, we selected a sample of articles from each cluster to ensure a representative and comprehensive perspective on the information flow of V2G. Articles within each cluster were ranked based on two criteria: the number of citations and cluster centrality⁶. We selected the top 25th percentile for each criterion. After applying this filtering process across all nine clusters, our final database comprised 150 publications.

Additionally, we analyzed the domain of the journals using the Web of Science classification. Our analysis revealed that Electrical Engineering is the predominant research domain across all clusters, with no significant distinction in their domain composition. This finding suggests that the clusters represent not distinct disciplinary perspectives but interconnected scientific communities linked through shared references. Table 2.3 summarizes the analysis of the clusters.

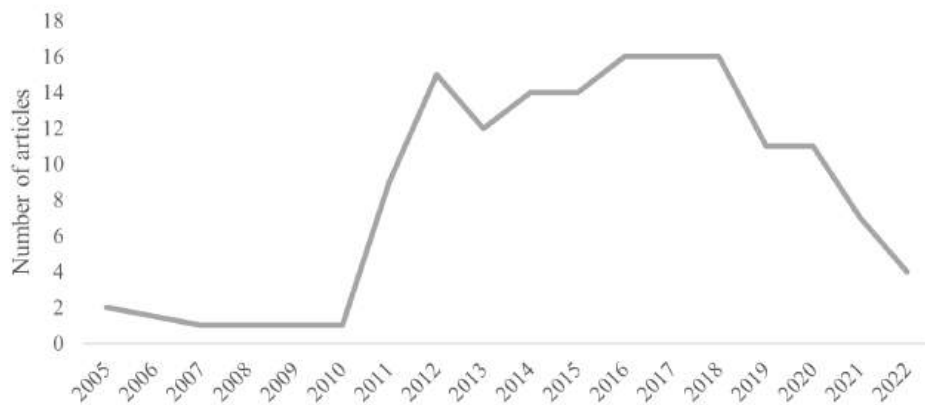
Furthermore, figure 2.3 shows the share of articles per year of publication included in the sample. Overall, our sample considers the full length of timeframe from 2005 up to 2023.

⁶Cluster centrality measures how extensively an article shares references with other articles within the cluster.

Table 2.3: Clustered Articles and Their Categories in Web of Science

Clusters	1	2	3	4	5	6	7	8	9	Total
Number of articles in the cluster	566	294	166	109	55	48	25	2	2	1,267
Articles filtered										
25 percentile by citations	16	8	7	5	4	2	1	1	1	45
25 percentiles by centrality	39	42	13	12	4	6	1	1	1	119
Both categories (duplicates)	3	-	-	1	1	-	-	1	-	5
Number of articles sampled	52	50	20	16	7	8	2	1	2	158
(% of articles sampled)	9%	17%	12%	15%	13%	17%	8%	50%	100%	12%
Categories of Web of Science										
Electrical/Electronic Engineering	23	21	14	13	8	6	1	1	0	87
Energy & Fuels	18	21	4	3	0	2	0	0	1	49
Computer science	2	0	2	0	0	0	0	0	0	4
Electrochemistry	0	1	0	0	0	0	1	0	1	3
Multidisciplinary	0	2	0	0	0	0	0	0	0	2
Transport	1	1	0	0	0	0	0	0	0	2
Environmental Sciences	1	0	0	0	0	0	0	0	0	1
Management science	0	1	0	0	0	0	0	0	0	1
Automation control systems	0	1	0	0	0	0	0	0	0	1
Economics	1	0	0	0	0	0	0	0	0	1

Figure 2.3: Articles selected by year of publication.



2.3.2 . Articles analysis

We analyzed each article to identify the actors involved in the V2G system and their specific information tasks. This process is iterative, allowing for standardizing task names across all articles. In Table 2.4, we show, as an example, the actors and information tasks from one of the analyzed articles. We refer to the table compiling all actor-task interactions over a given article as the 'V2G information task matrix'.

Table 2.4: Example of ‘V2G information task matrix’ tabulation from (Chandra Mouli et al., 2019)

Actor	Information Tasks	Articles citations - Design specification
EV	A-1. Monitoring	"The efficiency of the EV battery for charging and discharging is either obtained from the EV or stored in a database within the EMS for different EVs." (Chandra Mouli et al., 2019, p.1316)
EV user	A-2. Inputs preferences	"The users can enter the maximum and minimum charging and discharging power, respectively. By setting it to a non-zero value, the users can choose to participate in V2G services."
EV user	A-3. Communicates data	"The user links to the EMS, and the EMS instructs the user on which EV-PV charger he/she must connect to, based on two 'acceptance criteria"
CPO	C-1. Aggregates data	"Following the formulation in [15] and [16], an Energy Services Company (ESCO) acts as an intermediary between the wholesale market operated by the Independent System Operator (ISO) and the EV end-users." (Chandra Mouli et al., 2019, p.1315)
CPO	C-4. Forecast data	"The EMS uses solar forecast information as an input to predict the PV variation." (Chandra Mouli et al., 2019, p.1318)
CPO	D-1. Optimize strategy	"The ESCo operates at the workplace where employees drive to the office with an EV, and the building has overhead PV installation or a solar carport. The motive of the ESCo is to schedule the charging of the EV and feeding of PV power to the grid so that EV charging costs are lowered, regulation services are offered to the ISO, and at the same time, the income from PV is increased." (Chandra Mouli et al., 2019, p.1315)
CPO	E-1. Control	"The ESCo uses the EMS to control the solar-powered EV car park for energy trading with the grid." (Chandra Mouli et al., 2019, p.1317)

Analyzing each 'information task matrix,' we identified the messages exchanged between the actors involved for V2G to happen. We compile the messages exchanged in a new table that identifies who sends the message, who receives it, and the type of information being transmitted, we refer to such table as the "V2G information flow" of the article. Table 2.5 presents the information flow from 2.4.

Table 2.5: Information flow in Chandra Mouli et al. (2019)

From	To	Data Ex- change	Extraction
EV user	CPO	Energy de- mand	“The user links to the EMS, and the EMS in-structs the user on which EV-PV charger to connect to, based on two ‘acceptance criteria’. The first criterion is that the energy demand and parking time of all the EVs connected to one EV-PV charger must be within the power limits of the charger.” (Chandra Mouli et al., 2019, p.1316)
EV user	CPO	Parking time	“The user links to the EMS, and the EMS in-structs the user on which EV-PV charger to connect to, based on two ‘acceptance criteria’...”
EV user	CPO	Maximum discharge	“The user links to the EMS, and the EMS in-structs the user on which EV-PV charger to connect to, based on two ‘acceptance criteria’. The first criterion is that the energy demand and parking time of all the EVs connected to one EV-PV charger must be within the power limits of the charger.” (Chandra Mouli et al., 2019, p.1316)
EV user	CPO	Minimum SOC	““The user links to the EMS, and the EMS in-structs the user on which EV-PV charger to connect to, based on two ‘acceptance criteria’... The second criteria is that the arrival SOC of the vehicle must be above the minimum SOC as set by the user.” (Chandra Mouli et al., 2019, p.1316)
EV	CPO	Efficiency	“The efficiency of the EV battery for charging and discharging is either obtained from the EV or stored in a database within the EMS...”
CPO	EV user	Where to connect	“The user links to the EMS and the EMS in-structs the user on which EV-PV charger to connect to...”
CPO	Wholesale market operator	Sends energy to offer kWh	”The motive of regulation services are offered to the ISO.” (Chandra Mouli et al., 2019, p.1315)
Wholesale market operator	CPO	Accepted or rejected	”The motive of regulation services are offered to the ISO.” (Chandra Mouli et al., 2019, p.1315)

2.3.3 . Computing Connectivity and Algorithmic Complexity

To perform a quantitative of the information flow, we construct an adjacency matrix, $A_{(i,j)}$, for each article. We use the rows, i , to define the actor sending the information and the columns, j , to define the actor receiving the information. In the matrix space, we denote the message as $K(x_{(i,j)})$, which is defined as the algorithmic complexity of the information sent from actor i to j .

To compute the algorithmic complexity, we assume that all the actors across articles have a standardized number of bits for the same message exchange. This means that if in a given article, actor i sends the "time of departure" to actor j , and in another article, actor g sends also "time of departure" to actor l , $K(x_{(i,j)}) = K(x_{(g,l)})$. Such an assumption allows us to compare information flow under the same standard of information costs per message, focusing on the network characteristics of the information flow. Table 2.6 shows the standard we use for determining the number of bits exchanged in each message according to the precise data type being transmitted.

Table 2.6: Bit Representation of Different Data-Messages Types

Message Type	Bit Representation	Description
Boolean	1 bit	Represents a dichotomous (true/false or 0/1) information.
Integer	$\log_2(b - a + 1)$ bits	The number of bits is determined by the logarithm (base 2) of the difference between b the maximum value integer value, and a the minimum integer value plus 1.
Floating-Point	32 bits	Uses the (IEEE Standards Association, 2019) standard, which is used as an industrial standard to encode floating-point numbers.
String	$8 \times L$ bits	Each character in the string is encoded using 8 bits as proposed by American Standard Code for Information Interchange (ASCII) (American National Standards Institute, 1968) or more for Unicode, where L is the length of the string.

If a given message exchange $x_{(i,j)}$, contains several types of data messages, to determine what is the algorithmic complexity $K(x_{(i,j)})$ of the message, we consider the sum of all the bits from the data sent in the message. For example, in the example previously used from Chandra Mouli et al. (2019) shown in table 2.5, the "EV user" sends three data points to the CPO in a same message 'Energy Demand' (32bits⁷), 'Parking time' (13bits⁸), 'Maximum Discharge' (8bits⁹), and 'Minimum SOC' (8bits¹⁰); having in total the message an algorithmic complexity of

⁷A float.

⁸Hour, 6bits to communicate 24 hrs, and minutes, 8bits to communicate 60 minutes.

⁹8bits to communicate the % of the battery that can be discharge.

¹⁰idem

$$K(x_{(i,j)}) = 91bits.$$

The next step is to identify the branching points from which EVs will be added to analyze the scaling behavior of the information flow. We assume that if the Electric Vehicle Supply Equipment (EVSE) is explicitly included in the information flow, the branching point will be the node to which the EVSE is connected, implying that each EV may require a dedicated EVSE connection. Conversely, if the EVSE is not explicitly identified, we will consider the branching point as the node to which the EV is connected. However, there may be cases where the information flow explicitly defines a different branching point or specifies that multiple EVs can be connected to a single EVSE. In such instances, we will follow the specifications provided in the article to ensure consistency with the study's underlying assumptions.

Using the adjacency matrix, we iteratively compute the output messages of the branching node, starting with a single EV and increasing up to 1,000,000 EVs. For each case, we calculate both the individual algorithmic complexity of each node and the total algorithmic complexity of the entire information flow network. Furthermore, we evaluate the overall network connectivity using Equation 2.3.

Finally, we visualize our results using three log-log plots to identify scaling laws and characterize the information flow. These plots include: A $\log(\text{Connectivity})$ vs. $\log(N)$ plot to analyze the scaling laws of system connectivity in the information flow. A $\log(K)$ vs. $\log(N)$ plot to examine the scaling laws of algorithmic complexity. A $\log(\text{Connectivity})$ vs. $\log(K)$ plot to determine how algorithmic complexity, seen as the lower bound of computation costs, relates to connectivity—indicating the ease of distributing computation across different networks.

Below, we formalize how $\log(\text{Connectivity})$ and $\log(K)$ are computed:

$$\begin{aligned}\log(\text{Connectivity}) &= \log(1) + b_a \log(N), \\ \log(K) &= \log(1) + b_b \log(N).\end{aligned}\tag{2.5}$$

where:

- N is the number of EVs in the simulation.
- b_a represents the scaling law of connectivity.
- b_b represents the scaling law of algorithmic complexity.

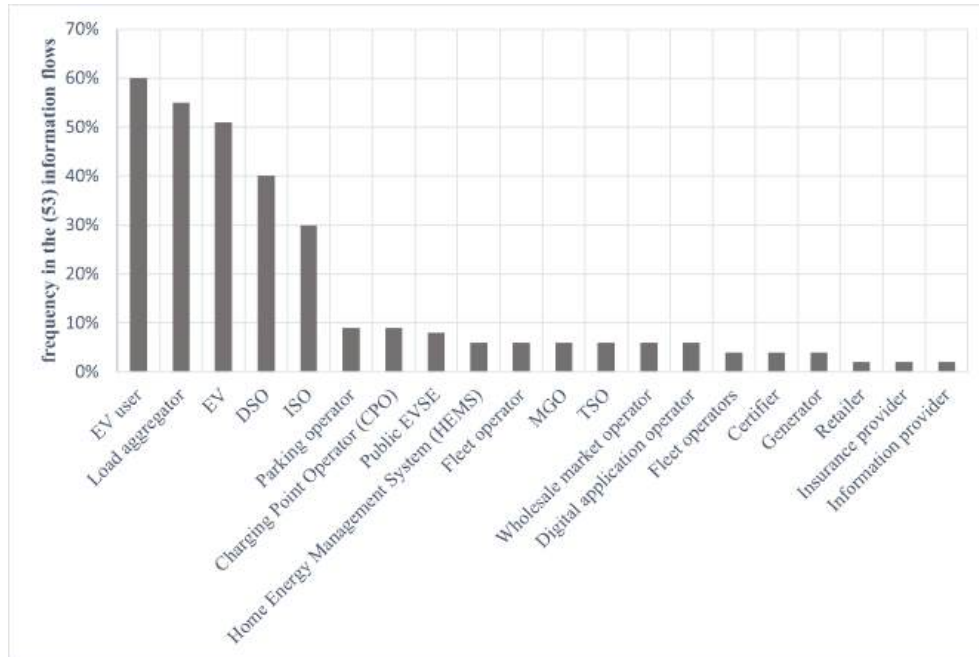
2.4 . Findings

We have divided the findings into two subsections. First, we summarize the analysis of the articles and then present the scaling analysis.

2.4.1 . V2G Information flows

After reviewing all 150 papers, we found that only 53 described an information flow with sufficient detail to identify the actors and their information tasks. The analysis shows that 64% of the articles analyzed on V2G did not explicitly define the information flow that makes V2G possible. Figure 2.4 shows the relative frequency of the 20 different actors considered in the articles. The main insight from Figure 5 is that several actors have a low percentage of presence in the information flow, which suggests that among the 53 papers, there is a large variability in which actors are considered in the information flows.

Figure 2.4: Relative frequency of actors in the analyzed information flow articles.



Note: EVs and EV users are considered in more than 50% of the articles as required in the information flow. Another important actor is the load aggregator, which has the sole purpose of aggregating information. We also observe an important participation of system operators, whether they are at the distribution level (DSO), European transmission level (TSO), or regional integrated market (ISO)

In addition to actor identification, we can also determine each actor's tasks from the literature analysis. Table 2.7 shows the information tasks performed by the actors as we had systematized them from the literature review. Almost all information flows require at least three tasks: aggregate data, optimize the charging discharge strategy,

and perform real-time charge control. At the same time, there are several tasks with a low frequency; such finding is aligned with the idea shown in the analysis of actors: that the information flows are different among themselves.

Table 2.7: Information tasks in the information flows.

Id	Tasks	Description	Relative Presence
1	Data aggregation	Aggregates data from different sources.	96%
2	Optimization of charging/discharging strategy	Computes optimal charge/discharge schedules for EVs.	92%
3	Power flow control	Real-time control of charge/discharge schedule execution.	92%
4	Write on the V2G application	EV owners' preferences influence charging and discharging.	72%
5	Network management	Computes and manages network infrastructure operation.	57%
6	Information sharing	Exchanges personal, technical, or economic data.	49%
7	Power market trading	Optimizes electricity trading and bidding in power markets.	49%
8	Communication provider	Supplies physical infrastructure for V2G communication.	36%
9	Monitoring	Senses and collects physical parameters.	28%
10	Software provider	Provides the digital interface for V2G interactions.	13%
11	Data validation	Validates identification of actors in the system.	6%
12	EV navigation	Computes optimal routes and energy demand for EVs.	4%
13	Insurance	Mitigates risks related to uncertain charging prices or capacity.	2%

Table 2.8 shows the relative presence of the content of the information exchanges performed by the actors in the information flow. We identify 68 different types of information exchanges, and what is noticeable for its distribution is that, like the distribution of actors across the information flows. We also observe that most frequently, a type of information is considered only on a small share of information flows. In complement of Figure 5, Table 5 describes the information exchanges and the range that the values of the information exchange can have. We take the base two logarithms to the range of values to determine the algorithmic complexity of the message.

Table 2.8: Summary of Data Information

Information	$K(x)$	Data-type	Count
Flow of power (+/-)	1	Boolean	58%
Time to finish service (hr)	8	Integer	53%
Time to finish service (minutes)	7	Integer	53%
Time to start service (hr)	11	Integer	53%
Time to start service (minutes)	7	Integer	53%
Accepting V2G (yes/no)	9	Boolean	51%
Time to departure (minutes)	1	Integer	47%
Price of electricity (USD/kWh)	32	Floats	45%
Time to departure (hr)	6	Integer	45%
Power (kW)	32	Floats	36%
Applied power (kW)	32	Floats	28%
Target SOC (%)	8	Integer	19%
Time to arrival (hr)	6	Integer	15%
Time to arrival (minutes)	7	Integer	15%
SOC (%)	8	Integer	13%
Correction of KWh	32	Floats	11%
Charging post EVSE (Id)	8	Integer	9%
Arrival Sign latitude (+/-)	1	Boolean	8%
Connection signal (yes/no)	1	Boolean	6%
Driving distance (km)	10	Integer	6%
Energy bidding (kWh)	32	Floats	6%
Latitude (degrees)	8	Integer	6%
Latitude (décimale)	32	Floats	6%
Longitude (décimale)	32	Floats	6%
Longitude (degrees)	7	Integer	6%
Minimum SOC (%)	8	Integer	6%
Sign latitude (+/-)	1	Boolean	6%
Sign longitude (+/-)	8	Boolean	6%
Time to perform correction (hr)	6	Integer	6%
Time to perform correction (minutes)	7	Integer	6%
Arrival Latitude (degrees)	8	Integer	4%
Arrival Latitude (décimale)	32	Floats	4%
Arrival Longitude (décimale)	32	Floats	4%
Arrival Longitude (degrees)	9	Integer	4%

Information	$K(x)$	Data-type	Count
Energy consumption (kWh)	32	Floats	4%
Number of EVs	8	Integer	4%
Power (kW)	32	Floats	4%
Power of EVs (kW)	32	Floats	4%
Reaction time (s)	7	Integer	4%
Starting Latitude (degrees)	8	Integer	4%
Starting Latitude (décimale)	32	Floats	4%
Starting Longitude (décimale)	32	Floats	4%
Starting Longitude (degrees)	7	Integer	4%
Starting Sign latitude (+/-)	1	Boolean	4%
Starting Sign longitude (+/-)	1	Boolean	4%
Average vehicle energy consumption rate (kWh/100km)	32	Floats	2%
Battery capacity (kW)	32	Floats	2%
Bid was accepted (yes/no)	8	Boolean	2%
Charging price threshold (USD/kWh)	32	Floats	2%
Correction of KW	32	Floats	2%
Daily mileage (km/day)	32	Floats	2%
Degradation cost (USD/SOC)	32	Floats	2%
Driving range (kms)	10	Integer	2%
Efficiency (%)	8	Integer	2%
Elapsed time for the battery (hours)	19	Integer	2%
Energy demand (kWh)	32	Floats	2%
Energy generated (kWh)	32	Floats	2%
Energy offered (kWh)	32	Floats	2%
Id	7	Integer	2%
Low voltage (kW)	32	Floats	2%
Max voltage (kW)	32	Floats	2%
Maximum SOC (%)	8	Integer	2%
Minimum SOH (%)	8	Integer	2%
Occupation signal (Yes/no)	6	Boolean	2%
Request for acceptance (yes/no)	7	Boolean	2%
Type (1-10)	5	Integer	2%
Types (1-5)	4	Integer	2%

2.4.2 . Scaling analysis

Figure 2.5 illustrates the impact of scaling on algorithmic complexity across 53 different information flow designs. Among the key observations, one notable case is an orange line that remains constant with scale. This corresponds to Kempton and Tomić (2005a), where a parking operator communicates directly with the System Operator (SO) in a simple, static design. In this setup, the number of EVs remains unchanged because the parking operator only receives signals from the SO without adapting to dynamic conditions.

A second, more general observation is that the scaling law exhibits a consistent slope across different information flows, ranging from approximately 0.97 to 1.1, with most flows clustering around a slope of 1. This suggests that the primary driver of information complexity is the communication between EVs and the branching node—primarily related to mobility needs—rather than constraints from the electricity system. However, deviations from linearity can be observed at small scales. For instance, a distinct curve below the main group of information flows eventually converges with a blue line. This indicates that at smaller scales, the proportion of total bits attributed to EV mobility is relatively higher, and its influence diminishes as the system scales.

Figure 2.5: Evolution of Algorithm Complexity with Increasing Scale.

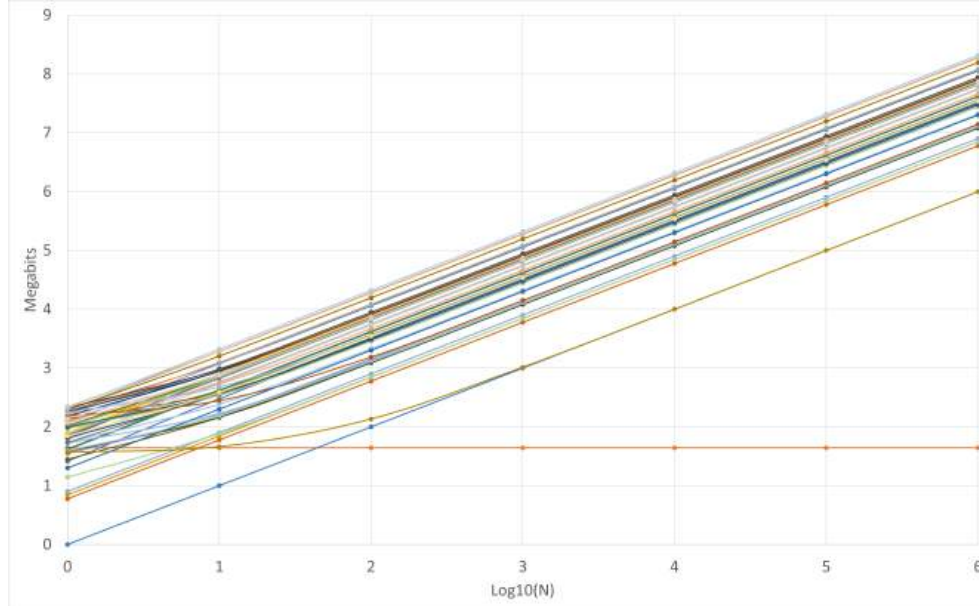


Figure 2.6 illustrates the scaling dynamics of connectivity. Unlike Figure 2.5, where scaling follows a more uniform pattern, connectivity exhibits significant variability across different designs. Several designs deviate from a linear scaling law, instead suggesting an exponential scaling behavior. This non-linearity arises from

the underlying structure of the information flow network, primarily driven by the inflow-outflow relationships among nodes.

Figure 2.6: Evolution of System Connectivity with Increasing Scale .

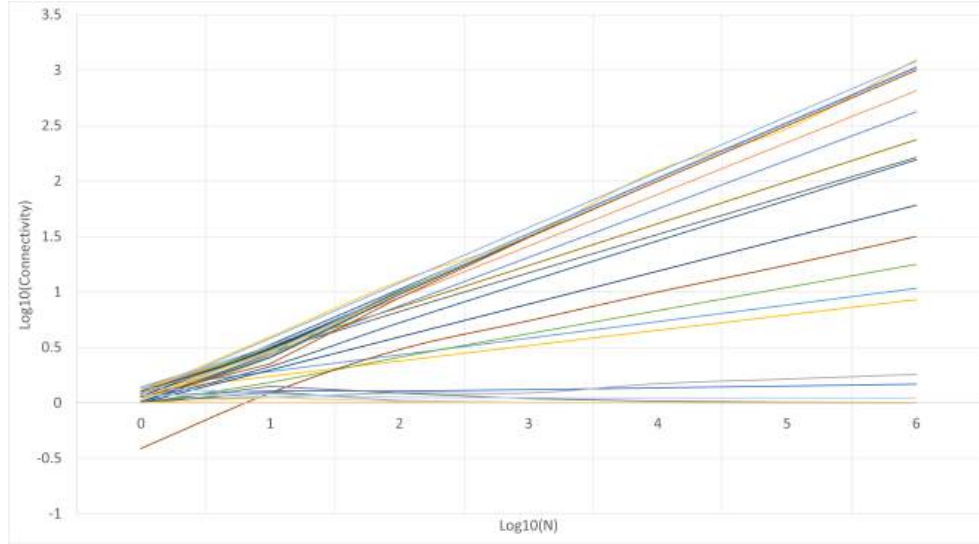
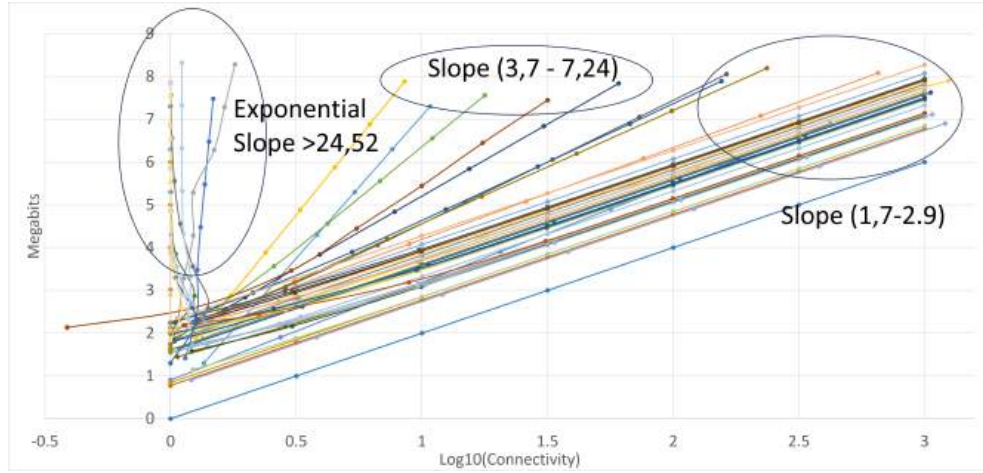


Figure 2.7 shows the relationship between our the alogirthmic complexity and connectivity measures. Each point on the observed lines represents a tenfold increase in scale (in terms of aggregated EVs). Overall, as we have seen before in 2.5 almost all the information flows reach a similar level of computation costs; with a lower-bound of 8 megabits. The second main remark, is that the information flows can be grouped by the ratio of algorithmic complexity to connectivity, or in other words; by how centralized or decentralized are the network once the system scale. The analysis of the ratio between these two measures allows us to divide the information flows into three main clusters that are visually identified on figure 2.7. Furthermore, each cluster can be identified quantitatively by comparing grouping the information flows by minimizing the within difference of the slope within this archetype.

The largest group of information flows, has a slope very close to “2 ” representing the most dominant design of V2G information flow; but also they are the information flow that more centralized; which increases the difficulty of distribut the computation costs among the network. Furthermore, the fact that one design dominates is surprising, as it shows that some underlying design principles might exist in terms of the information flows used for V2G optimization. In the second archetype, which are the information flow with a “2.7 to 3.9 slope” the network are almost by a half less centralized; which suggests that they are at least two times more likely than the first cluster to be able to decentralized the computation costs among the network nodes. Furthermore, we have a third archetype is defined as “Exponential slope”, where the information flows, the system connectivity decreases or remains constant; which means that the network scale with several nodes of connection equally impor-

tant, increasing the potential to distributed amongst computation costs. Finally, in the fourth archetype, “Hierarchical,” information flow is unidirectional. In this particular case, the level of information shared is not with the EV level but with the fleet operator level. This implies an assumption that EV owners are not participating in the information process directly, as all the information exchanges are known from the interaction of the EV with the EVSE. This archetype presents the least amount of examples.

Figure 2.7: Algorithmic complexity and Connectivity .



In Table 2.9, we classify information flows based on the slopes shown in Figure 2.7 and the actor responsible for deciding the charging or discharging behavior of EVs. We broadly group these actors, as previously illustrated in Figure 2.4, into three categories: aggregators, decentralized actors, and SOs. Aggregators refer to specialized entities that have entered the V2G business model as optimizers, including parking fleet operators, electricity retailers, and energy service companies. Decentralized actors are either EVs or EVSEs that make charging decisions independently. Finally, SOs represent regulated network operators, such as independent system operators (ISOs), transmission system operators (TSOs), and distribution system operators (DSOs).

Three key observations can be made from Table 2.9. First, the results align logically with what we would expect from information flow designs, where the SO aggregates information and performs the optimization. This is evident as SOs are only present in the '1.7-2.7' slope, which represents the most centralized scenario. Second, in some cases, a significant portion of the computation appears to be performed by decentralized resources, such as EVs or EVSEs, as indicated by the presence of several instances in the '1.7-2.7' slope. Finally, most information flows involve an aggregator, with notable differences in the assumptions regarding the degree of centralization within this actor.

Table 2.9: Classification of Information Flow by Slope and Actor Performing the Optimization

Slope	Actor performing the Optimization		
	Aggregator	Decentralized	SO
1.7-2.7	Dogan et al. (2018), Lopes et al. (2011), Nezamodini and Wang (2016), Sah et al. (2019), der Wardt and A. (2017), Del Razo et al. (2015), D. Q. Xu et al. (2013), Yu and Xue (2016), Broneske and Wozabal (2017), Escudero-Garzas et al. (2012), Ortega-Vazquez et al. (2013), Mehta et al. (2018), S. Han et al. (2010), H. Liu et al. (2014), Chandra Mouli et al. (2019), Ansari et al. (2015), S. Zhang and Leung (2022), Xie et al. (2016), Hou et al. (2017), Mohamed et al. (2014)	Schill (2011), Jindal et al. (2019), Ovalle et al. (2017), Hoang et al. (2017), Yao and Zhu (2012), Cheng et al. (2015), Y. Zhang et al. (2018)	Liang et al. (2019), H. Liu et al. (2019), Visakh and Manickavasagam Parvathy (2022), Wang et al. (2015), Honarmand et al. (2014), Morais et al. (2014), Erden et al. (2018a), Zhong et al. (2014), D. Liu et al. (2016)
3.2-7.24	Masuta and Yokoyama (2012), Karfopoulos and Hatziargyriou (2016)	Nefedov et al. (2018), W. Han and Xiao (2016)	

Continued on next page

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Slope	Actor performing the Optimization			
	Specialized gregator	Ag-	Decentralized	SO
Exponential	Ramakrishna Reddy et al. (2019), Guille and Gross (2009), S. Han et al. (2011), Janjic and Velimirovic (2015), Habibifar et al. (2020), Battistelli et al. (2012), Zarkoob et al. (2013)		Iacobucci et al. (2018), García-Villalobos et al. (2016), Mao et al. (2018), López et al. (2015)	
Hierarchical	Kempton and Tomić (2005a)			

2.5 . Discussions

The starting point of our paper was that SOs, are facing a particular challenge to integrate intermittent resources, and that Smart Grids could solve be an efficient technology to reduce the costs of integrating them by doing the electricity system reactive and smarter. However, while a lot of research have been done to study Smart Grid optimization, the literature has fully embraced the operational costs that might involved the computation that makes Smart Grids work at scale. We focused on one particular smart grid application – V2G, and applied scaling theory and information theory, to understand how the theoretical information flows would scale in terms of their computation costs. We believe this approach has implications for the literature on smart grid applications and optimization research.

2.5.1 . Implications for smart grid and optimization research

By integrating a scaling and information perspective to smart grid research, we provide the literature with a new perspective. We believe a scaling and information theory perspective is important, since most existing work on the design of smart grids applications has focused on the design of the algorithms or on the communication architecture, and has overlooked the importance of the information flow that enables

the smart grid applications to be smart in the first place, and how this information flow may have an impact on the feasibility or desirability of certain algorithms and communication architectures.

The scaling and information theory lenses has helped us to explore the implications of the design of the information layer and challenge the way we think about designing smart grids and IS (and V2G systems specifically) in a more comprehensive way. Building on existing work in the technical literature, our research shows that the information flow designs in this literature have important implications in terms of the actors participating on the information flow, the data needs, the algorithmic complexity and the connectivity, once we look at the evolution of the properties of their design at scale. Indeed, in the extant literature, it is generally assumed that the way information is gathered to feed smart grid algorithms has no implications. However, our study shows that this is problematic, since the structure of the information exchanges in smart grids impacts their computation costs at scale, how these costs might be distributed and therefore their performance. Given the disappointing uptake of V2G (Gschwendtner et al., 2021; Sovacool et al., 2020), despite technical readiness, we believe that (at least partially) this might be because the complexity risks of current assumed information flow designs may be too significant for actors in the field. For example, this may be the reason that an aggregation of EVs through corporate fleets seems to be preferred in practice, as the the information flow is then simpler to organize: “Fleets also help address some of the transaction costs and information challenges involved in distributed V2G diffusion” (Sovacool et al., 2020, p.11).

We also contribute to the smart grid literature by offering an assessment method to analyze the properties of information flow design at different scales by measuring two key dimensions: algorithmic complexity and system connectivity. Algorithmic complexity explains how a given design impacts computation costs, while system connectivity explains how these computation costs might be distributed (Albert et al., 2000; Crucitti et al., 2003, 2004; Perc, 2009).

This assessment method represents an important contribution to the analysis of large-scale IS systems that – to the best of our knowledge – has not been explored so far in Smart Grids or IS research. We believe both an information flow perspective, and the proposed assessment method offers fertile soil for future work in IS research, as combining these two information-related measures serve as important knowledge for researchers and practitioners in studying how smart grid applications may allow for optimizing electric system efficiency. In addition, the different scale patterns show that a clear classification of archetypes was possible: “1.7-2.7”, “3.2-7.4”, “Exponential” and “Hierarchical”. The successful evolution of smart grid applications might be contingent on how the information flow is designed according to these archetypes, especially if we consider the importance of computation cost, error tolerance, and system vulnerability.

Among the 53 cases of information flow we analyzed, there was only one case where the design was scale insensitive (Kempton & Tomić, 2005a). Understanding the difference between the four archetypes then enables a more informed choice of management strategy, with implications for potential business model success. The hierarchical archetype, for example, is the simpler type of design but removes all flexibility from the perspective of the prosumer. The “Exponential” the “3.2- 7.24” and the “1.7-2.7” archetypes, in that order, have increasing tradeoffs between the total cost of computation and higher system vulnerability or increasing the computation costs and reducing the dependency on certain nodes. Seeking to choose the optimal design of V2G or any other smart grid application, managers have an additional dimension to consider that might suit different types of use cases. For example, depending on the limitations on the limits on computation costs, one archetype might have more potential to develop than others. If computation costs are very constraining, the hierarchical approach will be the most efficient. In contrast, if computation costs are not a problem, then the Scale-free archetype will most likely be implemented.

Although previous research, particularly within the smart grid literature that we have classified as having an “algorithmic view” has analyzed the design of V2G information flow design, differentiating between centralized and decentralized control, our research offers a unique distinctiveness needed not only to explain specific aspects of the implications of design but also to understand that their implications vary with scale.

Finally, although at first sight V2G smart grid applications might appear to have significant differences in their design because they consider different types of actors and information. When we analyze their scaling behavior, most of the differences might disappear and we found four main archetypes when we look at their computation costs and their distribution, showing that the information flow analysis of smart grid applications provides a promising avenue for creating competitive advantages in the competition between smart grid applications.

2.5.2 . Limitations and avenues for future research

Future studies could build on our contributions and address several of the limitations in our work. First, to develop our archetypes of information flows, we have only considered a subset of the total V2G literature, which may limit what can be inferred from the information flow designs included in the analysis. Therefore, it would be unrealistic to consider that we would be able to generalize our findings and claim that we have mapped all the existing archetypes. However, using bibliographic clustering to decide which articles to consider in the sample, we attempted to combine influence and diversity in the clusters of V2G literature considered. Furthermore, as a robustness check, we specifically searched for keywords regarding V2G and ISs without finding results outside of what we had previously seen in our initial search. Another limitation could be that the articles were originally written for a different purpose, meaning that they aim to describe the design of an algorithm and not intended to

describe an information flow. However, the tabulation method we use in the articles enables us to identify the assumptions according to the description of the information flow in the article. We have included the matrix that we use to identify the actors and information exchanges in the appendix to offer scholars the opportunity to challenge our interpretation of the articles, making it possible to assess our coding but also use our data material in future research that might propose other methodology to build the information networks.

Finally, we evaluate the rate at which the lower bound on the computation costs of an IS artifact increases with scale by evaluating their algorithmic complexity. Nevertheless, the total computation costs of the system might depend on other factors we have not considered— e.g., security protocols (Franklin & Yung, 1992), computation complexity (Papadimitriou, 2003) and other computation costs from communication processes (Papadimitriou & Sipser, 1984). Therefore, future research that adopts a complexity lens could try to measure the upper limit of complexity that a smart grid can manage, particularly when considering that system operators might be required to manage several smart grid applications simultaneously, which therefore requires considering an organizational dimension of the organization of electric systems according to the advantages and disadvantages of the different archetypes.

2.6 . Conclusions

This paper proposes an alternative view of smart grid applications, emphasizing the relevance of more closely examining the information flow design that enables smart grids to be smart. We proposed an assessment method using scaling and information theory to analyze the information network, using two measures: algorithmic complexity and system connectivity. We suggest that this approach may serve as a foundation for informing our understanding of the operational impact of smart grid applications as they scale and particularly determining how the network structure impacts the minimum computation cost and their distribution as V2G applications increase in scale. If we do not use our proposed approach, perhaps the best algorithm might not work at scale because the complexity of the information flow has not been considered. Therefore, limiting the potential of smart grid applications.

We apply the complexity measures to the study of V2G and perform a systematic review of the academic literature to identify different designs proposed as smart grid applications. To date, there are no commercial implementations of V2G for end users, and all the research has been exploratory, mostly relying on proposing different algorithms to manage the charge and discharge of EVs. However, as our research shows, the assumptions taken by the literature on the information flow might have important implications, as the research has underlying assumptions that have important implications once we look at the evolution of the properties of their design with scale. Indeed, in the extant literature, there is a tendency to assume that the way data

is gathered for the algorithms has no implications. This is problematic since it tends to inhibit a comprehensive understanding of what information is available and how the structure of the information exchanges impacts the performance of smart grid applications.

In response, our approach shows that there are at least four design archetypes: “Hierarchical design,” “Exponential,” “2.7-7.4” and “1.7-2.7” each with their characteristics. From these archetypes, we offer theoretical implications that contribute to practitioners and Smart Grid researchers on their path to designing better artifacts that enable electric systems to be more sustainable. Finally, we propose the interest of future research to answer the following overarching question: How complex can smart grids be? We think that this question can provide further insights into managing the interactions between smart grid applications from a system operator perspective, providing insights on a meta-organization of electric systems that considers the properties and complementarities between the archetypes we identify in our research.

2.7 . References

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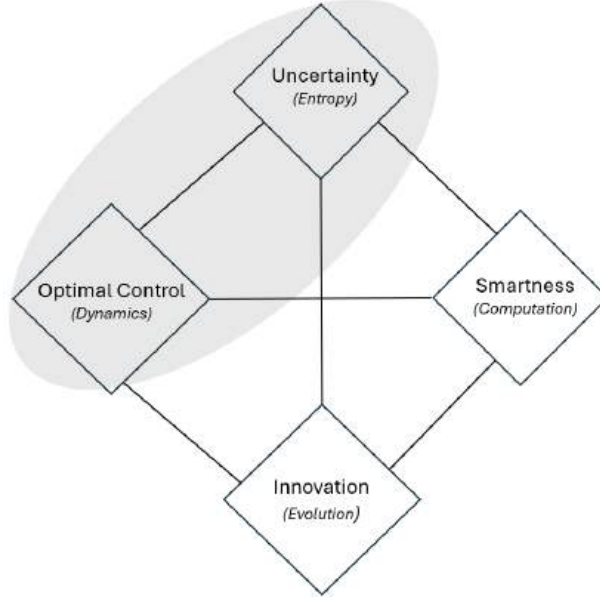
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3 - The value of information for V2G coordination

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Figure 3.1: The four pillars of complexity applied to Chapter 3. Adapted from (Krakauer, 2024)



The gray area highlights the two key pillars of this work: Optimal Control and Uncertainty. Optimal control is explored through the challenges faced by aggregators, who act as intermediaries to make EVs a reliable power source for electricity systems. Aggregators must predict EV behavior and design an IS that dynamically updates real-time EV status to achieve this. Uncertainty addresses the broader challenge of measuring the value of managing uncertainty and assessing the effectiveness of different IS designs. This is particularly crucial for coordinating inter-organizational V2G systems, where information is distributed among multiple stakeholders.

¹The original title of the paper is: *Evaluating Alternative Information Systems for Vehicle-to-Grid (V2G) Integration*. This title has been adapted to fit the structure of the dissertation in a coherent manner.

Abstract: Green Information Systems (Green IS) have been proposed as an information-oriented solution to enable environmentally sustainable business models by coordinating socio-technical and environmental variables. This paper evaluates how Green IS can become more effective on integrating electric vehicles (EVs) with electricity systems, specifically through Vehicle-to-Grid (V2G) services. As EV adoption increases, their aggregated battery capacity could support the integration of intermittent renewable energy sources, thereby enhancing grid stability and offering cost-saving opportunities for EV owners. However, large-scale V2G implementation remains constrained by uncertainties in EV user behavior and the need for effective inter-organizational information systems (IOIS). While existing communication standards facilitate basic data exchange between EVs, charging stations, and aggregators, they may not provide sufficient information for optimal decision-making. To address this gap, we investigate the value of alternative IOS scenarios compared to current industry standards for V2G aggregators. Given the nascent stage of V2G deployment, we employ a normative ex-ante approach, using a simulation framework that models uncertainties in EV mobility and evaluates their impact on aggregator profits and greenhouse gas emissions. Our results indicate that enhancing IOS beyond existing standards can significantly improve aggregator profitability—potentially doubling profits—while optimizing the integration of renewable energy. This research contributes theoretically by extending Green IS literature to inter-organizational systems and methodologically proposing a novel simulation framework applicable to energy and mobility systems.

3.1 . Introduction

Green IS - information systems (IS) that play a coordination role between environmental and socio-technical variables (Dedrick, 2010; Gholami et al., 2013; Leidner et al., 2022; Seidel et al., 2013) - can support organizations by providing information that enables environmentally sustainable business models. Among all the domains in which Green IS might impact business models, the two in which the literature has shown great potential have been the energy and mobility domains. In the latter, Watson et al. (2010) and Ketter et al. (2018) have called to investigate how IS can facilitate the integration of new electricity sources to defossilize electricity systems. In the mobility domain, Ketter et al. (2023) have called for the need for research on "*developing and evaluating digitally enabled smart, sustainable mobility business models*".

This paper articulates both calls by evaluating IS's role in integrating elec-

tric vehicles (EVs) with electricity systems. As the adoption of EVs increases, their aggregated battery capacity could help improve the share of intermittent solar and wind power of electricity production, providing dynamic grid support and offering cost-saving opportunities for EV owners (Kempton & Tomić, 2005b). Projections estimate that widespread adoption of EVs by 2030 could fulfill a significant portion of electricity storage needs required to support electricity systems defossilization through Vehicle-to-Grid (V2G) services (Xu et al., 2023). The core idea behind V2G relies on the fact that frequently, the battery capacity of EVs far surpasses the needs of daily mobility and that they are flexible on the time when they charge their batteries (Kempton & Tomić, 2005b). This flexibility allows for coordinating EV charging schedules to maximize the use of renewable energy sources like wind and solar, often wasted because their production exceeds real-time consumption (Bird et al., 2016). Additionally, V2G enables charging EV batteries beyond immediate mobility, which can be strategically discharged back to the grid during peak demand or low renewable production periods (Kempton & Tomić, 2005a).

Despite the promising benefits of V2G, large-scale commercial implementation remains limited, with only a small number of V2G-ready EVs currently available (Goncearuc et al., 2024). However, this may soon change, as several manufacturers have recently released or announced the commercial sale of V2G-compatible EVs². Yet beyond the necessary equipment, successfully integrating V2G services into existing electricity systems requires an essential intermediary: an "Aggregator" (Amamra & Marco, 2019; Han et al., 2010) who connects EV users and power markets, purchasing renewable energy for EV charging and selling surplus energy back to the grid through sequential electricity markets. Most power markets operate on schedules that require bidding or trading hours in advance—typically before EV users have finalized their travel plans. The Aggregator's fundamental value is to predict when EVs will be available for charging or discharging, managing uncertainties on both the supply and demand sides (Burger et al., 2017).

Over- or under-procurement of power can destabilize the grid and negatively impact electricity system operation, which requires maintaining a real-time grid balance between power supply and demand, potentially leading to costly penalties for the Aggregator, which could make their business model unprofitable (Codani et al., 2016). To avoid these penalties, Aggregators could manage the uncertainties of EV owner behavior by limiting the mobility of EV owners; however, one could argue that such an approach is un-

²The following EVs are reported to have V2G capabilities: Audi Q4 e-tron, Cupra Tavascan, Kia EV9, Nissan Leaf, Polestar 3, Renault 5 EV, Skoda Enyaq, VW ID.

likely to scale, as most EV owners buy or rent an EV for mobility purposes. A second approach, which has become a consensus among the industry and a mandate from governments in the USA and Europe, is to implement communication protocols that make mandatory a minimum inter-organizational information system (IOIS) that can enable different brands of EVs and any charging point operator to exchange mobility information with a V2G Aggregator (e.g., Neaimeh and Andersen (2020), Noel et al. (2019), and Tseng (2012)). Such protocols can be on the 'front-end' between the EV and the charging stations (e.g., ISO 15118-20 in Europe or DIN 70121 for California), formally referred to as electric vehicle supply equipment (EVSE), or the 'back-end' between the EVSE and the Aggregator (e.g., OCPP 2.0 in Europe, IEEE 2030.5 in California). These standards focus on power-line communication, which limits the data exchange only when the EV is parked and connected; they also guarantee that the Aggregator can access information on the EV battery's state of charge (SOC) and other technical characteristics of the EV.

Despite the existence of standards, prior research and pilot trials on V2G have revealed a wide range of perspectives on the type of IOIS aggregators needed to facilitate the information exchange required to deal with the uncertainties on mobility behavior (Gschwendtner et al., 2021; Kester et al., 2018). For instance, there is significant variation regarding the information the aggregator must know on the EV owner's mobility. In some cases, detailed driving behavior is included (Guille & Gross, 2009), while in others, it is omitted entirely (Yu et al., 2015). Similarly, differing approaches have been proposed for the timing of data exchange. In certain scenarios, EVs transmit information over the air to the aggregator (López et al., 2015). In contrast, in others, data exchange occurs only when the EV is physically connected to a charging station (Kempton et al., 2008).

Research on IOIS has consistently demonstrated that when managers must invest in or cooperate to share information across organizations, they require clear evidence of the net benefits associated with such investments or collaborations (Bharadwaj et al., 2007; Cao et al., 2022; Chwelos et al., 2001; Klein & Rai, 2009; Kohli & Grover, 2008; Kumar & Van Dissel, 1996; Salge et al., 2015; West Jr & Courtney, 1993). However, previous research studying EV integration using a green IS lens has had an intra-organizational scope; notably Valogianni et al. (2020), which utilized EV owner preference data to generate adaptive pricing to avoid peaks in consumption, or Kahlen et al. (2024), which developed a decision support system to manage EVs simultaneously as shared vehicles and for V2G services. This research has advanced our knowledge of the importance of IS for integrating EVs with electricity systems; however, it leaves a gap in our understanding of the value of going

beyond current communication standards as a form of IOIS. Therefore, to our knowledge, an important gap in V2G systems is that no value is estimated to increase current communication protocols and propose alternative IOIS. Against this gap, the potential of V2G services might be limited by hindering collaboration between the potential actors that could contribute to providing data to the aggregators, and rather than fostering data sharing to enhance the value of V2G services, lead to the creation of data silos or closed systems. Thus, to address these gaps, our research question is: *What type of IOIS optimizes the necessary data flow to enable V2G aggregators to play their role in smart grids?*

To address this question, the nascent stage of V2G developments and the lack of comparable pilot cases are the main barriers to empirically measuring the value of IOS. Thus, rather than performing an ex-post approach as most of previous IOS research has done (Leidner et al., 2022), we use a normative ex-ante approach that relies on simulations.

We developed a simulation framework that relies on methods to introduce uncertainty from resilience engineering, simulate uncertainty, and evaluate how different IOS impact the profits and GHG emissions of a V2G aggregator that buys and sells power in day-ahead and intraday power markets. Uncertainty allows us to distinguish between a 'real environment' and the 'Aggregator expectations', which is based on historical but very accurate data on EV mobility, where we model an IOS as a discovery process in which the Aggregator gets to inform itself about the 'real environment' of the Aggregator. We test different scenarios of IOS, modeling the information process of the aggregator by using the dimensions proposed by DeLone and McLean (2003) to evaluate IS success. Thus, our results on the value of information can relate to the characteristics of IS. Moreover, we can test the profit difference from going beyond the industry standard to integrate EVs into the electricity system.

We evaluate the potential profits of an aggregator through a case-study using real-data from Tenerife, Spain, during 2023, assuming it could perform V2G under various IOIS scenarios. which are twofold. First, our research makes a theoretical contribution by emphasizing the importance of the IOIS on Green IS and addressing the methodological challenges involved in their evaluation. We propose a novel simulation framework that overcomes these challenges and can be extended to other electricity and mobility systems applications. Second, we offer a practical contribution for practitioners, demonstrating that aggregator profits could increase by a factor of two by incorporating additional information about EV user mobility, such as future mobility needs and departure times. Specifically, our findings show that increasing

the information on departure times and future mobility needs can enhance profitability by up to +150% while simultaneously reducing CO₂ emissions by −6% compared to simply adhering to the industrial standard ISO 15-118. These insights underline the critical role of information completeness in optimizing V1G and V2G aggregation strategies.

The paper is organized as follows. In Section 3.2, we present the study's theoretical background. Section 3.3 introduces our simulation framework and the methods used to validate and verify the results. Section 3.4 presents the case study that calibrates the simulation framework using real mobility data. Section 3.5 discusses our findings and highlights the study's contributions. Finally, Section 3.6 presents our conclusions, acknowledges the limitations of our study, and proposes directions for future research.

3.2 . Theoretical background

We review four key research streams that inform our work. First, we examine studies that conceptualize the core value of V2G aggregators in power markets. Second, we explore various approaches for quantifying the value of IS. Next, we discuss the application of simulations in evaluating IS, which is particularly important in the context of new technologies like V2G, where data is often scarce. Finally, we analyze the main constructs in IS research that assess the determinants of IS success, which will guide the tailoring of our simulation framework for theory-building purposes.

3.2.1 . Fundamental value of V2G aggregators

Aggregator value can depend on specific market and regulatory conditions, which may change over time. For example, regulatory differences across countries impose varying participation barriers for EVs, such as minimum thresholds of the number of EVs an aggregator must manage to deliver V2G services (Borne et al., 2018). However, the aggregator's fundamental value does not change. It is defined as the "*value that stems from factors inherent to the act of aggregation itself*" (Burger et al., 2017, p. 396), such as leveraging economies of scale and scope to manage the uncertainties associated and ensuring reliable service to the electricity system while simultaneously reducing price risks for EV owners (Burger et al., 2017).

While recognizing that regulations and market conditions can present challenges for V2G services, in this paper, we focus on the aggregator's funda-

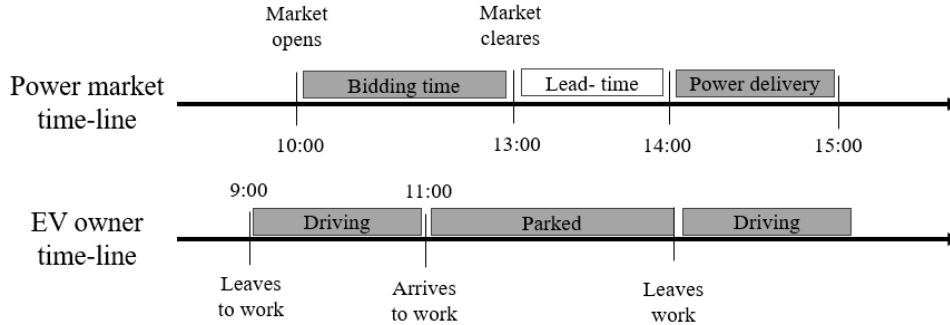
mental value (Burger et al., 2017), particularly the value it creates by managing EV users' uncertainty. The value of managing price risks for EV owners has been extensively studied in the retail segment literature. Much discussion has centered on electricity customers' risk tolerance for price fluctuations and the complexity of energy markets (Littlechild, 2009). From this perspective, the aggregator's role is analogous, as it shields consumers—especially regular EV owners—from the risks and demands of buying or selling power (Russo et al., 2022). Indeed, the aggregator ideally could provide service offerings that match individual customers' risk profiles and preferences, allowing them to participate in V2G at the minimum cost (Momber et al., 2015).

The value of managing uncertainty is rooted in the physical constraints imposed by Kirchhoff's current law, which mandates a continuous balance between supply and demand (Joskow & Tirole, 2000). This requirement has significant implications in the case of liberalized electricity systems³, energy resources are often allocated in sequential steps, with power markets setting commitments in advance—typically hours or even days before the actual delivery (Meeus, 2020). This "*lead-time*" is supposed to allow the system operator (SO) to balance power demand and supply. In this context, V2G aggregators face an important challenge for delivering their fundamental value: they must predict EV availability for discharging energy into the grid in advance.

Figure 3.2 illustrates a specific example where the prediction of EV availability requires special attention from the aggregator perspective. In particular, we observe the misalignment between the power market timeline and a typical EV owner's schedule.

³Electricity system that has introduced competition in the generation and retail segments of electricity systems.

Figure 3.2: Example of EV owner and power market timelines the aggregator might face.



Note: The top timeline shows the sequence of events in a typical electricity market. The market opens at 10:00 AM, allowing participants to place bids for energy. The bidding window remains open until 13:00 hrs, after which the market clears—meaning bids are accepted and prices are determined. This is followed by a "lead time" from 13:00 hr to 14:00 hrs, allowing for preparation before power delivery begins at 14:00 hrs. In contrast, the bottom timeline shows a typical EV owner's daily schedule. The EV owner leaves for work at 9:00 hrs, arriving at 11:00 hrs, after which the vehicle remains parked until 14:00 hrs when the owner leaves to drive home.

The mechanisms that allow aggregators to manage the difference in timelines to ensure that V2G services, committed in advance, are reliable can be broadly classified into two approaches. The first approach involves restricting the EV owner's mobility through a contract that provides the aggregator with 'call options' for exclusive control over charging power within a specific timeframe (Oren, 2001; Sezgen et al., 2007). Such an approach has been particularly popular for demand response services, where aggregators can curtail electricity consumption (Campaigne & Oren, 2016). However, to our knowledge, it has been mostly overlooked as an approach for V2G services because EV's main purpose is generally considered for mobility. The second approach combines statistical techniques with IS to aggregate data without restricting mobility (Gao et al., 2013). From both approaches, the latter is generally considered more scalable (Parsons et al., 2014), as a significant restriction on mobility for energy services would likely deter many EV owners from participating in V2G. Therefore, it limits aggregators on the benefits they can derive from economies of scale.

3.2.2 . Evaluation of IS value

The main challenge in finding a quantitative measure of IS value in terms of a monetary currency lies not necessarily in measuring its costs but instead in its broad impact (Glazer, 1993; Keen, 1981; Kumar & Van Dissel, 1996), which extends beyond direct outcomes to include benefits like cost savings, cost avoidance, and enhanced operational performance (Citroen, 2011; Glazer, 1993; Im & Rai, 2014; King & Schrems, 1978; Melville et al., 2004; Riggins et al., 1994; E. T. Wang et al., 2006; Yao & Zhu, 2012). Moreover, IS outputs are rarely standalone products with market-established values; instead, they serve as complementary goods within broader productive processes, and their value depends on effectively combining information with other resources (Bharadwaj et al., 2007; Kohli & Grover, 2008; West Jr & Courtney, 1993).

This broad scope of IS impact poses significant management challenges in developing IS and common IOIS, such as those required for V2G services. Empirical research highlights the critical importance of addressing this challenge, particularly in industries like the automotive sector (Holweg & Pil, 2008; Mithas et al., 2008), where the perceived value of IS often becomes the primary determinant for managers; similarly, that is the case for managers deciding to invest in IS and collaborate with other actors through IOS (Cao et al., 2022; Chwelos et al., 2001; Klein & Rai, 2009; Kumar & Van Dissel, 1996; Salge et al., 2015). Indeed, not having a clear measure of IS value can lead to hesitancy or stagnation in IS investment due to managers' difficulty demonstrating clear profit improvements associated with IT initiatives. This phenomenon has been called the *'feet to the fire syndrome'* (Matlin & Land O'Lakes, 1979).

A rich literature on IS has tried to address this challenge, with several methods proposed to measure the value of IS for an organization. These methods can be roughly divided between those that have used an ex-post analysis mainly through field works (Dhillon & Torkzadeh, 2006; Nicolaou & McKnight, 2006; Salge et al., 2015), case studies; (E. T. Wang et al., 2013), or experiments (Dickson et al., 1977) and those that have performed an ex-ante analysis primarily relying on decision theory to estimate the normative value of information (Ahituv, 1980; Kanungo et al., 1999).

In an ex-post analysis, two main measures are typically used: the perceived value, which reflects the subjective evaluation of the worth of the information (Gallagher, 1974), and the revealed value of information, which implies an objective measure of all IS benefits. While the revealed value is considered ideal, it requires experimentation, particularly an IS that can collect information on IS effectiveness. Therefore, it isn't easy to set such an experiment, and only a few examples use such a method. A well-known ex-

ample is the Minnesota experiment that examines the significance of various information system characteristics on decision activity (Dickson et al., 1977). Another example considers (Mock, 1969) business game that required participants to reach decisions concerning production and quantities with different delays in which the information is communicated.

In ex-ante analysis, the normative value of information is built significantly on the economics of information (Ahituv, 1980; Avriel & Williams, 1970), an outgrowth of the economic theory of decision under uncertainty (Hirshleifer, 1973). This constrains the value of IS to the benefits from improving the outcomes of the decision-making process, in which decision-makers are imperfectly informed (Marschak, 1971). Thus, information is measured as the expected value of a result of a decision with information minus the expected outcome without information (Hilton, 1981; Hirshleifer, 1978).

3.2.3 . Dimensions of comparison for IS

To develop a theory explaining how a particular IOIS can create value through simulations, we operationalize the information flow process using a model of IS. In practice, such IS defines how the aggregator receives information from the "real behavior" of EVs within the simulation and enables the design of comparable IOS scenarios to inform IS theory. We adopt the standard IS success model proposed by DeLone and McLean (2003) as our primary framework to structure these scenarios. This model evaluates the success of an IS by analyzing mainly two critical dimensions of information quality: completeness and timeliness. Completeness refers to the availability of all necessary information for decision-making, avoiding gaps or partial datasets. Timeliness ensures that information is delivered within a time frame that supports effective decision-making.

Building on this theoretical foundation, the next section details how we integrate these elements into a simulation framework. This framework characterizes the sequential decisions of V2G aggregators in power markets and evaluates how different IOS configurations influence their performance.

3.3 . Methodology

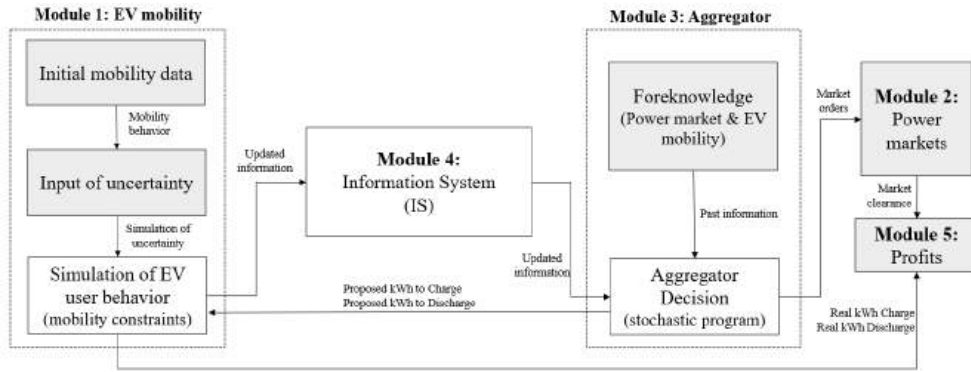
This section is organized into two parts. First, we introduce our simulation framework, detailing its structure and components. Then, we outline the

validation and verification processes, ensuring the reliability of the simulation results.

3.3.1 . Simulation framework

Figure 3.3 shows the simulation framework comprising five modules. This simulation primarily models the temporal changes in energy available in the EV's battery throughout different mobility states, considering when EVs are driving, parking, charging, or discharging. Furthermore, it integrates the aggregator's decisions to maximize profits while adhering to the mobility constraints of EV users and the sequential power market. We also describe how we model the information flow process from which the aggregator acquires new information on EV owner's behavior. Furthermore, Table 3.1, summarizes the notations used in the simulation.

Figure 3.3: Simulation framework



Note: Module 1 (EV mobility) comprises all the steps required to generate a virtual model of EV users' behavior that might be detailed enough for our IS value analysis. Module 2 models the timeline and price dynamics in the power markets, where the aggregator places orders to buy or sell energy from EVs. In this framework, the aggregator is assumed to be a price taker, meaning its market orders do not influence market prices. Module 3 (Aggregator) simulates how the aggregator determines proposed charging or discharging kWh to EVs and sets market orders (linking Module 2 with Module 1). Module 4 (IS) models the communication process as an information flow between EV users and the aggregator. This flow of information enables the aggregator to update its foreknowledge of EV mobility with more accurate information. It is modeled using the framework of the IS success model proposed by DeLone and McLean (2003). Module 5 calculates profits ex-post by comparing the kWh quantities proposed for charging/discharging in the market orders with the actual kWh executed, it also details how we determine the emissions generated by the EV.

Table 3.1: Summary of Notation for the Model

Notation	Description
Indexes	
t	Time index representing a time step of the model.
n	Aggregator client index representing a given EV owner.
m	Index representing a given power market.
s	Scenario index representing a potential outcome the aggregator expects.
k	Scenario index representing a type of IS.
h_m	Time index representing the lead time between financial and physical transactions in a given market.
Decision variables	
$x_{m,t,n}$	Order to buy power for EVs in a given market (kWh).
$y_{m,t,n}$	Order to sell power from EVs in a given market (kWh).
$c_{t,n}$	Power consumption signal to the EVSE in real-time (kWh).
$d_{t,n}$	Power supply signal to discharge the EV in real-time (kWh).
EV state variables	
Δt	Duration of a time step (hours, minutes, seconds).
$\text{SOC}_{t,n}$	Energy (kWh) stored in the EV battery at time step t for EV owner n .
$\text{driving}_{t,n}$	Energy consumed (kWh) when the EV is driving during time step t for owner n .
$\text{evse}_{t,n}$	Power (kW) available to charge or discharge the EV during time step t for owner n .
$t_{(t,n)}^{\text{departure}}$	Time-steps until next departure.
$t_{(t,n)}^{\text{next charge}}$	Time-steps until next charge.
$\alpha_{t,n}$	Energy required for driving until the next charging session (kWh).
$\beta_{t,n}$	Charging opportunities in current charging session (kWh).
Flexibility indicators	
$\delta_{t,n}^{\text{needs}}$	Energy required to comply with the EV owner's mobility needs (kWh).
$\varphi_{t,n}^p$	Flexibility in production (kWh): Power the EV can provide to the grid.

Table 3.1: Summary of Notation for the Model

Notation	Description
$\varphi_{t,n}^c$	Flexibility in consumption (kWh): Power the EV can absorb from the grid.
Market prices	
$p_{m,t}$	Clearance price on a given market (€/kWh).
$p_t^{\text{imb-high}}$	Upper-imbalance price for time t (€/kWh).
$p_t^{\text{imb-low}}$	Lower-imbalance price for time t (€/kWh).
Others	
T	Duration of the model (time-steps).
T_m^B	Duration of bid-time for market m (time-steps).
N	Total number of EV users aggregated.
S	Number of potential outcomes.
tariff_t	Tariff EV owners pay to charge their vehicle (€/kWh).
τ_n	Cost of battery degradation for additional cycling (€/kWh).
$\text{Ef}_n^{\text{driving}}$	Driving energy efficiency (kWh/km).
Ef^c	Energy efficiency conversion factor from charging.
Ef^d	Energy efficiency conversion factor from discharging.
ε	A generic random variable ε .
F^ε	Cumulative probability distribution of random variable ε .
$\text{bid}_m^{\text{min}}$	Minimum bid-size (kWh) for bidding on market m .
$\text{SOC}_n^{\text{Max}}$	Maximum energy (kWh) that can be stored in the EV battery of owner n .
$\text{SOC}_n^{\text{Min}}$	Minimum energy (kWh) that can be stored in the EV battery of owner n .

Module 1: EV mobility.

To incorporate statistical uncertainty (Savage, 1972) into the simulation, we adopted the framework proposed by Oberkamp et al. (2002, 2004), a widely recognized approach in risk assessment literature for representing and propagating uncertain parameters. This framework was implemented in three main steps. First, we defined the equations governing EV behavior from an energy perspective. Second, we calculated system (ontological) uncertainties,

which, in this context, are limited to the initial energy stored in EV batteries. Third, we model environmental variability, focusing on three key factors: EV drivers' departure time, arrival time, and EV energy efficiency. This variability, in combination with the limited knowledge then become t

Step 1: Model of EVs energy system - The first step is modeling EV owner behavior as an energy asset to track the EV battery's SOC, representing the energy available for mobility or energy purposes. The SOC is influenced by the energy consumed during driving, charging, and discharging activities. Equations 3.1 to 3.7, describe the evolution of SOC and the constraints governing the charging and discharging processes.

$$\text{SOC}_{t+1,n} = \text{SOC}_{t,n} + c_{t,n} - (\text{driving}_{t,n} + d_{t,n}) \quad (3.1)$$

subject to (s.t):

$$0 < n \leq N \quad (3.2)$$

$$0 < t \leq T \quad (3.3)$$

$$0 \leq \text{SOC}_{t,n} \leq \text{SOC}_n^{\max} \quad (3.4)$$

$$0 \leq \text{driving}_{t,n} \quad (3.5)$$

$$0 \leq c_{t,n} \leq \text{evse}_{t,n} \times \Delta t \times E f^{\text{charging}} \quad (3.6)$$

$$0 \leq d_{t,n} \leq \text{evse}_{t,n} \times \Delta t \quad (3.7)$$

Step 2: Simulating system uncertainty - System uncertainty refers to the inherent variability in the system's parameters or initial conditions that cannot be precisely modeled Oberkamp et al. (2004). In our case, the uncertainty stems from the initial state of charge $\text{SOC}_{(t=0,n)}$ of the EV battery, which is determined by the EV's initial state on the model. Initial conditions are a key type of uncertainty because they set the starting point for the system's evolution. These uncertainties can propagate through the simulation, affecting decision-making processes and the system's overall performance.

We model this uncertainty as a random draw from a uniform distribution between $a \times \text{SOC}_n^{\max}$ and $\text{SOC}_n^{\max}$, where $a \sim U(0.5, 1)$ is a random variable uniformly distributed between 0.5 and 1.

$$\text{SOC}_{(t=0,n)} \sim U(a \times \text{MaxSOC}_n, \text{MaxSOC}_n) \quad (3.8)$$

Step 3: Environmental uncertainty - Environmental uncertainty refers to the variability in external factors that affect the system's behavior but are exogenous to the system that is being modeled (Oberkamp et al., 2002, 2004).

In the context of EV simulations, three key sources of environmental uncertainty are the time of departure, time of arrival, and energy efficiency of the EV. These factors are highly dynamic and influenced by complex conditions, such as traffic patterns, driving habits, and weather conditions.

We have divided the process of introducing environmental uncertainty into three steps. First, we detail how we process the data input required to generate environmental uncertainty. Second, we consider the uncertainties associated with EV owners' arrival and departure times and specifically focus on driving distance and timing. Third, we incorporate the variability in the energy efficiency of the EVs, which affects how much energy is consumed during driving and charging events.

Step 3.1: Processing data input - First, we require input data. The minimum necessary data consists of a series of time steps detailing the kilometers driven by the EV and the power of the EVSE to which the vehicle is connected. This data provides the essential information to simulate the EV's behavior over the desired analysis period, denoted as T . With these basic premises, the first step in the simulation is to identify the arrival and departure times of the EV owners based on the initial data. These timestamps serve as the foundation for modeling the subsequent behaviors of the EVs, such as charging, discharging, and driving patterns.

Algorithm 1 can process any input data and incorporate environmental uncertainty into the simulation.

Algorithm 1 Identify Arrival and Departure Times for EV Owners

```

1: for each EV owner  $n$  in range  $(0, N)$  do
2:   for each time-step  $t$  in range  $(0, Initial\_data)$  do
3:     if  $driving_{(t,n)} = 0$  and  $driving_{(t-1,n)} \neq 0$  then
4:       Add  $t$  to  $arrival_n$ 
5:     else if  $driving_{(t,n)} = 0$  and  $driving_{(t+1,n)} \neq 0$  then
6:       Add  $t$  to  $departure_n$ 
7:     else
8:       Continue
9:     end if
10:  end for
11: end for

```

Step 3.2: Uncertainties from drivers' departure and arrival - To introduce uncertainty from driver departure and arrival, we can account for different types of driving behaviors, each introducing distinct levels of environmental uncertainty into the system that might be suitable for most EV owners. An

example of two simple driving behaviors could be 'home-work-home,' which occurs from Monday to Friday. This can be simulated as a driving pattern that is largely consistent weekly, with small variations in time of arrival and departure. A second type of behavior, which could be during the 'weekend,' occurs on Saturday and Sunday and is highly variable, with irregular driving patterns that differ significantly across weeks.

Algorithm 2 incorporates mobility uncertainties into the simulation, introducing randomness into key aspects of EV owner behavior. For each EV owner, random variations in kilometers driven are applied at each time step, sampled from a normal distribution, simulating real-world driving unpredictability. Additionally, uncertainties in arrival and departure times at charging stations are modeled by introducing random deviations in the arrival time, adjusting the departure time accordingly, and recalculating the stop duration. The algorithm then updates the driving and charging status for each time step, ensuring that EVs are correctly assigned to charging stations during their stops. Furthermore, the algorithm handles periodic mobility patterns by incrementing a week index and remapping input data as needed, allowing for a realistic representation of mobility uncertainties over multiple weeks.

Algorithm 2 Algorithm for Including Mobility Uncertainties in Simulation

```

1: for each EV owner  $n$  in range  $(0, N)$  do
2:    $w \leftarrow 0$  ▷ Week index for input data mapping
3:   for  $t$  in range 0 to  $T$  do
4:      $\Delta\text{kms} \sim N(0, \sigma^2)$  ▷ Introduce random variation to kilometers driven
5:      $\text{driving}_{(t,n)} \leftarrow \text{driving}_{(t,n)} + \Delta\text{kms}$ 
6:     if  $t$  in  $\text{arrival}_n$  then
7:        $\Delta t \sim \text{int}(N(0, \sigma^2))$ 
8:        $\text{new\_departure} \leftarrow \text{departure}(\text{stop}, n) + \Delta t$ 
9:        $\text{new\_arrival} \leftarrow \text{arrival}(\text{stop}, n) + \Delta t$ 
10:       $\text{duration} \leftarrow \text{new\_departure} - \text{new\_arrival}$ 
11:      for  $\text{stop\_time}$  in range 0 to  $\text{duration}$  do
12:         $\text{evse}_{(t=\text{new\_arrival}+\text{stop\_time},n)} \leftarrow \text{evse}_{(t,n)}$ 
13:         $\text{driving}_{(t=\text{new\_arrival}+\text{stop\_time},n)} \leftarrow 0$ 
14:      end for
15:    end if
16:    if  $t \geq (\text{length}(\text{Initialdata}) \times (w + 1))$  then
17:       $w \leftarrow w + 1$ 
18:    end if
19:  end for
20: end for

```

Step 3.3: Uncertainties of EV energy efficiency - Energy efficiency can vary due to factors such as wind conditions, traffic, and the speed of the EV. To account for these variations, the energy efficiency factor is modeled as a random variable that is uniformly distributed within the range $[a, b]$, where a can be negative, reflecting scenarios of reduced efficiency, and b is the upper bound representing increased efficiency. However, it is important to ensure that the driving distance remains non-negative as constrained by equation 5. Equation 3.9 describes how the efficiency variation is incorporated into the calculation of the driving distance for each EV owner and time step in the simulation:

$$\text{driving}_{(t,n)} = \max \left(0, \text{driving}_{(t,n)} \times \left(\text{Ef}_{(n)}^{\text{driving}} + \Delta \text{efficiency} \right) \right) \quad (3.9)$$

Module 2: Power markets

We model a power market as a clearance mechanism that has three stages. It has an open-market phase, where market actors can submit bids to buy or sell power. This stage is characterized by the type of price revealing mechanism, i.e., when the market actors receive information on the clearance price of the market. We characterize these mechanisms as being of two types: they can be either in a closed auction form, which means that the market participants will make bids without knowing what is the market price until the bidding stage is over, or continuous, which means that the market participants can observe the price change during the open-market phase.

The second stage is the lead time, which is the time between the market closure and delivery time, which we denote as h_m . The third stage is the delivery time, which we characterize through two main characteristics: the duration of the bid, which we denote T_m^B , and the minimum bid size, which we denote as $\text{bid}_m^{\min}$.

Module 3: Aggregator decision-making

We model the aggregator's decision-making process as a three-stage stochastic optimization problem, building significantly on the approaches developed by Ayón et al. (2017) and Liu et al. (2015). Ayón et al. (2017) proposed a probabilistic optimization method for aggregator bidding in the day-ahead and intraday electricity markets, while Liu et al. (2015) analyzed micro-grid

strategies. In contrast to them, we will focus on a V2G aggregator with uncertainty on EV owner behavior.

In the first two stages, the aggregator determines market orders for future periods $t + h_m$. To fix ideas, in a concrete example, let us consider that the first market is a day-ahead market ($m = 1$) where the energy is traded at time t for the next 24 hours with a minimum lead-time of 12 hours and a maximum lead-time of 36 hours such that in that market they are at least 24 lead-times to consider for the same bidding period ($h_1 = 12, 13, \dots, 36$). Each bid, however, has the same bidding time of 1 hour (T_1^b). At each bidding time, the aggregator will have to decide its bidding strategy $(x_{1,t+h_1,n}, y_{1,t+h_1,n})$. In such a decision, the bidding time will overlap with the second market, which could be the intraday market ($m = 2$) where the energy is traded with 1-hour lead-time (h_2) and 1 hour from bidding time (T_2^b). Therefore, during the bidding time of Market 1, the aggregator also needs to consider the potential of bidding on Market 2 $(x_{2,t+h_1,n}, y_{2,t+h_1,n})$. These decisions rely on information gathered through the aggregator's IS $I_k(t)$ at the bidding time t in Market 1 regarding the current and projected states of EV users' flexibility for charging and discharging.

The aggregator's uncertainty on future mobility conditions is modeled for any of the markets through a set of continuous random variables, which includes the future battery state-of-charge ($\text{soc}_{t+h_m,n}$), EVSE connection status ($\text{evse}_{t+h_m,n}$), driving energy consumption ($\text{driving}_{t+h_m,n}$), future time of departure $t_{(t+h_m,n)}^{\text{departure}}$, and the next time the EV will have the opportunity to charge again $t_{(t,n)}^{\text{next charge}}$. These variables determine the flexibility for future charging or discharging, such as the mobility needs, $\delta_{t+h_m,n}^{\text{needs}}$, among others that we define below. Each of them has a given cumulative distribution function F_ε , representing the foreknowledge that the Aggregator has on EV drivers' behavior.

In the third stage, the aggregator observes the realized EV flexibility and executes recourse actions accordingly. Equation 3.10 models the recourse action. The first term represents the revenue generated from selling electricity for EV charging. It also accounts for the payments the aggregator must make to the EV owner to compensate for the additional degradation of the EV battery due to increased cycling (τ). For simplicity, we assume that this degradation cost is constant. The second term models the balancing costs incurred by the aggregator due to under-procurement. The third term accounts for the balancing costs associated with overbidding.

$$\begin{aligned}
Q_{t+h_m,n} = & \text{tariff}_{(t+h_m)} \times c_{(t+h_m,n)} - \tau \times d_{(t+h_m,n)} \\
& - p_{(t+h_m)}^{\text{imb-high}} \times \left(\frac{C_{(t+h_m,n)}}{E f^c} - (x_{(1,t+h_m,n)} + x_{(2,t+h_m,n)}) \right)^+ \\
& - p_{(t+h_m)}^{\text{imb-low}} \times \left(x_{(1,t+h_m,n)} + x_{(2,t+h_m,n)} - \frac{C_{(t+h_m,n)}}{E f^c} \right)^+ \\
& - p_{(t+h_m)}^{\text{imb-low}} \times (x_{(1,t+h_m,n)} + x_{(2,t+h_m,n)}) - d_{(t+h_m,n)} \times E f^d)^+
\end{aligned} \tag{3.10}$$

Equations 3.11 to 3.19 model the constraints governing the energy flexibility of the aggregated EVs, where $(charge_{t+h_m,n}^1)$ represents the energy charged (kWh), and $(discharge_{t+h_m,n}^2)$ the energy discharged (kWh) in a given time-step of the model. Equation 3.11 limits the sum of the potential recursive actions, ensuring that they do not exceed the power capacity of the EVSE, which is another system's physical constraint (the first is given by 3.4). Equation 3.12 models a main assumption of this module (Assumption 1) that by contractual obligations, the Aggregator always provides the power consumption required to satisfy EV owner's mobility needs, which we denote as $\delta_{(t+h_m,n)}^{\text{needs}}$. The mobility needs, $\delta_{(t+h_m,n)}^{\text{needs}}$, are defined in equation 3.13 as the difference between the available SOC in the battery (the first term) and the future mobility needs, $\beta_{(t+h_m,n)} - \alpha_{(t+h_m,n)}$ (the second term). Furthermore, equation 3.14 models a third physical constraint by limiting the maximum energy capacity of the EV, $\phi_{(t+h_m,n)}^c$, limited by the size of the battery SOC^{max} .

s.t.

$$c_{(t+h_m,n)} + d_{(t+h_m,n)} \leq evse_{(t+h,n)} \times \Delta t, \tag{3.11}$$

$$\delta_{(t+h,n)}^{\text{needs}} \leq w_{(t+h,n)}^1 \leq \phi_{(t+h,n)}^c, \tag{3.12}$$

$$\begin{aligned}
\delta_{(t+h,n)}^{\text{needs}} = & (SOC_{(t+h,n)} - SOC_n^{\text{min}}) \\
& - (\beta_{(t+h,n)} - \alpha_{(t+h,n)}),
\end{aligned} \tag{3.13}$$

$$\phi_{(t+h,n)}^c = SOC^{\text{max}} - SOC_{(t+h,n)}, \tag{3.14}$$

$$0 \leq w_{(t+h,n)}^2 \leq \phi_{(t+h,n)}^p, \tag{3.15}$$

$$\phi_{(t+h,n)}^p = \begin{cases} 0, & \text{if } \phi_{(t+h,n)}^p \leq 0, \\ \frac{\delta_{(t+h,n)}^{\text{needs}}}{E f}, & \text{if } \delta_{(t+h,n)} > 0, \end{cases} \tag{3.16}$$

$$\alpha_{(t+h,n)} = \sum_{t \in T_{(t,n)}^{\text{nc}}} driving_{(t,n)}, \tag{3.17}$$

$$\beta_{(t+h,n)} = evse_{(t+h,n)} \times (t_{(t,n)}^{\text{departure}} - t), \tag{3.18}$$

Equation 3.15 imposes a limit on the maximum discharge during the re-

course action, which is defined by $\phi_{(t+h,n)}^p$. This flexibility is determined based on the value of $\delta_{(t+h_m,n)}^{needs}$, as shown in equation 3.16. Specifically, suppose $\delta_{(t+h_m,n)}^{needs}$ is negative. In that case, it indicates that the EV can discharge energy without affecting its future mobility needs, either because it can charge again later in the same session or because it has enough remaining energy to cover its future driving requirements, $\alpha_{(t+h_m,n)}$. Finally, equations 3.17 and 3.18 define the calculation of the future mobility needs and the charging opportunity, respectively.

Equation 3.19 represents the aggregator's decision problem in the first stage, considering all three phases of the decision-making process. The first two lines capture the expected value of the aggregator's first-stage decision. The third and fourth line accounts for the bidding decision in the intraday markets, while the fifth and sixth line incorporates the recursive action defined in Equation 3.10. The problem is subject to constraints defined by equations 3.20, which imposes a non-negativity constraint, preventing negative market orders.

$$\begin{aligned} \max_{x,y} Z = & \sum_{t \in T_1^b} \sum_{n \in N} -E[p_{(1,t+h_1)} | I_k(t)] \times [(x_{(1,t+h_1,n)} - y_{(1,t+h_1,n)})] \\ & + \sum_{t \in T_1^b} \sum_{n \in N} -E[p_{(2,t+h_1)} | I_k(t)] \times [(x_{(2,t+h_1,n)} - y_{(2,t+h_1,n)})] \quad (3.19) \\ & + \sum_{t \in T_1^b} \sum_{n \in N} E[Q_{(t+h_1,n)} | I_k(t)], \forall h_1 \end{aligned}$$

s.t.

$$0 \leq x_{(1,t+h_1,n)}, y_{(2,t+h_1,n)} \quad (3.20)$$

Equation 3.21 represents the aggregator's decision problem in the second stage, considering the decisions taken in the first stage x . The first line captures the expected value of the aggregator's accounts for the bidding decision in the intraday markets. While the second line incorporates the recursive action defined in Equation 3.10.

$$\begin{aligned} \max_{x,y} W(x_1, y_1) = & \sum_{i \in T_2^b} \sum_{n \in N} -E[p_{(2,t+h_2)}^2 | I_k(t)] \times [(x_{(2,t+h_2,n)} - y_{(2,t+h_2,n)})] \\ & + \sum_{i \in T_2^b} \sum_{n \in N} E[Q_{(t+h_2,n)} | I_k(t)] \end{aligned} \quad (3.21)$$

s.t.

$$x_{(1,t+h_2,n)} + y_{(1,t+h_2,n)} + x_{(2,t+h_2,n)} + y_{(2,t+h_2,n)} \leq evse_{(t+h_2,n)} \times \Delta t \quad (3.22)$$

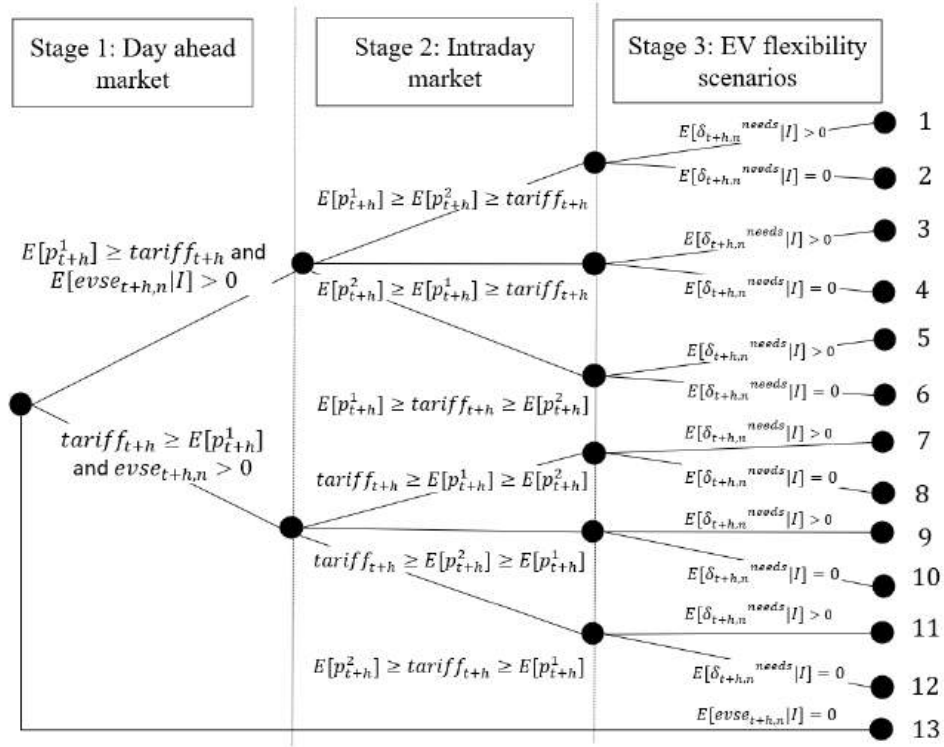
$$0 \leq x_{(2,t+h_2,n)}, y_{(2,t+h_2,n)} \quad (3.23)$$

We solve the above problems using a scenario-based approach to determine the optimal stochastic solutions according to the knowledge of the distribution of future outcomes (Birge & Louveaux, 2011). The stochastic solution is widely applied in contexts with future uncertainty because it integrates risk management into decision-making processes by introducing hedging considerations according to the aggregator information on EV owner flexibility.

The first branching point arises from the first stage, where the aggregator evaluates whether the day-ahead price $p_{1,t}$ is higher or lower than the charging tariff that is paid by the EV users when charging, $tariff_t$. In the second branching stage, the aggregator must decide between at least three potential paths, determined by the relationship between the expected intraday prices $p_{2,t}$, the day-ahead prices $p_{1,t}$, and $tariff_t$. At the third branching point, the aggregator faces two key scenarios related to flexibility after all market transactions are finalized. In this stage, the aggregator must account for the EV owner's specific mobility needs, $\delta_{(t,n)}^{needs}$, which may constrain the aggregator's actions. For instance, if the EV owner needs to drive a significant distance but has limited time to charge, the aggregator is compelled to prioritize charging ($charge_{(t,n)}$) over-discharging ($discharge_{(t,n)}$). Additionally, the aggregator must assess whether the EV is physically connected to an EVSE. If the EV is not connected, charging or discharging is impossible. To reduce the scenarios, Therefore, to eliminate unnecessary complexity in the modeling scenario, we consolidate all redundant scenarios where the EV is disconnected, and no market bids should be made in scenario 13, where the response is "not to bid."

Let the index s denote potential outcome scenarios, which we have simplified to thirteen potential scenarios, as illustrated in Figure 3.4, where we describe the scenarios as an Aggregator participating on day-ahead at a first stage, after on intraday day markets at second stage; and finally at the recourse action, where the aggregator is required to anticipate EV flexibility.

Figure 3.4: Scenarios of potential outcomes on aggregator flexibility.



Note: If we consider the case of only a single market or the scenario where the first-stage decisions have already been made, the aggregator would already know the specific node they are in during the second stage. As a result, the number of scenarios would be reduced by a half.

Given aggregators are exposed to costs from over- and under-procurement, the optimal solution is easier to determine through backward induction by looking first at the optimal recourse action, specified on Proposition 1 and then by resolving for each scenario by looking at Proposition 2 .

Proposition 1 - Optimal Recourse Action: Let $p_{(1,2),(t+h_m)}$ represent the set of prices in market 1 or 2 at time $t + h_m$, which are known by the Aggregator. The optimal charging and discharging decisions in the recourse action are given as follows:

$$c_{(t+h_m,n)}^* = \begin{cases} \delta_{(t+h_m,n)}^{\text{needs}}, & \text{if } p_{(1,2),t+h_m} > \text{tariff}_{t+h_m}, \\ \phi_{(t+h_m,n)}^c, & \text{if } p_{(1,2),t+h_m} \leq \text{tariff}_{t+h_m}. \end{cases}$$

$$d_{(t+h_m, n)}^* = \begin{cases} \phi_{(t+h_m, n)}^p, & \text{if } p_{(1,2), t+h_m} > v_{t+h_m} + \tau, \\ 0, & \text{if } p_{(1,2), t+h_m} \leq v_{t+h_m} + \tau. \end{cases}$$

Proof. Proposition 1: If market prices exceed the charging tariff paid by the EV user, tariff_t , the Aggregator will try to minimize the amount of energy that will be charged to the EV and charge whatever it needs to satisfy EV mobility needs ($\delta_{(t+h, n)}^{\text{needs}}$). Charging more will increase Aggregator losses; charging less is impossible because EV users will not be able to arrive at their next destination. On the other hand, if the expected prices are lower than or equal to tariff_t , the aggregator has the potential to arbitrage and will want to charge as much as the EV's battery allows, $E[\phi_{(t+h, n)}^c]$. Secondly, on the discharging strategy, if the market prices are higher than the price the aggregator needs to pay to the EV owner τ , the aggregator maximizes its profits by discharging as much as it can, only limited by the EV's flexibility to discharge ($\phi_{(t+i, n)}^p$). Conversely, if the prices do not meet the profitability threshold, the aggregator refrains from discharging, setting the discharging decision to zero. $\square$

Proposition 2: Optimal bidding decision Let F_ε be the cumulative distribution function of a given continuous random variable denoting EV flexibility. We define the optimal bidding decisions by each scenario in Table 3.2.

Table 3.2: Optimal bidding decision by scenario

s	$x_{t,n}^1$	$y_{t,n}^1$	$x_{t,n}^2$	$y_{t,n}^2$
1	0	0	$F_{\delta needs} \left(\frac{p^1 - \text{tariff}_{t,n}}{p^1 + p^{i-low}} \right)$	0
2	0	$F_{\phi p} \left(\frac{p^1 - (\tau)}{p^1 + p^{i-high}} \right)$	0	0
3	$F_{\delta needs} \left(\frac{p^1 - \text{tariff}_{t,n}}{p^1 + p^{i-low}} \right)$	0	0	0
4	0	0	0	$F_{\phi p} \left(\frac{p^2 - (\tau)}{p^2 + p^{i-high}} \right)$
5	0	0	$F_{\delta needs} \left(\frac{p^2 - \text{tariff}_{t,n}}{p^2 + p^{i-low}} \right)$	0
6	0	$\begin{cases} 0, \mathbb{E}[Z(x^2) \geq Z(y^1) I] \\ F_{\phi p} \left(\frac{p^1 - (\tau)}{p^1 + p^{i-high}} \right), \text{ else} \end{cases}$	$\begin{cases} 0, \mathbb{E}[Z(y^1) > Z(x^2) I] \\ F_{\phi c} \left(\frac{p^1 - \text{tariff}}{p^1 + p^{i-high}} \right), \text{ else} \end{cases}$	0
7	0	0	$F_{\phi c} \left(\frac{\text{tariff}_{t,n} - p^2}{p^2 + p^{i-high}} \right)$	0
8	0	$\begin{cases} 0, \mathbb{E}[Z(x^2) \geq Z(y^1) I] \\ F_{\phi p} \left(\frac{p^1 - (\tau)}{p^1 + p^{i-high}} \right), \text{ else} \end{cases}$	$\begin{cases} 0, \mathbb{E}[Z(y^1)] > Z(x^2) I \\ F_{\phi c} \left(\frac{p^1 - \text{tariff}}{p^1 + p^{i-high}} \right), \text{ else} \end{cases}$	0
9	$F_{\phi c} \left(\frac{\text{tariff}_{t,n} - p^1}{p^1 + p^{i-high}} \right)$	0	0	0
10	$\begin{cases} 0, \mathbb{E}[Z(y^2) \geq Z(x^1) I] \\ F_{\phi c} \left(\frac{p^2 - \text{tariff}}{p^2 + p^{i-high}} \right), \text{ else} \end{cases}$	0	0	$\begin{cases} 0, \mathbb{E}[Z(y^2) > Z(x^1) I] \\ F_{\phi p} \left(\frac{p^2 - (\tau)}{p^2 + p^{i-high}} \right), \text{ else} \end{cases}$
11	$F_{\phi c} \left(\frac{\text{tariff}_{t,n} - p^1}{p^1 + p^{i-high}} \right)$	0	0	0
12	$\begin{cases} 0, \mathbb{E}[Z(y^2) \geq Z(x^1) I] \\ F_{\phi c} \left(\frac{p^2 - \text{tariff}}{p^2 + p^{i-high}} \right), \text{ else} \end{cases}$	0	0	$\begin{cases} 0, \mathbb{E}[Z(y^2) > Z(x^1) I] \\ F_{\phi p} \left(\frac{p^2 - (\tau)}{p^2 + p^{i-high}} \right), \text{ else} \end{cases}$
13	0	0	0	0

Proof. Proposition 2: First, given the costs associated with over-procurement and under-procurement, the optimal decision aligns with the recourse action defined in Proposition 1. Specifically, the solution minimizes the expected costs by dynamically adjusting decisions based on observed conditions. Second, the actions of charging or discharging are infeasible if $evse_{t+h,n} = 0$, as the electric vehicle supply equipment (EVSE) is not operational. Consequently, no bidding should occur in such scenarios, particularly when $s = 13$. Third, for all impaired scenarios, $s \in \{1, 3, 5, 7, 9, 11\}$, the Aggregator, by assumption, must prioritize ensuring the mobility needs of electric vehicles. Hence, it follows that $y_{t,n}^1 = y_{t,n}^2 = 0$ in these scenarios, as charging and discharging are infeasible under these conditions. Fourth, in impaired scenarios, the Aggregator must make a comparative decision between charging in the first or second market. The optimal strategy involves purchasing power in the market offering the lower price. Specifically, $x_{t+h,n}^1$ is preferable when $s \in \{3, 9, 11\}$, whereas $x_{t+h,n}^2$ is preferable when $s \in \{1, 5, 7\}$. Fifth, in paired scenarios where $s \in \{2, 4\}$, the electric vehicles exhibit flexibility, allowing the Aggregator to either charge or discharge. However, since prices

in both markets exceed the tariff, the Aggregator has no incentive to charge. Consequently, $x_{t+h,n}^1 = x_{t+h,n}^2 = 0$. Moreover, the Aggregator will prefer to discharge at the highest price, resulting in $y_{t+h}^2 = 0$ when $s = 2$ and $y_{t+h}^1 = 0$ when $s = 4$. Sixth, in all other scenarios, i.e., $s \in \{6, 8, 10, 12\}$, the decision-making process necessitates the evaluation of expected profits. This involves a simultaneous comparison of the benefits of charging or discharging in both markets, optimizing the strategy based on expected values. Finally, as demonstrated by Birge and Louveaux (2011), a stochastic solution is superior to a deterministic solution. Optimality can be achieved when the solution is derived from continuous random variables. Therefore, we reformulate the deterministic solution from Proposition 1 into its stochastic counterpart, $F_\varepsilon(CR)$, which represents the CR-quantile of the distribution function of the random variable ε . Here, CR denotes the critical ratio, defined as the relationship between potential gains and potential losses resulting from prediction errors. This transformation ensures that the stochastic solution is robust and accounts for uncertainty. $\square$

Module 4: Information system

The IS module aims to model how the Aggregator receives mobility-related data to predict EV owners' flexibility to charge or discharge their batteries. According to the reference model of DeLone and McLean (2003), we model the communication process by focusing on two main dimensions, as we have already suggested in the theoretical framework.

The first dimension is *completeness*, which refers to the extent to which the IS captures and conveys data about EV owner behavior—a critical attribute of IS success DeLone and McLean (2003). The aggregator relies on various inputs to make its bidding decisions, including the state of charge of the battery ($soc_{t+h_m,n}$), driving consumption ($driving_{t+h_m,n}$), EV connection status to the EVSE ($evse_{t+h_m,n}$), time to departure in the current charging session ($\beta_{t,n}$), and energy required for driving until the next charging session ($\alpha_{t,n}$). These variables are essential for calculating the flexibility indicators that inform the aggregator's decisions. Whenever an IS, I_k , lacks completeness for a specific piece of information, the aggregator substitutes it with foreknowledge of EV behavior derived from historical records.

The second dimension is *temporality of the information exchange*, which specifies whether the aggregator receives information at time t , such that an IS exchange is defined as $I_k(t)$. To model this dimension, we differentiate between two communication channels, each represented as a specific set of

conditions that must be met for the aggregator to receive information about the EV owner’s mobility. The channels considered are power-line communication (PLC), which requires the EV to be parked and connected to an EVSE, and over-the-air communication (OAC), which is not subject to this limitation.

Table 3.3 provides examples illustrating the IS dimensions and how they affect the information received by the aggregator. The first example, Communication Protocol Only, represents a minimum scenario where the IS relies solely on PLC communication. In this case, the aggregator only receives basic information, such as the SOC and whether the EV is connected to an EVSE. There is no provision for anticipating future driving needs, and communication is limited to when the EV is physically connected. The second example, ‘Communication Protocol + Navigation App,’ introduces additional information content such as location and km driven anticipating EV owners driving needs. Furthermore, temporality includes both PLC and OAC, enabling the aggregator to access data even when the EV is not connected to an EVSE. This setup provides a richer dataset for decision-making, reflecting the potential for more advanced planning and optimization in V2G operations. Furthermore, regarding foresight, we consider that the EV owner knows its driving needs until the end of the current trip; however, not further.

Table 3.3: Examples of IOIS Modelling

Scenario	Channel	Information				
		$driving_{t+h_m,n}$	$evse_{t+h_m,n}$	$soc_{t+h_m,n}$	$\beta_{t,n}$	$\alpha_{t,n}$
Industrial Standard	PLC.	No	Yes, only if connected.	Yes, only if connected.	No	No
Navigation App + Industrial Standard	PLC + OAC.	Yes, if driving until arrival.	Yes, only if connected.	Yes, only if connected.	No	No

Module 5: Profits and emissions

This module performs the ex-post evaluation of the aggregator’s profit and greenhouse gas emissions. We model these aspects using two equations to compare the performance of the IOIS. Equation 3.24 maintains the same structure as the recourse problem, while Equation 3.25 demonstrates that overall emissions generated by EVs arise from their charging activities. Conversely, when EVs discharge, we assume they offset the generation from electricity sources with an average emission factor equivalent to that of the electric system.

$$\begin{aligned}
\pi_k = & tariff_t \times c_t - \tau \times d_t \\
& - p_{(t)}^{\text{imb-high}} \times \left(\frac{c_{(t,n)}}{Ef} - (x_{(1,t,n)} + x_{(2,t,n)}) \right)^+ \\
& - p_{(t)}^{\text{imb-low}} \times \left((x_{(1,t,n)} + x_{(2,t,n)}) - \frac{c_{(t,n)}}{Ef} \right)^+ \\
& + (x_{(1,t,n)} + x_{(2,t,n)}) - d_{(t,n)} \times Ef)^+
\end{aligned} \tag{3.24}$$

$$kgCO_2 = (c_t - d_t) * emissionfactor_{kgCO_2/kWh} \tag{3.25}$$

3.3.2 . Validation and verification

To validate our simulation and verify our results in addressing our research question, we adopt the approach recommended by Sargent (2010). This iterative process includes running the model multiple times to identify inconsistencies, debugging the code, and carefully reviewing the simulation outputs and results. We conducted four main types of tests to ensure simulation validity and result verification.

First, we perform graphical validation by visually analyzing the simulation framework's outputs, focusing on the algorithms introducing uncertainty into the model. This helps identify any unusual patterns or anomalies. Second, we filter out simulation results that exceed what would be expected from normal driving behavior. For instance, during the randomization process, there may be cases where the SOC of an EV drops to zero because the vehicle drives more than it has the opportunity to charge, irrespective of the aggregator's decisions. Such cases are excluded from subsequent analysis.

Third, we carry out a conceptual validation of the IOIS being tested, ensuring that errors in the aggregator's decisions are consistent with reasonable expectations of the IOIS's performance. For example, if an IOIS relies on information from a navigation app, we expect minimal errors in predicting driving consumption and EV arrival times. Finally, we analyze the statistical significance of the IOIS's value across the entire sample of simulated EV drivers.

3.4 . A case study on Tenerife island, Spain

To implement our framework, we chose the island of Tenerife in Spain as a case study for two main reasons. First, because of data availability, and

second, because the government of the Canary Islands, from which Tenerife is one of the islands in its jurisdiction, has the ambitious dual objective to defossilize its electric grid and vehicle fleet by 2040.

We have divided this section into three parts. First, we present an overview of the main data for numerically calibrating our simulation parameters and main assumptions. Then, we present the IOIS scenarios we evaluate, and finally, we present the results from the simulation.

3.4.1 . Data and assumptions for the calibration

Mobility data

As primary input for our simulation, we have a data set of the SOC from 5 624 EV drivers, measured every 10 minutes for five days (Monday to Friday). Rojano-Padrón et al. (2023) produced this dataset through a multi-agent simulation. Their study used data derived from mobility surveys conducted in 2019 with the inhabitants of Tenerife to propose the optimal deployment of charging infrastructure. The main strength of this dataset lies in its representation of rational charging behavior exhibited by a multi-agent system, i.e., a simulation in which the optimal behavior of the agent considers the interactions with other agents and the availability of charging infrastructure.

Figure 3.5 shows the average duration of the charging session of the initial dataset and the power at which they charge. The distribution of the duration of the charge suggests that, in most cases, EVs tend to have long periods of charging during the night and sometimes over several days without disconnecting their EV. Furthermore, the figure shows that most of the time, the EVs are connected to an EVSE of 7kW.

Figure 3.5: Charging sessions in the initial data.

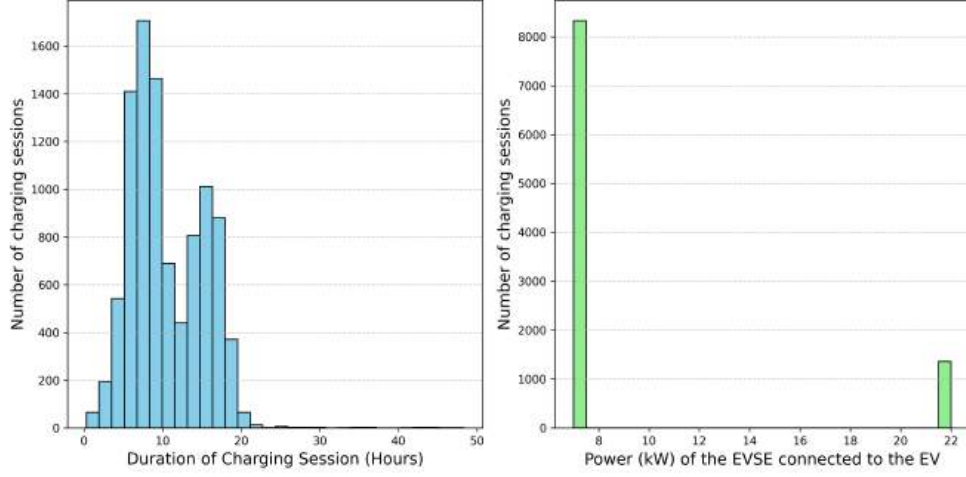
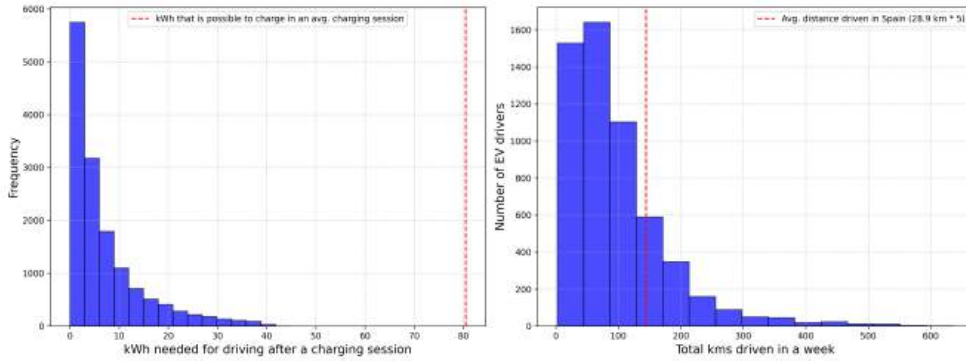


Figure 3.6 shows the flexibility potential; most of the time, the charging sessions allow the EV drivers enough time to charge their vehicles more than they require for their next drive. Furthermore, the total amount of km that the EV owners drive in Tenerife is usually lower than the average km driven by a driver in Spain. Overall, this shows that the EV behavior from the week-length dataset from Rojano-Padrón et al. (2023) shows a high level of flexibility for V2G services.

Figure 3.6: Flexibility potential in the initial data.



Assumptions for simulation

Simulating the uncertainty of EV owner driving behavior requires high temporal granularity and long simulation periods, making it computationally in-

tensive. To optimize computational resources and reduce processing time, we select a random sample of 100 EV drivers from a total population of 5,624. This allows us to capture representative behavioral patterns while maintaining a manageable computational load.

To introduce uncertainty in the simulation, we specify certain assumptions to implement Algorithm 2, which incorporates mobility randomness into key aspects of EV owner behavior, and Equation 3.9, which describes driving efficiency variation.

We consider two main types of driving patterns for mobility behavior, each with a different level of uncertainty introduced through distinct mechanisms. The first type of driving behavior is defined as '*home-work-home*' behavior. In this case, uncertainty is introduced by varying the departure and arrival times within a 30-minute from the initial data, which covers Monday to Friday. This means an EV owner may arrive or leave up to 30 minutes earlier or later than the scheduled time. The second type of driving behavior is defined as '*weekend*' behavior. For this pattern, we model uncertainty by taking a random draw from any given day exhibiting '*home-work-home*' behavior.

For driving efficiency, we introduce randomness by sampling from a range between $\frac{150\text{Wh}}{\text{km}}$ and $\frac{160\text{Wh}}{\text{km}}$. This range accounts for variations caused by road slope and wind conditions.

Parameters

Table 3.4 summarizes the main parameters required to calibrate our simulation framework and the main parameters that one should consider to model the Aggregator decision-making.

Table 3.4: Parameters of calibration

Parameter	Description
Sample of EV drivers	100 EVs randomly selected.
Δt	10 minutes.
T	A year: $365 \times 24 \times 6$.
$tariff_t$	From Monday to Saturday: 0.075 €/kWh (0-8hrs) or 0.15 €/kWh (8-24hrs). Sunday 0.075 €/kWh (0-24hrs) (based on an existing electricity tariff for EVs in Spain).
τ_n	The Aggregator can discharge up to 1 MWh in a year without activating EV warranty; beyond this, a battery degradation cost of 0.08 €/kWh applies ¹ (Sagaria et al., 2025).
$E f^c$	92.25% ² (Apostolaki-Iosifidou et al., 2017)
$E f^d$	77.47% ³ (Apostolaki-Iosifidou et al., 2017)
SOC_n^{Max}	56 kWh for all EVs.
SOC_n^{Min}	10 kWh for all EVs.

Notes: ¹ To estimate compensation for battery degradation due to cycling, we used a compensation amount of €1,599, based on average EV usage and moderate V2G scenarios. This was distributed across the total expected additional V2G cycles (351 cycles) and the cycle size (56 kWh), resulting in: $0.081 \text{ €/kWh} = 1599 / (351 \times 56)$. ² Assuming 40 A current: 1.69% loss from the EV battery, 5.77% from the Power Electronics Unit (PEU), and 0.29% from the EVSE. ³ Assuming 40 A current: 1.91% loss from the EV battery, 19.23% from the PEU, and 1.39% from the EVSE.

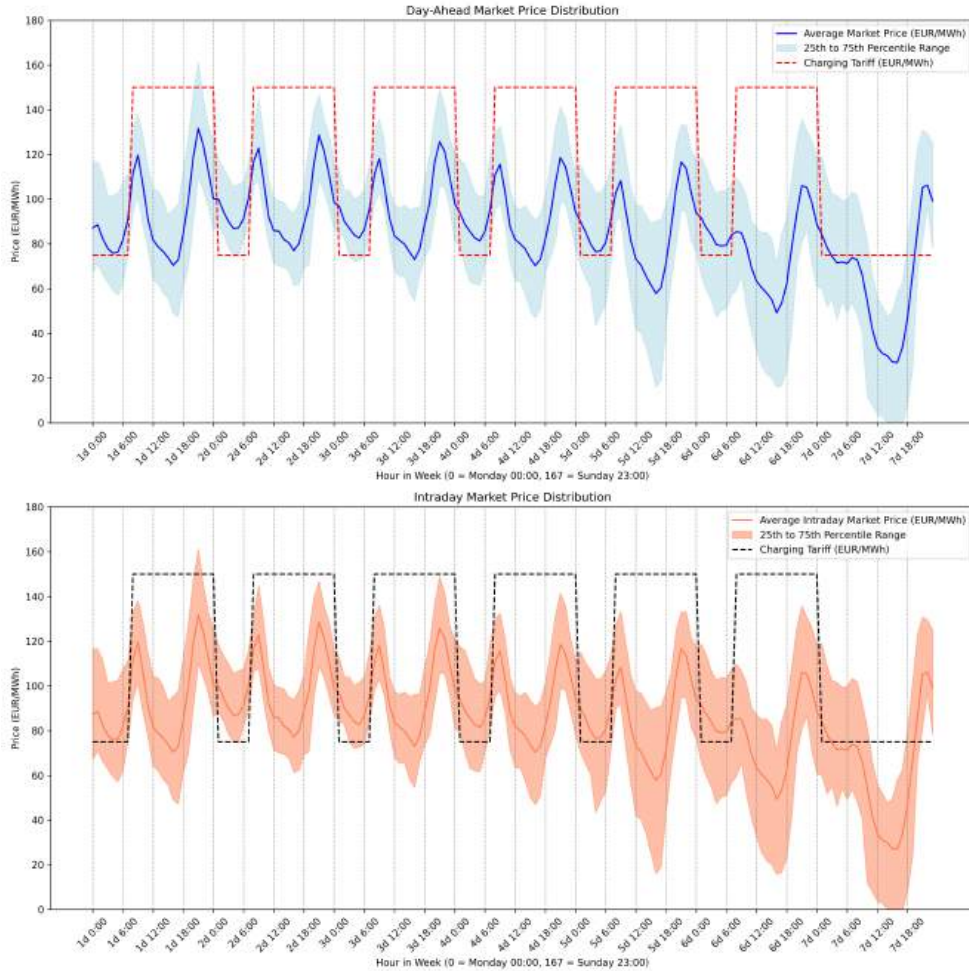
Power market data

While not physically integrated with mainland Spain's wholesale electricity market, Tenerife's electric system is administratively and regulatorily considered part of the national market system. This ensures Tenerife's residents benefit from energy access and pricing similar to those on the mainland. Consequently, an aggregator operating in Tenerife must participate in wholesale electricity markets to buy and sell power.

We consider participation in two primary markets. First, the day-ahead market, ($m = 1$), which closes at 12:00 CET, publishes results by 12:45 CET, and has a minimum lead time of **12 hours** for delivery, covering the range $h_1 = [12 \text{ hrs}, 13 \text{ hrs}, 14 \text{ hrs}, \dots, 36 \text{ hrs}]$. Second, the continuous intraday market, ($m = 2$), which allows bidding 24/7, with delivery possible up to **1 hour before** the start time, $h_2 = 1 \text{ hr}$.

Figure 3.7 illustrates the distribution of prices throughout the year, weekly, from Monday to Sunday. It includes the tariff prices charged to EV owners, highlighting the potential revenue opportunities from charging and discharging.

Figure 3.7: Distribution of power-market prices in Spain, 2023.



Notes: The data used in this figure was obtained from the OMIE (Operador del Mercado Ibérico de Energía) platform. The detailed market prices for the Day-Ahead and Intraday markets in Spain for 2023 were sourced from <https://www.omie.es/es/file-access-list>.

The imbalance prices data for Spain were obtained from ENTSO-E (ENTSO-E, 2024), while the emission factors for the electricity system were sourced from Red Eléctrica de España (REE) (REE, 2024).

Aggregator foreknowledge on EV drivers behavior and power market prices

We assume that the aggregator has access to the full distribution of EV driver behavior, allowing it to observe all potential scenarios for a given EV driver throughout the year, including driving, parking, and being connected at specific times. To illustrate this, consider an example where the aggregator attempts to predict whether an EV will be parked at 10 AM on a Monday. While the aggregator can observe the EV driver's behaviors over the year, it does not know exactly what will happen on that particular Monday. However, if the EV was parked 25 times and not parked 25 times throughout the year, the aggregator can establish a probability of this event occurring.

In the case of power markets, specifically in the day-ahead markets, as previously defined, the aggregator does not know the exact market prices at the time of bidding. However, we assume the aggregator knows the price distribution for a given hour and calendar day over a month. This assumption allows the aggregator to account for seasonal variations in market prices. On the other hand, for the continuous intraday markets, there is no need for such prior knowledge, as the continuous nature of the market allows the aggregator to observe the prices in real time.

3.4.2 . IS scenarios

We began by selecting IS scenarios based on different IOS identified in prior V2G research. Using the IS model framework presented in Section 3.3.1, we expanded the scenario development to include alternative IOIS solutions that we consider promising for the V2G aggregator.

Table 3.5 summarizes these scenarios, relating the variables of mobility that we have defined in our simulation framework and the different dimensions from which we model the information exchange. For simplicity, we will assume in all of these scenarios that there are no errors in the message or the information conveyed by the EV user exchange.

Table 3.5: IOIS scenarios

Id - IO;IS	Channel	Information received				
		$driving_{t,n}$	$evse_{t,n}$	$soc_{t,n}$	$\beta_{t,n}$	$\alpha_{t,n}$
(1)- No industrial standard	None	-	-	-	-	-
(2)- ISO 15118	PLC	-	Yes	Yes	-	-
(3)- ISO 15118 + OEM	PLC + OAC	-	Yes	Yes	-	-
(4)- ISO 15118 + Nav.App	PLC + OAC	Yes	Yes	Yes	-	-
(5)- ISO 15118 + OEM + Nav.App	PLC + OAC	Yes	Yes	Yes	-	-
(6)- ISO 15118 + CPO	PLC	-	Yes	Yes	Yes	-
(7)- ISO 15118 + OEM + CPO + Nav.App	PLC + OAC	-	Yes	Yes	Yes	-
(8)- ISO 15118 + MSP	PLC + OAC	Yes	Yes	Yes	Yes	Yes
(9)- ISO 15118 + MSP (+1day)	PLC + OAC	Yes	Yes (1 day before)	Yes	Yes (1 day before)	Yes (1 day before)

The first scenario examines a case where no industrial standard exists, and the aggregator relies solely on its foreknowledge to perform bidding activities. This scenario is significant as it serves as a benchmark for evaluating the benefits of implementing communication standards.

Scenarios two and three compare the impact of having access to the SOC of the EV via OAC. Scenario two serves as the baseline, assuming the adoption of the front-end industrial standard (ISO 15118-20), where an independent aggregator receives minimal information from the EV whenever it is connected to an EVSE. The data provided include the state of the connection (i.e., $evse_t > 0$) and the EV battery's SOC. This approach represents the prevailing assumption in the literature and will be maintained in subsequent scenarios. The third scenario explores integration with an original equipment manufac-

turer (OEM), such as a car manufacturer. OEMs may access EV telematics or OAC for warranty or maintenance purposes. This scenario assumes the aggregator always receives real-time SOC data and connection status. Previous research by Masuta and Yokoyama (2012) and H. Wang et al. (2015) has proposed this approach.

Scenarios four and five consider the availability of arrival time information. The fourth scenario, our original proposition, involves cooperation with a navigation app. The app provides the aggregator with real-time information about the estimated time of arrival and the expected energy consumption (kWh) for the trip. The fifth scenario combines the third and fourth scenarios, assuming that the navigation system is integrated within the EV's telematics. In this case, the aggregator receives information from both a navigation app and the EV telematics, as previously proposed by (Hou et al., 2017).

Scenarios six and seven incorporate departure time information. The sixth scenario assumes integration between the aggregator and a charging point operator (CPO), which manages the EVSE. Communication occurs via PLC, and the EV driver reports their departure time after completing a charging session. Examples of this approach can be found in Dogan et al. (2018), Erden et al. (2018), Honarmand et al. (2014), Mouli et al. (2017), and Zhong et al. (2014). The seventh scenario builds upon the sixth by also integrating navigation and OEM services. This allows the aggregator to receive both arrival and departure time information, an approach proposed by Iacobucci et al. (2018) in the context of autonomous taxis and robotic vehicle fleets.

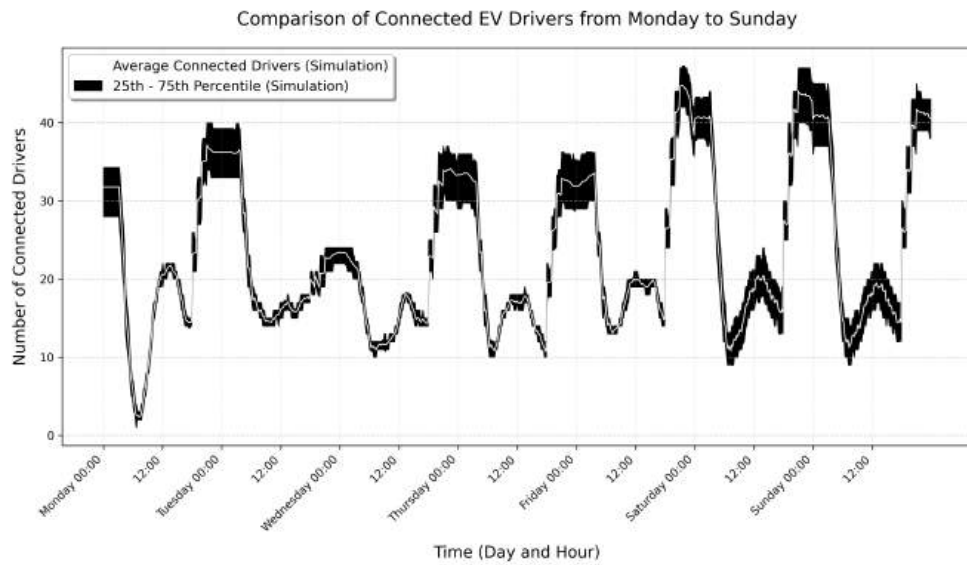
The eighth scenario, another proposed approach, assumes that an independent aggregator cooperates with a mobility service provider (MSP). The MSP oversees the overall mobility behavior of EV owners and can inform the aggregator about the mobility needs of the next trip. Finally, the ninth scenario extends the eighth by assuming that the MSP can access EV owner behavior data one day in advance.

3.4.3 . Simulation findings

Following our validation and verification procedure, we analyze the simulation results by graphically examining the simulation outputs. To simulate the driving behavior throughout a year, we took a sample of 600 EV drivers. Figure 3.8 displays the distribution of the aggregated number of EV drivers connected throughout the year, represented as a weekly distribution, it shows that on average 10% of the EVs are connected during the night, and that at the time where fewer EVs connected, they are around 15 EVs. The dis-

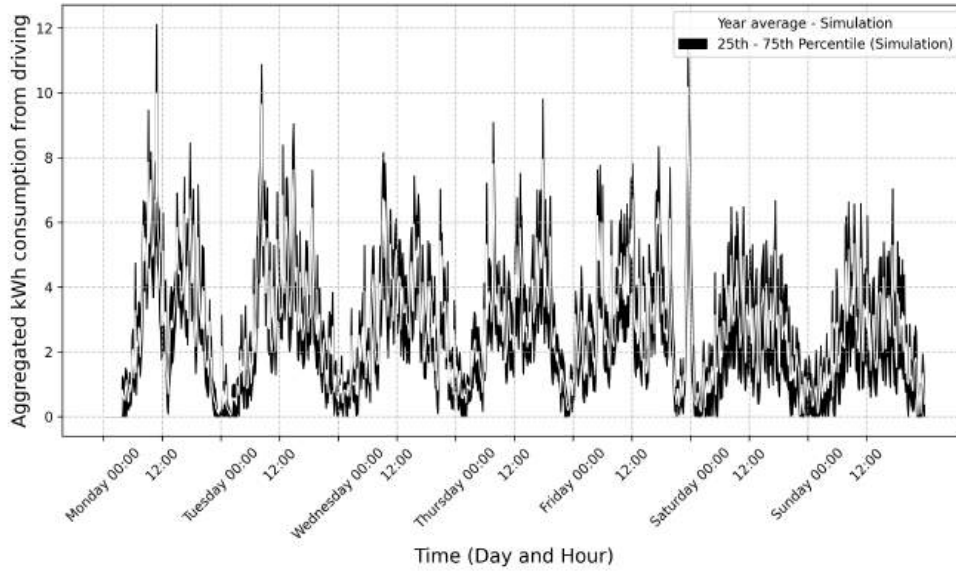
tribution of the amount of EVs satisfies what we expected from the behavior of the simulation. Furthermore, figure 3.9 displays the distribution of the aggregated kWh consumption of EV drivers over the year, similarly represented as a weekly distribution.

Figure 3.8: Distribution of EVs connected



Notes: The black area indicates the 25th and 75th percentiles, showing that the number of connected EV drivers varies across weeks. This variability demonstrates the successful implementation of algorithms introducing uncertainty into the simulation. Moreover, the distribution is wider during weekends, reflecting the assumption that weekend behavior is more random compared to weekdays. The white line, representing the average behavior, indicates that the aggregator possesses foreknowledge of EV driver behavior, an assumption discussed in the previous section.

Figure 3.9: Distribution of kWh consumed from driving.



Notes: As with Figure 3.8, it is evident that the behavior is more random during weekends compared to weekdays. This observation further validates that the algorithms effectively introduce the intended uncertainty to the original behavior modeled for weekdays.

Table 3.6 presents the main statistics of the simulation, which, as of today, has been implemented for 32 EVs.⁴ The first three rows assess whether, during the simulation, the introduction of uncertainty ever results in an EV's SOC dropping below the required level. Additionally, the aggregator's foresight⁵ influences the risk of an EV owner not having sufficient battery after a short charging session following a long one.

The fourth row presents the average percentage of time that EVs are connected, along with the standard deviation. The results indicate significant variation in connection times, with an average of 27%, ranging from as high as 35% to as low as 19%. These relatively low connection rates align with the findings of Rojano-Padrón et al. (2023), whose simulation focused on EV owners relying solely on public charging infrastructure.

The fifth and sixth rows represent the total power charged and discharged by an EV in each scenario. The values are consistent, with the kms reported on the initial data and the average energy efficiency; overall, as it is an island,

⁴We are currently simulating additional drivers to improve the results.

⁵It is important to note that our foresight optimizes only two charging sessions, the current and the next.

it is not surprising that the MWh consumed in a year is on the vicinities of 1.6 MWh, when the rule of thumb of an EV most of the times is for 2 MWh. From a scenario perspective, the energy charge and discharge increase as the aggregator has more information and typically can charge and discharge more times than the EV. However, it is remarkable that in scenario 1, when the EV has no additional data, it seems to charge and discharge more often than whenever it has partial information. We interpret such a result as if the Aggregator is overestimating most of the parameters in the simulation; at the same time, we show that the standard deviation also increases by 0.3 points.

The seventh to tenth rows represent the imbalances in each scenario. While the last six rows shows the average error between the expected value of a parameter and the real value of the parameter, for each of the scenarios. The results are consistent with what would expect, in terms of the information that they received in each scenario.

Table 3.6: Summary of results by Scenario

Scenario	1	2	3	4	5	6	7	8	9
Total Drivers	32	32	32	32	32	32	32	32	32
Filtered (SOC<0)	4	7	7	6	6	7	7	7	6
Final	28	25	25	26	26	25	25	25	26
% Connection Time	26.99 (8.67)	26.99 (8.67)	26.99 (8.67)	26.99 (8.67)	26.99 (8.67)	26.99 (8.67)	26.99 (8.67)	26.99 (8.67)	26.99 (8.67)
MWh Charged	2.24 (1.1)	1.86 (0.88)	1.86 (0.88)	1.84 (0.86)	1.84 (0.86)	2.01 (0.81)	1.97 (0.8)	1.97 (0.8)	2.37 (0.9)
MWh Discharged	0.61 (0.61)	0.36 (0.37)	0.36 (0.37)	0.34 (0.37)	0.34 (0.37)	0.46 (0.34)	0.44 (0.32)	0.44 (0.32)	0.72 (0.43)
V1G Pos. Imb. (kWh)	1112.59 (590.31)	259.27 (127.7)	259.35 (127.65)	150.95 (45.86)	150.95 (45.88)	142.88 (40.92)	143.18 (39.72)	142.39 (37.79)	12.67 (21.11)
V1G Neg. Imb. (kWh)	393.56 (278.65)	1031.27 (507.13)	1031.27 (507.13)	1047.31 (504.19)	1047.28 (504.18)	1051.83 (530.4)	1173.81 (544.1)	1098.6 (456.83)	892.31 (378.37)
V2G Neg. Imb. (kWh)	65.37 (26.51)	35.73 (20.07)	35.73 (20.07)	28.39 (16.55)	28.39 (16.56)	44.66 (46.2)	38.53 (46.19)	32.03 (30.14)	3.33 (4.68)
Error SOC	-6.1 (7.98)	0.72 (0.78)	0.72 (0.78)	2.08 (0.71)	2.07 (0.71)	1.16 (0.82)	2.14 (0.79)	1.83 (0.51)	2.45 (0.35)
Error Φ Discharge	-12.08 (14.72)	2.77 (9.55)	2.77 (9.55)	3.31 (9.37)	3.31 (9.38)	-14.57 (1.99)	-14.5 (1.96)	-9.73 (0.17)	-9.79 (0.11)
Error Φ Charge	-11.4 (9.1)	-36.17 (2.96)	-36.17 (2.96)	-38.96 (2.76)	-38.95 (2.76)	-1.48 (0.58)	-1.97 (0.43)	-1.9 (0.38)	-2.07 (0.28)
Error Δ Needs	-0.25 (1.05)	0.9 (0.25)	0.9 (0.25)	0.87 (0.22)	0.87 (0.22)	1.08 (0.16)	1.08 (0.15)	1.06 (0.13)	1.05 (0.13)
Error β	24.58 (11.75)	23.46 (11.91)	23.46 (11.91)	23.46 (11.91)	23.46 (11.91)	0.1 (0.32)	0.1 (0.32)	0.1 (0.32)	0.1 (0.32)
Error α	0.84 (0.64)	1.24 (0.71)	1.24 (0.71)	1.24 (0.71)	1.24 (0.71)	4.67 (2.11)	4.67 (2.11)	0.0 (0.0)	0.0 (0.0)

Notes: The table reports the average values without parentheses and the standard deviation within parentheses.

Figure 3.10, 3.11, 3.12, and 3.13, show in a boxplot graph the distribution of our main results. Furthermore, we have included calculating the percentage change in the median of each scenario relative to Scenario 2 (ISO-15118).

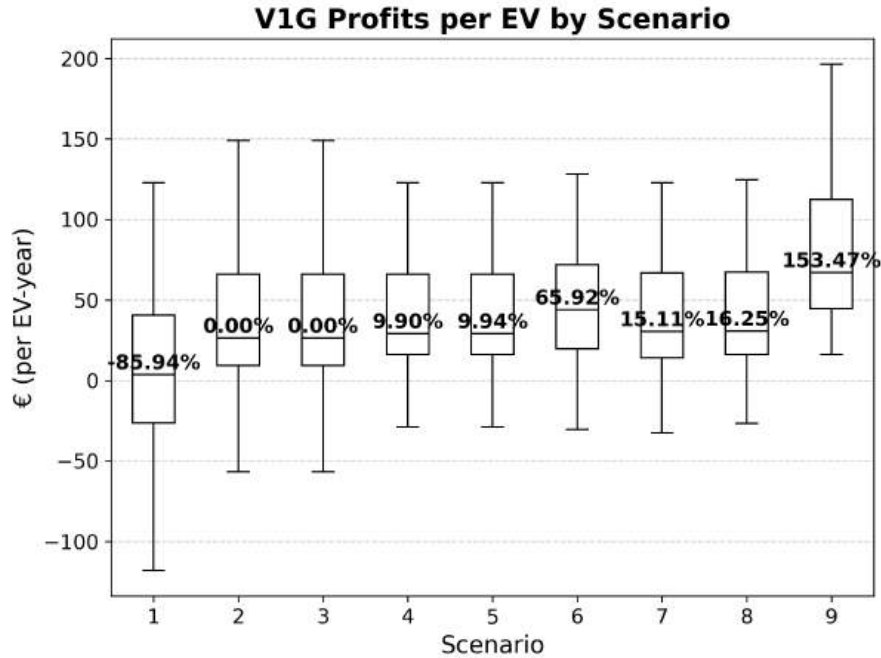
We recall that V1G profits arise from selling electricity to the EV owner at the retail price and purchasing it at the market price, minus the penalties paid from imbalances. The key observation in Figure 3.10 is the significant variance in results, with nearly all scenarios showing cases where the Aggregator could incur losses from signing an EV owner while also highlighting substantial gains from other cases. This underscores the importance of timing between the EV owner's behavior and the market's charging prices.

Two additional important points are worth noting: first, there is an 85% difference in median profits between the EV owner and the scenario with ISO 15118, emphasizing the importance of having a standardized protocol. Among the various scenarios, increasing the level of information or adding SOC data over the air shows no significant effect, whereas including arrival time leads to a 9% increase in profits in scenarios 5 and 6.

The most striking finding is observed in Scenario 6 (CPO scenario, where the aggregator has information on the time of departure and ISO 15118 but lacks other data), where the median profit significantly increases compared to the other scenarios, while the overall distribution remains similar to that of Scenarios 7 and 8, where the aggregator has more information. One could expect the median to also be higher in these scenarios. This could indicate that in Scenario 6, the aggregator is overestimating driving needs and charging more, which might be influenced by having more data on the EV's energy consumption.

Finally, adding an extra day of mobility data results in a nearly 150% increase in profits. This substantial gain can be attributed to the aggregator's ability to leverage both day-ahead and intraday market opportunities better.

Figure 3.10: Distribution of V1G profits per Scenario.



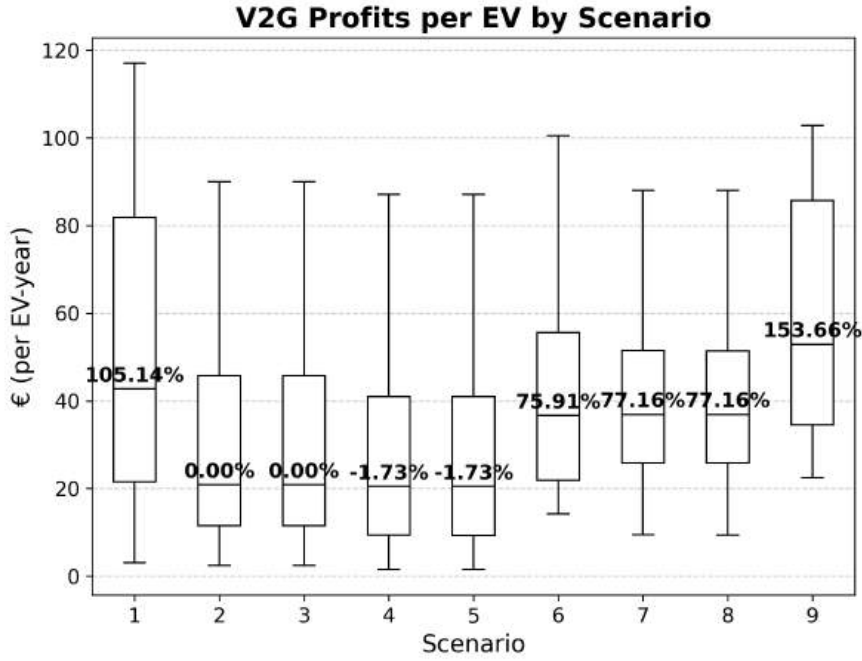
Scenarios:(1)- No industrial standard, (2)- ISO 15118, (3)- ISO 15118 + OEM, (4)- ISO 15118 + Nav.App, (5)- ISO 15118 + OEM + Nav.App, (6)- ISO 15118 + CPO, (7)- ISO 15118 + OEM + CPO + Nav.App, (8)- ISO 15118 + MSP, (9)- ISO 15118 + MSP (+1day)

V2G profits arise from the aggregator selling power to the electricity system, with up to 1 MWh being discharged without compensating the EV owner, while any additional discharge incurs battery degradation costs. A key observation in Figure 3.11 is that, unlike V1G profits, V2G does not have direct costs below the 1 MWh threshold. However, there are indirect costs, as the EV must later recharge to compensate for the discharged energy, which may occur during periods of high electricity prices. Consequently, in the scenario without information sharing (No IS), the aggregator tends to overestimate the available energy and oversell power, potentially leading to costly recharging—an effect evident in Figure 3.12.

Furthermore, incorporating arrival time information, as in Scenarios 4 and 5, appears to reduce variability in V2G profits. This suggests that when the aggregator lacks mobility data, it overestimates available energy, limiting opportunities for discharging. However, V2G profits are significantly influenced by departure time information, showing an increase of approximately 75%.

Moreover, when mobility data extends by an additional day, profits nearly double, highlighting the value of improved forecasting in optimizing charging and discharging strategies.

Figure 3.11: Distribution of V2G profits per Scenario.



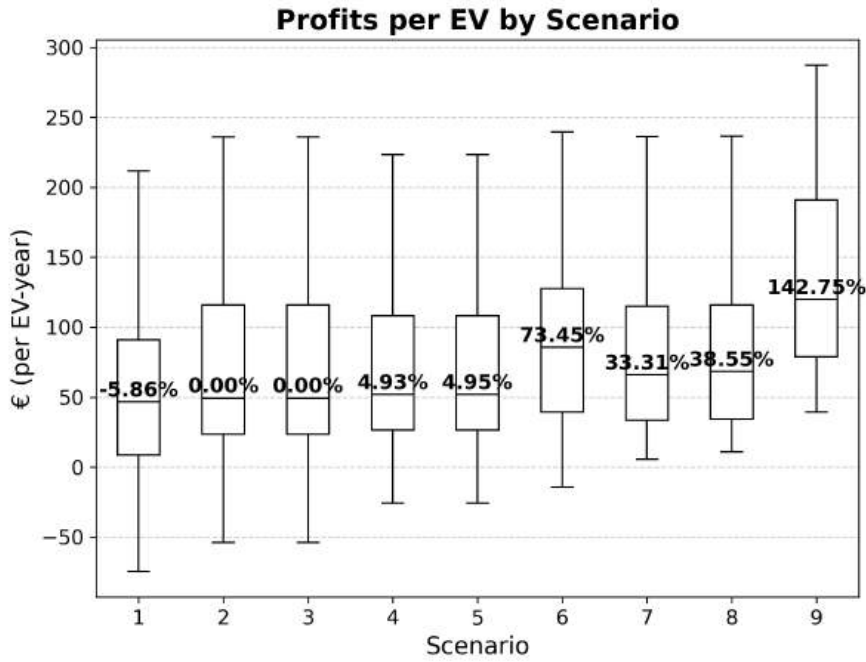
Scenarios:(1)- No industrial standard, (2)- ISO 15118, (3)- ISO 15118 + OEM, (4)- ISO 15118 + Nav.App, (5)- ISO 15118 + OEM + Nav.App, (6)- ISO 15118 + CPO, (7)- ISO 15118 + OEM + CPO + Nav.App, (8)- ISO 15118 + MSP, (9)- ISO 15118 + MSP (+1day)

Figure 3.12 presents the distribution of annual profits that the Aggregator would gain from each EV owner, combining both V1G and V2G profits. The median profit ranges from €50 in Scenario 1 to €125 in the most favorable case. However, from the perspective of the aggregator's business model, analyzing the differences across distributions provides more valuable insights.

Notably, in Scenario 2 (ISO 15118), a significant portion of the EV user distribution remains above the €20 profit mark, with fewer instances of substantial losses. Furthermore, the figure highlights that the anomalous median profit observed in Scenario 6 for V1G (Figure 3.10) remains elevated. However, in Scenario 6, the variance of the distribution is also noticeably higher compared to Scenarios 7 and 8, suggesting that they must be some EV drivers

in this scenario that might have better performance with this scenarios, but many others which do not.

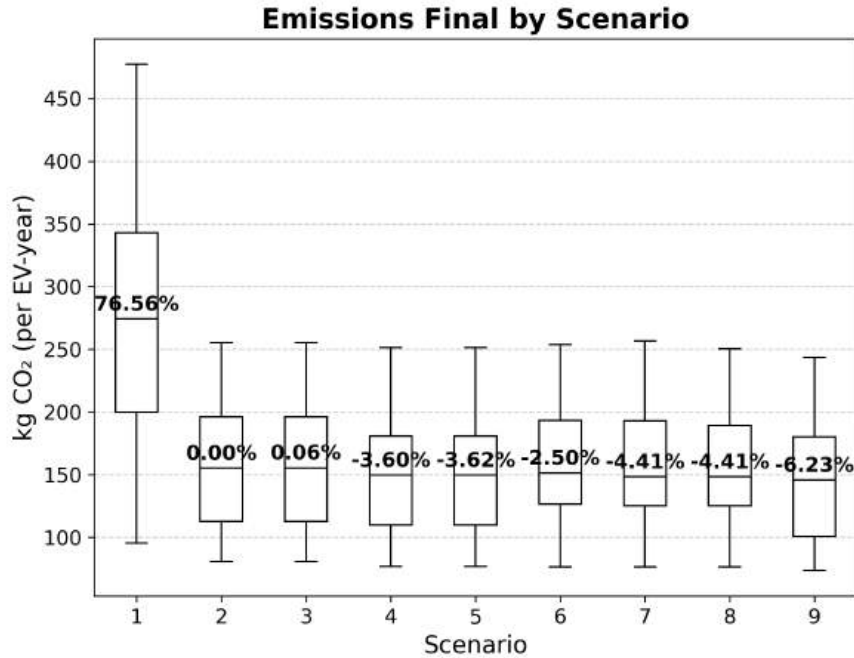
Figure 3.12: Distribution of total profits per Scenario.



Scenarios: (1)- No industrial standard, (2)- ISO 15118, (3)- ISO 15118 + OEM, (4)- ISO 15118 + Nav.App, (5)- ISO 15118 + OEM + Nav.App, (6)- ISO 15118 + CPO, (7)- ISO 15118 + OEM + CPO + Nav.App, (8)- ISO 15118 + MSP, (9)- ISO 15118 + MSP (+1day)

Finally, Figure 3.13 serves as a useful proxy for system imbalances, as these are reflected in the additional emissions resulting from dispatching in each scenario. It is important to recall that the aggregator's optimization is driven by economic objectives rather than environmental considerations. The results show that while the difference in profits between Scenarios 1 and 2 was not particularly significant, the disparity in emissions is much more pronounced. This can be attributed to the imbalances caused by the lack of information and the relatively low cost of these imbalances. Furthermore, as expected, greater information availability leads to lower GHG emissions from EVs. However, the differences between having access to information one day ahead appear to be less significant, as the emission factor remains constant regardless of whether the aggregator bids in the day-ahead or intraday market.

Figure 3.13: Distribution of emissions per Scenario.



Scenarios:(1)- No industrial standard, (2)- ISO 15118, (3)- ISO 15118 + OEM, (4)- ISO 15118 + Nav.App, (5)- ISO 15118 + OEM + Nav.App, (6)- ISO 15118 + CPO, (7)- ISO 15118 + OEM + CPO + Nav.App, (8)- ISO 15118 + MSP, (9)- ISO 15118 + MSP (+1day)

3.5 . Discussion

Given the unique constraints of electricity markets, we focus on evaluating V2G aggregator IS under the hypothesis that surpassing the normative IOIS could enhance profitability and environmental impact. We propose a comprehensive framework for V2G aggregators designed to assess the value of information regarding its timeliness and completeness. This framework is applied in a case study to evaluate how different IOIS configurations could enable a V2G aggregator to boost profits through efficient EV integration and reduce GHG emissions. Our framework and findings contribute to two key areas: first, advancing the research agenda for Green IS, and second, providing actionable insights for practitioners looking to optimize V2G operations for both financial and environmental benefits.

3.5.1 . Contribution to Green IS research

From the outset, our goal has been to conduct IS research with the purpose of specifically examining how IS can contribute to the environmental and economic sustainability of the energy and mobility sectors (Ketter et al., 2018; Ketter et al., 2023; Watson et al., 2010). However, as we explored the available methods for this purpose, we observed that, despite the literature indicating that the value of IS drives decisions regarding the formation or investment in new types of IOIS (Cao et al., 2022; Chwelos et al., 2001; Klein & Rai, 2009; Kumar & Van Dissel, 1996; Salge et al., 2015), most studies have derived this value *ex-post* (Dhillon & Torkzadeh, 2006; Nicolaou & McKnight, 2006; Salge et al., 2015). This situation presents a significant challenge from the Green IS perspective: on the one hand, we are tasked with advancing new, potentially sustainable business models; on the other, we are constrained in evaluating these alternatives, as most methods are *ex-post*.

In most cases, detailed mobility data is rarely publicly available. When it is, it often suffers from a trade-off between detail and time length. For instance, government statistics may provide average driving behavior for a region over a year, offering a broad overview but lacking the granularity needed to account for individual uncertainties. On the other hand, specialized surveys may capture high-detail information, such as precise driving routines over a week. However, these short-term datasets must reflect long-term variability, making it difficult to account for the uncertainties relevant to an aggregator. As a result, the lack of detailed, long-term mobility data poses significant limitations for accurately modeling EV owner behavior. Therefore, in the following subsection, we review how simulations can serve as a viable alternative to model uncertain EV owner behavior to evaluate Aggregators IS.

The framework that we propose in this paper draws from prior literature that employs a normative approach to evaluate IS value (Feltham & Demski, 1970; Mock, 1969) and advances Green IS by integrating uncertainty simulation tools from resiliency engineering (Oberkampff et al., 2002, 2004) with stochastic programming techniques (Ayón et al., 2017; Birge & Louveaux, 2011; Liu et al., 2015). By applying these approaches, we can simulate an aggregator that updates its knowledge of EV mobility states through an information flow that can be modeled in terms of information timeliness and completeness (DeLone & McLean, 2003), without relying on extensive nor detailed datasets of mobility. Such datasets are often difficult to obtain at the level of detail required for this type of analysis. Furthermore, this framework allows us to control the feedback loops that influence the aggregator's decisions regarding available energy on the EV. This level of control would be challenging to replicate in an empirical evaluation, given that it would require

testing simultaneously for several IS on the same case study.

Future research could build on our framework and extend it to other smart grid applications, addressing new design challenges in Green IS (Watson et al., 2010). In particular, managers often face critical investment decisions in industrial environments where dominant solutions may be favored, potentially overlooking more effective alternatives. This challenge is especially relevant in cases where a consensus exists around a specific type of IOIS for enabling technology despite multiple competing alternatives. For instance, in demand response programs or car-sharing fleets, various IS architectures have been proposed independently; however, systematically comparing them could reveal which creates the most value and leads to superior economic and environmental outcomes. By leveraging our approach, future studies could provide a structured evaluation of these alternatives, supporting decision-making that aligns profitability with sustainability goals.

3.5.2 . Contributions to practitioners

From a business perspective, the viability of V1G and V2G aggregation hinges on aligning charging strategies with market price fluctuations while mitigating exposure to imbalance penalties. In the complex landscape of V2G deployment, practitioners often face a fragmented array of IS options, with the impact of information considered neutral or underestimated, assuming that the aggregator has certainty. Our findings challenge this assumption, demonstrating that although standardized industry protocols—such as power-line communication—capture a large share of the IS value, increasing information completeness can substantially enhance profitability.

An aggregator might ask: What IS creates the most value for delivering V2G services? A review of the V2G literature offers multiple answers. As highlighted in our introduction, managers exploring their role and opportunities in V2G services will encounter diverse perspectives on how IS can support aggregators in predicting EV users' mobility. However, while some papers propose that aggregators could directly collect all necessary information from EV users, most assume collaboration among multiple entities, such as "aggregator–charging point operators" (Mouli et al., 2017) or "aggregator–fleet operator–charging operator partnerships" (Jindal et al., 2019).

Despite these discussions, research has yet to systematically analyze the value contributed by each actor within the same research framework. This represents a critical gap, as understanding the value of each actor's contribution could prove essential in decision-making processes where actors consider

whether to collaborate to provide V2G services. Without this knowledge, V2G services may likely not scale. Our method allows us to put value into information. Indeed, our results show that increasing the information on departure time and future mobility needs can further increase the potential gains from day-ahead market fluctuations, with an estimated profitability boost of up to +150% while reducing -6% CO₂ emissions compared to only complying with the industrial standard ISO 15-118.

This finding underscores a critical business model challenge: incentivizing EV users to share mobility data. Greater information completeness allows aggregators to more effectively align charging strategies with real-time market price fluctuations, thereby maximizing value creation. In particular, the departure time emerges as the most valuable piece of data, as it directly influences the flexibility available for cost-minimizing charging strategies. Therefore, expanding the range of EV owner commitments

Economics: From an economic standpoint, the market for EV owner attention and information is highly competitive. The most promising business models for monetizing mobility data will likely revolve around tailored, data-driven approaches that create mutually beneficial outcomes for both aggregators and EV owners. Practitioners could focus on developing models that offer incentives aligned with market conditions, fostering participation and ensuring profitability while avoiding exposure to penalties.

Behavioral: From a behavioral perspective, understanding how to engage and retain EV owners' participation is pivotal. The aggregation process can be enhanced by improving insights into EV owner behavior, particularly their charging preferences, driving routines, and willingness to share mobility data. Aggregators need to leverage behavioral analytics to predict and influence user behavior, ensuring higher engagement rates and better alignment with optimal charging strategies. Tailoring communications and offering incentives for data sharing are strategies that will likely increase user involvement and, consequently, improve overall profitability.

3.6 . Conclusions

This study has explored the role of Green IS in integrating EVs with electricity systems through V2G services. By leveraging a simulation framework that introduces uncertainty from resilience engineering, we have demonstrated how different IOIS configurations impact the profitability and GHG reduction potential of a V2G aggregator operating in power markets. Our

results show that current industry standards while providing a baseline for interoperability, may not fully capture the potential value of information exchange, leading to suboptimal decision-making and missed economic and environmental opportunities.

From a theoretical perspective, this research contributes to the Green IS literature by extending the focus from intra-organizational IS to inter-organizational information sharing, highlighting the necessity of considering IOIS beyond existing communication protocols. Our approach also underscores the importance of simulation-based ex-ante evaluation methods in assessing emerging technologies and business models, particularly when empirical data is scarce.

Practically, our findings suggest that aggregators could significantly enhance their profitability—potentially doubling it—by integrating more detailed mobility information, such as future travel needs and departure times. This insight can inform policy decisions and industry practices, encouraging the development of more advanced IOIS that foster collaboration rather than creating data silos.

However, our study is not without limitations. While we have focused on IS economic and environmental value, further work is needed to explore the economics of information competition for Aggregators, and the behavioral aspects of EV owners relationship with Aggregator IS. Overall, this study provides a foundation for future research on IOIS in V2G systems, emphasizing the value of enhanced information exchange in facilitating sustainable mobility and electricity system integration. We encourage further exploration of alternative IOIS models and their impact on broader energy and mobility ecosystems.

3.7 . References

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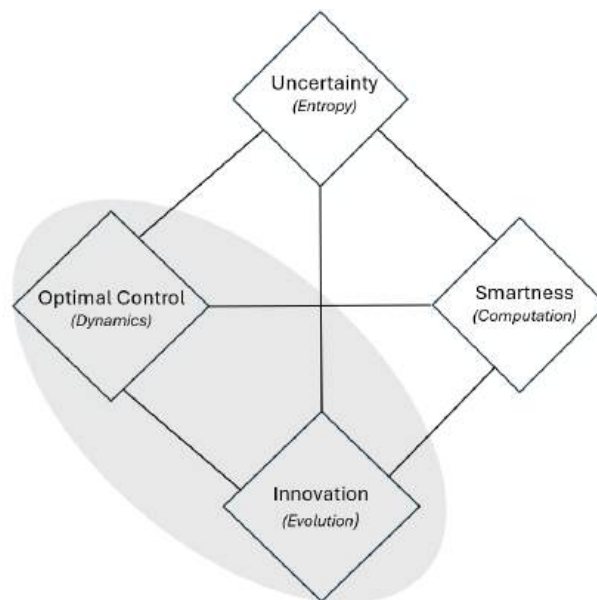
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4 - The economic governance of EV owners in smart grids.

Authorship: This paper was co-authored by Yannick Perez and Jan Lepoutre (ESSEC Business School).¹

Figure 4.1: The four pillars of complexity applied to Chapter 4. Adapted from (Krakauer, 2024)



The gray area represents the key pillars highlighted in this work: Uncertainty and Innovation. The former is addressed in the paper through the challenges faced by regulators in increasing the share of electricity production from renewable sources. These challenges introduce new regulatory complexities, as renewable energy makes the electricity system and markets more intricate. Simultaneously, this issue is also tied to innovation, which is shaped by the historical context of the regulators themselves, who are tasked with regulating through a set of tools and objectives. In this paper, we argue that regulatory mandates serve as a form of information that shapes the perspective through which regulators approach new technologies.

¹The original title of the paper is: *The economic governance of residential prosumers in smart grids*. This title has been adapted to fit the structure of the dissertation in a coherent manner.

Abstract: As smart grids integrate more decentralized energy resources (DERs), their success increasingly depends on managing residential prosumers, households that consume and produce electricity through assets such as electric vehicles and rooftop solar panels. However, integrating prosumers requires addressing privacy concerns on prosumers' data and providing the right economic incentives. This paper examines the different organization structures proposed to integrate prosumers through a unifying framework based on transaction cost theory (TCT), which we use to characterize the economic governance of different modes of organization. By distinguishing between monitoring and switching costs, we identify four key governance models and analyze their impact on prosumer integration (transaction) costs. We apply our framework to business model archetypes in the literature and perform a comparative study of business model implementation in France, the United Kingdom, and California. Finally, our framework informs important policy discussions on Transparency, Standardization, Automation, and Market Power to advance residential prosumer integration.

4.1 . 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 stand out as 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 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. To validate our framework, we apply it to a comparative case study of business models in California, the United Kingdom, and France.

This framework offers two important contributions. First, it provides theoretical insights into how different organizational structures shape prosumer integration and the risk of opportunism in smart grids. Second, it serves as a comparative tool for assessing the implications of alternative systems. More importantly, our framework provides a theoretical foundation for policy discussions under-explored in research and regulatory agendas. Specifically, we highlight four critical factors that might drive the emergence of a particular type of economic governance: Transparency, standardization, automation, and market power.

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.

4.2 . 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 applied to study organizational phenomena in electricity systems.

4.2.1 . 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 high-powered incentives from competition. However, as the transaction increases in complexity, requiring specific investments or risks, transaction costs might increase due to monitoring costs or sunk investments, thus potentially shifting from market organizations into vertically integrated arrangements, such as firms, that can align incentives by improving coordination under unified ownership.

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).

Behavioral assumptions

There are mainly two assumptions, 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 fully and rationally. Thus, 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).

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).

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).

4.2.2 . 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) (Finnon & 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.

4.3 . 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. We propose and characterize governance models that 'economize' on transaction costs using these dimensions.

4.3.1 . 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 introduces 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.

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 be-

comes 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.

Control arrangements

Control arrangements define how prosumers' DERs are managed. Through direct or indirect control², 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.

²In 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.

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.

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 understand the implications of their choices fully. 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 4.1 summarizes the main transaction costs previously mentioned.

4.3.2 . 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 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.

Table 4.1: Comparison of Transaction Costs in Non-Smart Grids and Smart Grids

Transaction Type	Cost	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.

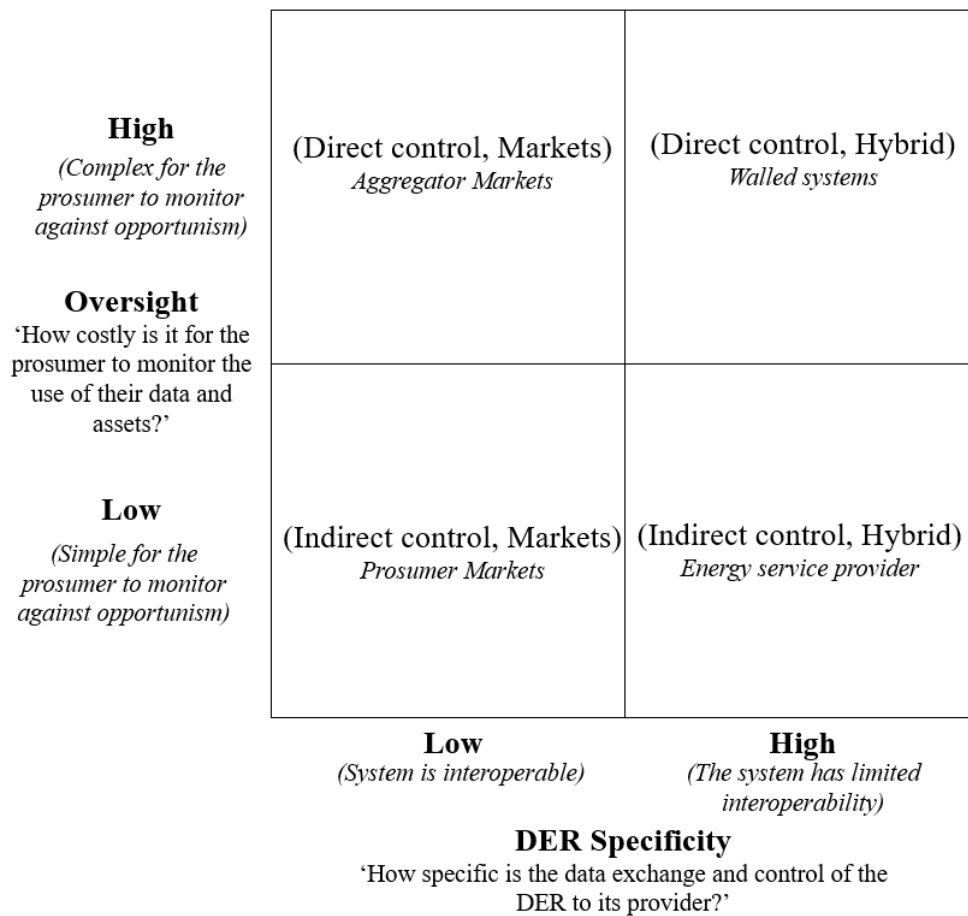
Figure 4.2 presents our framework as a two-by-two matrix, distinguishing between two levels of transaction costs for each dimension. These magnitudes are represented relative to high or low transaction costs. For instance, high DER specificity increases switching costs by making it more difficult and 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 4.2, 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.

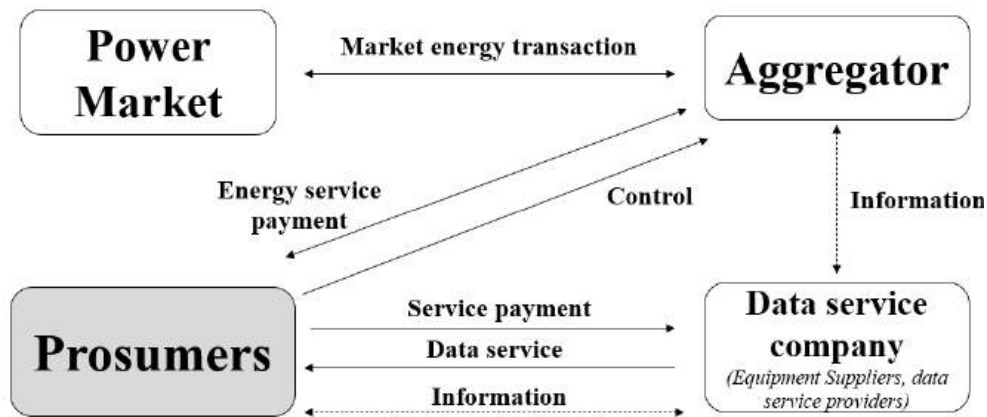
Figure 4.2: Prosumers framework for economic governance



Aggregator Markets

In Figure 4.3, 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 4.3: Transactions of Aggregator Markets

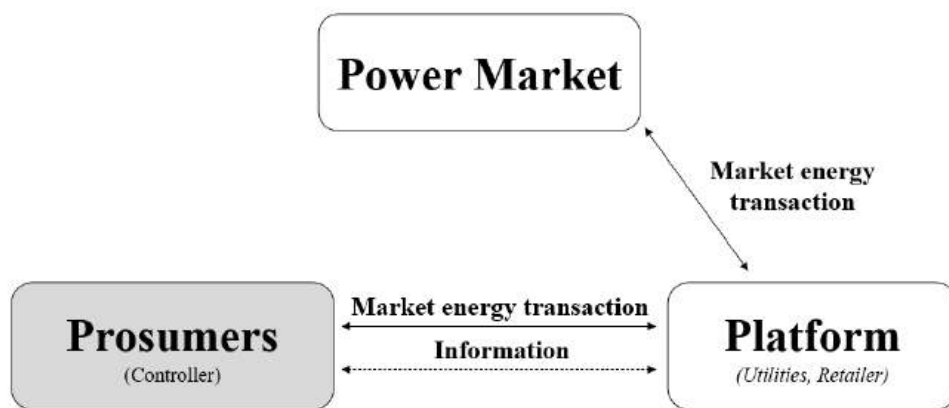


Prosumer Markets

Figure 4.4 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.

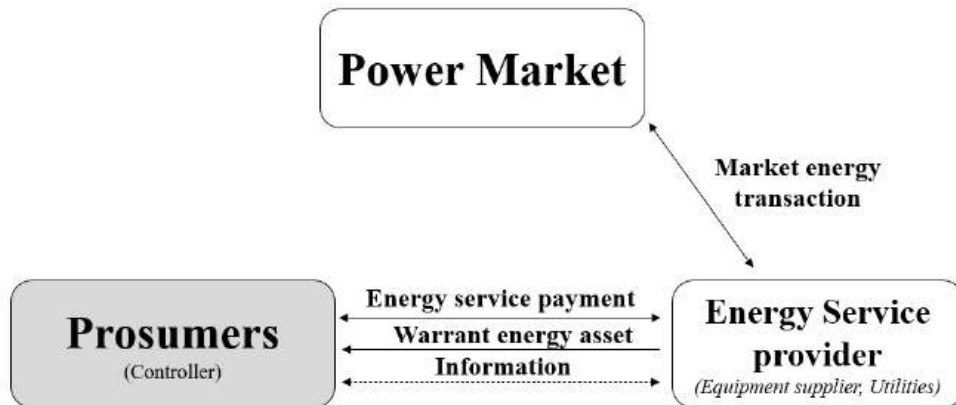
Figure 4.4: Transactions of Prosumer Markets



Energy service providers

In Figure 4.5, 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.

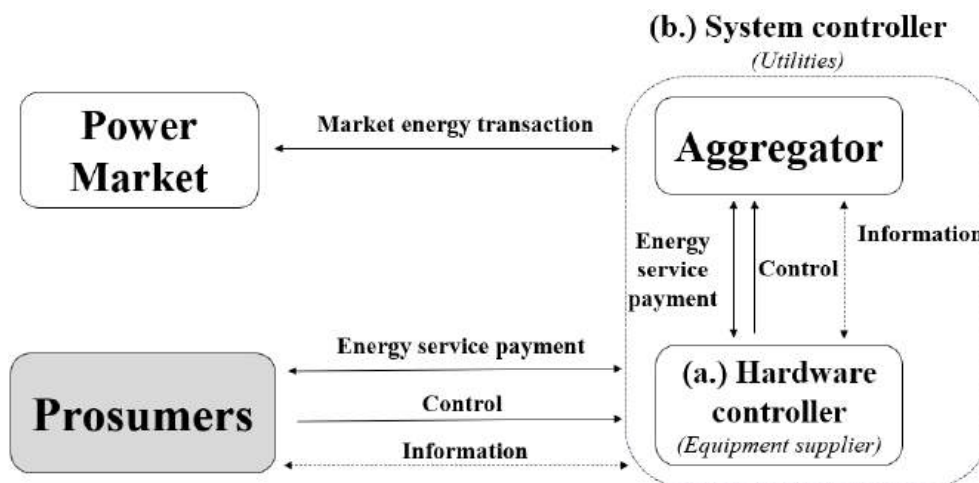
Figure 4.5: Transactions of Energy service providers



Walled Systems

In Figure 4.6, 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 4.6: Transactions of Walled Systems

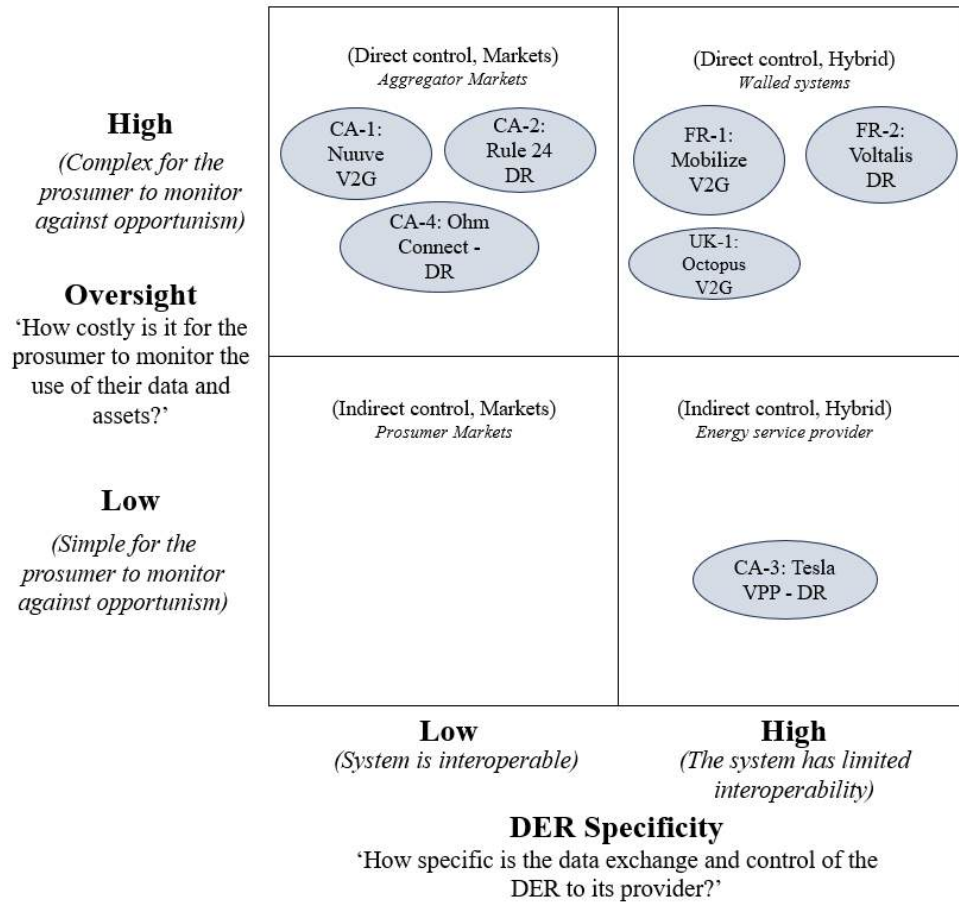


4.4 . A comparative analysis using the framework

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

Figure 4.7, compares the five business model archetypes and eight existing business models we reviewed in this section in the conceptual framework we proposed in the previous section. In what follows, we provide details on how we arrive at such a classification.

Figure 4.7: Comparison of business models



4.4.1 . Strategy for comparative analysis

To extend our framework beyond theoretical archetypes, we examine business models for integrating prosumers in France, the United Kingdom, and California. These regions were selected for their advanced efforts in deploying DERs and their 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.

4.4.2 . 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 California Privacy Protection Agency 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 request 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 inter-connection 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 Leapfrog 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.

4.4.3 . 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.

4.4.4 . 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.

4.5 . Discussions

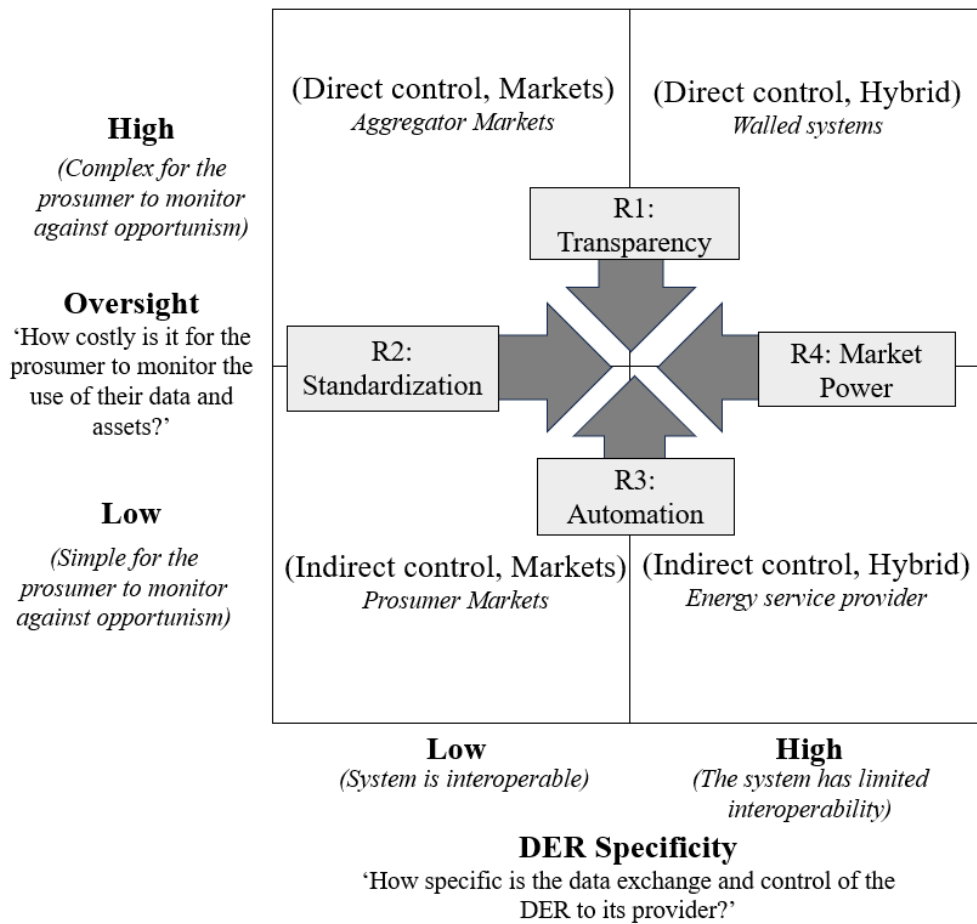
Our research was motivated by prior studies that proposed various organizational structures for integrating prosumers into smart grids. However, no unified perspective currently clarifies whether prosumers should rely on an intermediary, engage directly in the market, or whether the choice of intermediary is inconsequential. This lack of a coherent framework creates a significant gap in the literature, especially as smart grids are at an early stage of development. Therefore, we aim to close this gap to guide managers and regulators into developing new mechanisms to integrate residential prosumers in smart grids that might consider prosumer privacy concerns, economic incentives, and fairness in value redistribution.

To address this gap, we apply the lens of TCT to analyze the transaction costs prosumers may encounter. We characterize the transaction costs associated with theoretical and existing business models by developing a conceptual framework. Our analysis, illustrated in Figure 4.7, highlights two organizational characteristics that help differentiate the type of economic governance that might be exposed to each prosumer by differentiating organizations by (i) the distinction between direct and indirect control, which relates to oversight costs, and (ii) the role of markets and hybrid forms, which help differentiate switching costs.

This framework offers two important contributions. First, it provides theoretical insights into how different organizational structures shape prosumer integration and the risk of opportunism. 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. Second, it serves as a comparative tool for assessing the implications of alternative systems. More importantly, our findings encourage a deeper reflection on how organizational structures and institutional contexts influence the efficiency and sustainability of consumer participation in smart grids.

In Figure 4.8, 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 4.8: Research questions



4.5.1 . 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.

4.5.2 . 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.

4.5.3 . 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.

4.5.4 . 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.

4.6 . Conclusions

This study contributes to the ongoing research on smart grids by examining residential prosumer integration and developing a conceptual framework based on TCT. By analyzing monitoring and switching costs, we identify four governance models that shape prosumer participation. Through comparative case studies, we demonstrate how our framework provides valuable theoretical insights into the trade-offs inherent in different governance structures, particularly control mechanisms and interoperability. Future research should investigate how evolving regulatory frameworks, technological advancements, and market structures influence consumer participation. Additionally, exploring the role of transparency, standardization, automation, and market power can provide deeper insights into optimizing governance models for residential prosumer integration. Finally, 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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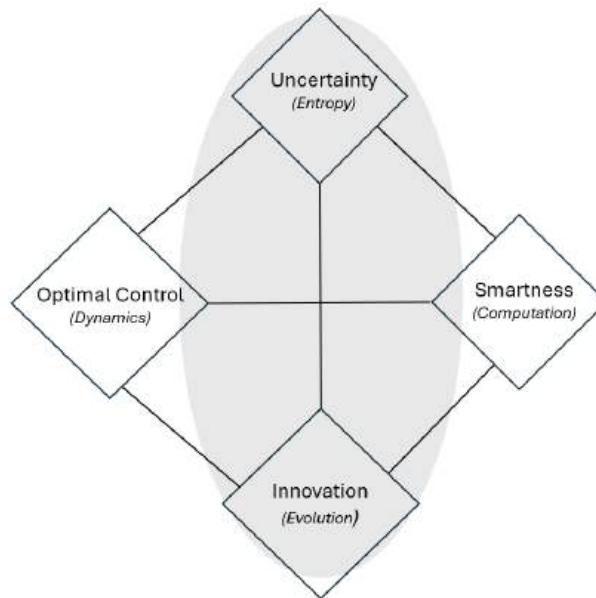
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5 - Tensions in the regulatory regimes of electricity systems.

Authorship: This paper was co-authored by Carlos Gonzalez (first author) and Eric Brousseau, both from the University Paris-Dauphine (PSL), Governance and Regulation Chair.¹

Figure 5.1: The four pillars of complexity applied to Chapter 5. Adapted from (Krakauer, 2024)



The gray area represents the key pillars highlighted in this work: Uncertainty and Innovation. The former is addressed in the paper through the challenges faced by regulators in increasing the share of electricity production from renewable sources. These challenges introduce new regulatory complexities, as renewable energy makes the electricity system and markets more intricate. Simultaneously, this issue is also tied to innovation, which is shaped by the historical context of the regulators themselves, who are tasked with regulating through a set of tools and objectives. In this paper, we argue that regulatory mandates serve as a form of information that shapes the perspective through which regulators approach new technologies.

¹The original title of the paper is: *Impact of Regulatory Governance Regimes on Renewable Energies: An Empirical Analysis of European National Regulatory Agencies from 2013 to 2018*. This title has been adapted to fit the structure of the dissertation in a coherent manner.

Abstract: This chapter explores how path-dependence creates tensions in the economic logic governing electricity systems, specifically in the context of National Regulatory Agencies (NRAs) and their role in supporting renewable energy transitions. We examine the liberalization reforms in Europe and the mandates assigned to NRAs by governments, which aim to maintain fair competition in electricity markets, incentivize investment, reduce consumer bills, and enhance the efficiency of electric networks. However, in recent years, decarbonization has gained widespread political support, and the growing share of renewable energy in many European countries has begun to conflict with the objectives of liberalization. We hypothesize that independent NRAs, in their alignment with liberalization goals, may inadvertently slow the adoption of renewable energies. To test this hypothesis, we conduct a panel data analysis of 24 EU countries between 2013 and 2018, assessing the impact of NRA governance on the share of renewable energy in total energy consumption. Our findings reveal a significant, negative relationship between NRA independence and the share of renewable energy generation, highlighting the challenges of balancing liberalization objectives with the push for decarbonization.

5.1 . Introduction

In electric systems, energy policy plays a crucial role in promoting the adoption of renewable energies. Most investments in renewable energy power plants rely significantly on policy backing, particularly financial support (e.g., tax subsidies, feed-in tariffs, purchase obligations, and long-term contracts), to foster their development. The primary motivation behind these support schemes is the expectation that experience effects will eventually render renewable technologies competitive with conventional generating technologies.

However, renewable sources, characterized by (almost) zero marginal costs of production and intermittent availability, challenge the established market design. This design, tailored to remunerate conventional technologies (e.g., coal, gas, nuclear) with positive marginal costs and permanent availability, as noted by Joskow (2011), clashes with the unique attributes of renewables. Low marginal costs and a high share of renewables threaten to diminish the remunerations of generation units with conventional technologies of production as they are placed higher in the dispatch order and the average of wholesale market prices decreases. Furthermore, the rise in intermittency necessitates additional capacity to equilibrate power demand with power supply, thereby increasing the costs of grid balancing and capacity adequacy in electric systems (Newbery, 2016).

Most energy policy research addressing renewable energy integration in competitive markets has implicitly assumed that the institutional framework in which policymakers operate is neutral in the effectiveness of policies (Blazquez et al., 2018; Lund, 2009; Newbery et al., 2018; Tolmasquim et al., 2021). However, differences in institutional frameworks can significantly impact their performance (Scully, 1988), especially when policy and regulation design result from the interaction among multiple national authorities. Building on the notion of institutional tensions, that has been used to study the relationship between the *de jure* and *de facto* power (Acemoglu & Robinson, 2006). We aim to examine if tensions might arise between National Regulatory Authorities (NRAs), endowed with formally delegated powers to regulate electric systems, and Member States that aim to comply with stringent decarbonization objectives. Our research question is: *Does the governance regime of NRA is in tension with the growth of renewable energy in the EU?"*

Initially, in the EU, most electric systems were controlled by nationally owned vertically integrated monopolies. With the advent of liberalization reforms in electricity systems, Member States formally delegated regulatory authority—comprising formally delegated powers and decision-making autonomy—to enforce and decide on the “economic rules” of electricity systems. NRAs were conceived as specialized entities tasked with monitoring and steering fair competition and stable rules for market participants, irrespective of the generation of technology. The ultimate objective of NRAs is to secure system reliability at affordable costs for consumers by implementing competitive markets and cross-border integration (Joskow, 2008).

European Union Member States commitment to ambitious rates of decarbonization has incentivized the exercise of their executive power to promote renewable energy integration through various support schemes. As highlighted by Pollitt and Anaya (2016), these schemes often provide incentives that surpass market levels, resulting in an oversupply of renewable resources. This scenario jeopardizes the market’s ability to remunerate traditional electricity sources. Given the above, our thesis is that NRAs endowed with regulatory power to comply with liberalization mandates generate “resistance” to the pace at which renewable energies enter the national mix, driven by Member States’ support schemes. In this context, resistance implies that NRAs exercise caution about how renewable energies might negatively impact competition. This caution stems from their main liberalization objectives. In other words, NRAs’ choices prioritize overall system efficiency and reliability over favoring a specific technology.

To test our thesis, we conduct an empirical analysis using panel data to measure the impact of NRAs’ governance on the share of renewable energy

(and electricity tariffs) in EU member states. However, measuring governance is challenging, as publicly available indicators are not comparable over time. Therefore, we utilize a novel governance regime dataset provided by Brousseau and Gonzalez-Regalado (2022), which processes OECD regulatory governance surveys (Organisation for Economic Co-operation and Development, 2016). We combine these data with text-analysis methods to derive governance indicators, using data variability to identify relevant features and their importance for a governance regime.

Our results indicate that between 2013 and 2018, NRAs endowed with legal power (independence) were negatively associated with the share of renewable energy sources (RES) in total energy consumption. Our contribution is twofold. First, prior research analyzing the institutional context of policy-makers (Alesina et al., 2005; Anderton et al., 2020; Égert, 2018) has primarily focused on the effects of reforms (policy output) on economic performance (investments, factor productivity, and labor markets). We contribute to the empirical literature on the effects of the liberalization of utilities by distinguishing between the impacts of regulation per se and the impacts of governance arrangements that implement it. Second, we contribute to the literature on the drivers of decarbonization by discussing the policy implications that our results hold for NRAs and environmental objectives. We highlight an ongoing tension between the desire to support renewable energy development and operate electricity systems at affordable prices through competition. Furthermore, we contextualize our results by discussing the policy implications of the ambitious targets to decarbonize electricity systems in the EU by 2050.

This study has eight sections. In the second section, we propose an overview of the emergence of NRAs from an EU perspective, considering the mandates of liberalization reform on their design. The third section provides the background on the tension between renewable energies and current market design. The fourth section describes our theoretical framework. Section five is the data used and our empirical strategy. Section six presents our main results, while section seven discusses them in detail. Section eight offers our main conclusions.

5.2 . Background on electricity systems in the EU

5.2.1 . National regulatory agencies in the EU

In Europe, the liberalization reforms aim to facilitate the integration of EU electric systems: incentivize the investments needed to develop transmission

lines for exchanging electricity amongst MS and improve the system reliability and efficiency Joskow (2008). These reforms required the privatization and vertical separation of formerly state-owned (national) monopolies, which often controlled the totality of electric assets within a country. However, the unbundling of state-owned vertically integrated monopolies appeared insufficient to attract investments in the EU from the start of the liberalization process. Furthermore, specialized wholesale markets were created, and a common regulatory framework was developed to guarantee fair competition.

Despite the implementation of the liberalization reforms, the market power from the ancient monopolists was still relevant. Therefore, NRAs were assigned to steer the market implementation and become technical referees to guarantee fair competition. The reasoning was that new investors needed stronger guarantees of fair treatment while competing with state-owned incumbents and protection from short-term political interests that could threaten their returns by changing market rules ². Indeed, until the liberalization reforms, policy-making and enforcement were primarily in the hands of public bodies directly overseen by ministries. Therefore, politicians in power could have incentives to favor the state-owned (private) incumbent (Stigler, 1971) or to depart from long-term policy commitments in exchange for political support (Majone, 1996).

Consequently, during the early 1990s, several European governments delegated regulatory functions to independent NRAs to signal policy stability and transparency to new investors (Glachant, 2012). In addition, independent bodies could solve information gaps (Glachant et al., 2013), policy commitment concerns (Gilardi, 2002, 2005; Gilardi & Maggetti, 2011), arbitrate disputes, and monitor industry performance.

As shown in Table 5.1, several European Directives set overarching principles of competition on the NRA institutional framework. The regime was gradually implemented, with member states transferring regulatory tasks to NRAs (e.g., interconnection rate setting, monitoring duties) that could contribute to ensuring fair third-party access to the transmission and distribution segments (Article 4 of regulation 2003/54/EC (European Parliament, Council of the European Union, 2003)) ³. Later, the Third Electricity Package expanded the NRA regulatory powers/responsibilities by allowing them to modify contract terms and conditions, oversee interconnection issues, and

²Investment in utilities requires the deployment of high-cost specialized capital. Under the presence of return risk (political instability), firms might not deploy optimal capital levels (underinvestment) or even not invest at all (hold-up problem).

³The Second Electricity Package likewise included provisions for NRA independence, with a focus on limiting the possibility of incumbents' regulatory capture.

solve disputes between market actors (Article 36 of 2009/72/EC (European Parliament, Council of the European Union, 2009)).

The Third Electricity Directive formally established independent NRAs in member states. First, it required member states to delegate regulatory responsibilities to a *single* national body, and second, it ruled on measures that granted this authority autonomy while limiting undue political influence on its decisions. The Directive, in particular, created limits between the NRA's top management and the government (and with the industry). Several rules, for example, prohibited top management from working for both the government and the NRA simultaneously or established “cooling-off” periods before NRA top management could join the industry. Additional measures restricted politicians' and political cycles' influence by creating fixed governing periods and limiting arbitrariness in executive management dismissal. Furthermore, the Directive required member states to ensure proper NRA operation by providing stable funds/human resources and allowing the NRA to administer its resources autonomously (Article 35 of directive 2009/72/EC (European Parliament, Council of the European Union, 2009)).

The latest EU directive objectives (the Clean Energy Package) have deviated from previous directives by implementing new sustainability mandates for the NRA operations. The NRAs are tasked with creating the technological and economic conditions that allow renewable electricity and “flexibility” services to participate in the market. In other words, NRAs' actions must guarantee the inclusion of additional renewable energy generation, electricity storage systems, and demand management mechanisms cost-efficiently. Yet, as discussed in the following section, these additional environmental requirements create contradictions between the market reform, the governance regime, and sustainability objectives.

5.2.2 . Tension in the economic logic between renewables and conventional sources of electricity.

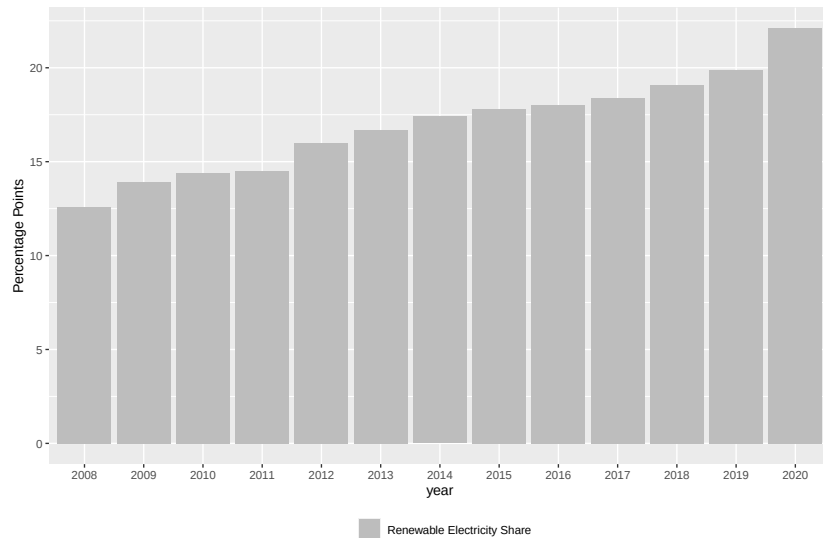
Since 2004, the share of renewable energies has doubled, reflecting the political commitment to decarbonization targets. Governments either supported the reduction in the investment costs in renewable generation (mainly for solar and wind units) or guaranteed positive and stable revenue streams through support mechanisms such as feed-in-tariffs / premiums, quotas, and other instruments. Figure 5.2 shows the positive evolution in the share of renewable energy as a percentage of total energy consumed in the 27 EU member states. The support instrument used the most was feed-in tariffs, which represented a subsidy of €53 billion in 2019 (ec, 2021). Because feed-in tariffs have sup-

Table 5.1: Summary of legal instruments for EU NRAs in Europe

Actors	Legal origins Principles and tools	Delegation
Member States	Competition - MS shall ensure electricity markets are operated following the competition, security, and environmentally sustainable principles. (Article 3 Directive 2003/42/EC; Article 3 Directive 2009/72/EC). Non-Discrimination – If financial compensation (other forms) and exclusive rights that ME grants for fulfilling the obligations shall be done in a non-discriminatory and transparent way (Article 3 Directive 2003/42/EC). ME shall ensure the implementation of a system of third-party access to the transmission and distribution systems based on published tariffs. (Article 24 Directive 2003/42/EC) Monitoring - ME shall ensure the monitoring of the security of supply. Where MS consider it appropriate, governments may delegate this task to the regulatory authorities (Article 4 Directive 2003/42/EC)	Delegation - ME shall designate a single national regulatory authority at the national level. (Article 35 Directive 2009/72/EC) Independence - Member states shall guarantee the independence of the regulatory authority and shall ensure that it exercises its powers impartially and transparently. Member states shall ensure that regulatory authority can take autonomous decisions independently from any political body and has separate annual budget allocations (Article 35 Directive 2009/72/EC)
NRAs	Responsibilities - Regulatory authorities shall ensure non-discrimination, effective competition, and efficient market monitoring. (Article 36 Directive 2009/72/EC) They should be responsible for: (a) rules on the management and allocation of interconnection capacity, (b) the level of transparency and competition, (c) methodology to calculate tariffs, and (d) help achieve in the most cost-effective way the development of secure, reliable and efficient production of electricity (Article 36 Directive 2009/72/EC).	Independence - Regulatory authorities shall be wholly independent of the interests of the electricity industry (Article 35 Directive 2009/72/EC) Accountability - Regulatory authorities shall submit formal decisions to the relevant body in the Member State regarding the methodologies to calculate tariffs. Member states may approve or reject the propositions of regulators (Article 36 Directive 2009/72/EC). Authority – Regulators shall have the authority to require transmission and distribution system operators, to modify the terms and conditions, tariffs, and rules, to ensure that they are non-discrimination. Regulators may also act as dispute settlement authority between parties (Article 36 Directive 2009/72/EC).

ported renewable energies, and renewable energies reduce the price in wholesale electric markets, the subsidies from feed-in tariffs have become more expensive over time (Council of European Energy Regulators, 2021; Henriot & Glachant, 2013; MacLean et al., 2015).

Figure 5.2: Evolution in the share of renewable energy as a share of gross energy consumption



The growth of renewable energy has been a main driver of several EU Directives ruling on decarbonization that have focused mainly on setting emission targets. These directives started in 2001 under the Kyoto Protocol, which agreed on a binding target for the EU to reduce 2012’s emission levels by 5% to its 1990s emissions. The first renewable electricity directive (2001/77/EC) ruled that member states should define renewable energy targets, update them every five years, and encourage them to use national economic mechanisms until the EU defines a common framework. Its update in 2009 (2009/28/EC) required member states to define obligatory objectives of RES for 2020, and its last version in 2018 (2018/2001/EU) set a binding target for collectively ensuring that the share of energy from RES is at least 32% in 2030. European Green Law (Regulation EU/2021/1119) is the most recent commitment from the EU to climate change targets. It legally binds the Green Deal, defining a target of achieving a 55% reduction in emissions below 1990 levels by 2030, increasing the ambition of the existing EU Emission Trading System (EU ETS), and the ambitious objective of EU climate neutrality by 2050.

However, the current wholesale market organization is designed to reward generators based on cost efficiency in a setting where generators have positive marginal costs (e.g., the fuel cost for thermic plants) and can produce energy

at any given time. Plants with low marginal costs supply electricity to the network first. As the demand increases, generators with higher marginal costs deliver electricity until the demand is met. The marginal cost of the last generator participating in the market sets the wholesale price paid to all electricity suppliers.

Therefore, additional renewable generation leads to lower wholesale electricity prices because of the zero marginal cost of producing an additional electricity unit. Low prices in the wholesale market may not provide enough incentives for new investors and may prevent current plants from covering their costs or not utilizing their total capacity (Blazquez et al., 2018). To correct this problem, European member states implemented onerous subsidy schemes to incentivize renewable generation. The importance of these subsidies has increased over time, as evidenced in Figure 5.3, which shows the extent of subsidies as a fraction of the cost of an electricity unit ⁴.

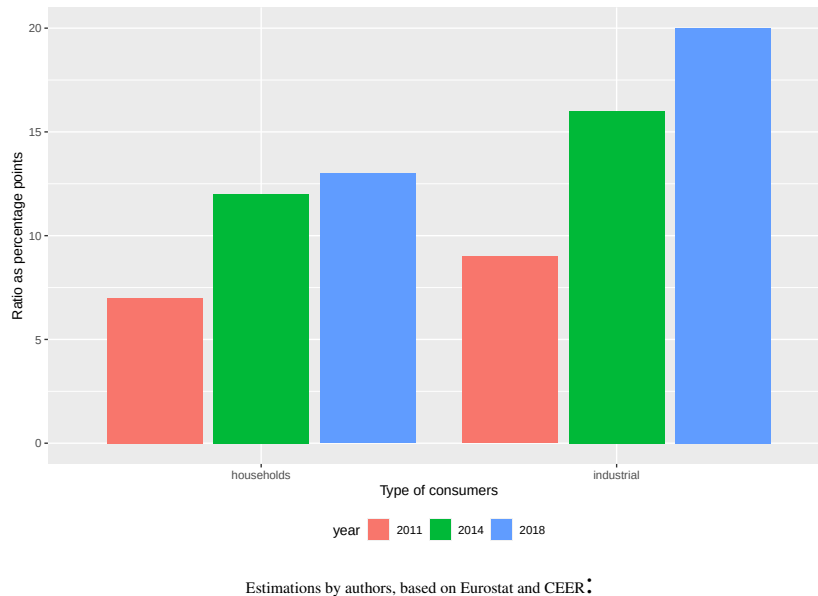
The rise of renewable energy support has stressed the need for additional investments in the power system to handle the mismatch between unmonitored supply and market demand. In response, capacity markets have been developed to rectify the balance, focusing on compensating backup generation, frequently of a thermal nature ⁵. Nonetheless, a notable drawback of these markets lies in their dependence on complex calculations grounded in various technical assumptions. Unfortunately, these assumptions, while considered effective in meeting the real needs of the power grid, have led to an excess of available power and consequently have raised the prices consumers pay. Empirical studies show a significant correlation between the share of renewables in the energy mix and higher electricity prices in the OECD countries (da Silva & Cerqueira, 2017; Moreno et al., 2012).

Given the tension between renewable generation, the current market design, and, ultimately, the liberalization objectives, we explore the role of NRAs in easing or stressing the tensions introduced by renewables, given the liberalization mandates. Although the reform set broad environmental principles for NRAs, they are mandated and accountable for reducing system costs, transmitting rents to customers, and encouraging new investments. The extent to which NRAs can carry out their mandates or choose to pursue other (environmental) objectives highly depends, among other elements, on

⁴For 2011, the share was calculated using the renewable energy support of 2010 and the generation and supply costs of 2011. The authors calculated the ratios. The data used in the numerator is the weighted average of the surveyed countries as calculated by the Council of European Energy Regulators (CEER) in their 2011, 2014, and 2018 Renewable Energy.

⁵Capacity mechanisms usually rely on decentralized carbon-based generation plants that do not participate in the market.

Figure 5.3: Renewable energy tariff support / electricity tariff ratio by type of consumer



the preferences of agencies, national governments, and European institutions (Alesina & Tabellini, 2008), and the NRAs' degree of autonomy from external intervention, discretion on resource usage and the breadth of powers delegated to execute their assignments.

5.3 . Theoretical framework

5.3.1 . Governance regime's characteristics

The assessment of governance regimes has focused on exploring whether NRAs carry out their mandates and objectives independently and on methodologies to estimate NRAs autonomy (Levi-Faur, 2005; Thatcher & Sweet, 2002). Gilardi (2002, 2005) compared the governance of NRAs in economic and social sectors by assessing their decision-making independence (from the government and the industry). Following the literature on central bank independence, the author estimated a metric that considered the appointment length of agency authorities and provisions for their dismissal, budgetary autonomy, internal resource management, and delegated tasks as the most essential features of NRA independence ⁶.

⁶Gilardi (2002) operationalizes the independence dimension by constructing a weighted index that summarizes survey information by assigning different scores when agencies have

However, recent studies suggest that even if *independence* is a fundamental dimension, other dimensions are needed to contrast regimes and study their impacts. C. J. Hanretty et al. (2012) discuss the role of transparency and accountability in improving the regulatory decision-making process. They suggest that both features encourage bureaucrats to perform better in their duties and to stick to the agency mandates. Transparency in regulatory intervention has increased substantially in the electricity sector since the beginning of the market reform Pollitt (2019). The decision-making processes are open to public scrutiny, and regulatory authorities and staff are evaluated periodically by legislative bodies. However, these features are complex to measure because regulators differ in objectives and are embedded in different institutional systems.

Besides *independence* and *transparency*, the breadth of delegated powers is also relevant to describe and discriminate among governance regimes. Organisation for Economic Co-operation and Development (2016) stresses the importance of regulatory levers to enforce market regulation, such as specifying network access conditions, setting prices and tariffs, settling disputes between market actors, and requesting information from market players. The availability of such powers increases the regulators' abilities to solve complex and unexpected problems (Jamashb & Pollitt, 2005).

Jordana et al. (2018) and Brousseau and Gonzalez-Regalado (2022) used factor analysis and text analysis algorithms, respectively, to identify alternative regime arrangements. Both studies proposed alternative arrangements that partially contrast with mainstream studies (e.g., Organisation for Economic Co-operation and Development (2016)). Jordana and co-authors propose a four-dimension model (Political independence, Managerial Autonomy, Regulatory Responsibilities, and Public Accountability) to discriminate between economic and social regulators worldwide. In contrast, Brousseau and Gonzalez-Regalado proposed a four-dimensional model focusing on economic European NRAs in network industries, including the electricity sector.

Their model uses detailed OECD surveys to follow the implementation of the current EU governance regime (part of the EU electricity market reform) across NRAs between 2013 and 2018. In detail, the model defines regime features as follows:

1. **Independence from the government** estimates the degree of separation between the regulatory agency and the executive's undue influence

or not a head/board appointment process, budget, and organizational levers, and the scope of regulatory powers.

⁷. The main objective of independence is to support the stability of market access and competition rules (Gilardi & Maggetti, 2011).

2. **Discretion** describes the agency level of "flexibility.". The dimension portrays an agency's freedom to manage its internal decision-making process and resources and to interpret its mandates.
3. **Scope of market monitoring** describes the regulator's ability to monitor/coordinate the competitive process, supervise the industry behavior, and manage economic incentives.
4. **Transparency** reflects the regulators' role in reducing information asymmetries between operators, public authorities, and users ⁸; in particular, to ensure compliance and limit behavioral drift.

In the following sections, we use the model in Brousseau and Gonzalez-Regalado (2022) to associate differences in NRAs' governance regimes to energy mix heterogeneity across European countries.

5.3.2 . The reform, system efficiency, and the environment

The literature evaluating market reforms and their impact on renewable electricity generation cannot showcase a significant relationship. Generally, market reforms improve member states' environmental performance but do not necessarily encourage new renewable generation units to enter the market. Pollitt (2019) suggest that the decrease in pollutant emissions associated with market reforms results from the entry of efficient gas generators (replacing coal generators) and not new renewable units. Asane-Otoo (2016) finds similar results and suggests that the introduction of competition in generation and privatization attracted efficient (thermic) generators to the market and reduced emissions, but surprisingly, they did not find evidence of an increase in renewable generators. Nicolli and Vona (2019) propose that the market reform, particularly the reduction of entry barriers and the access of new generators, reduced the incumbent's power to lobby against renewable support policy. Their empirical evidence displays that an extended market reform (OECD PMR index) positively correlates with public support for renewable energy. However, no empirical evidence of superior renewable energy generation is provided.

⁷Gilardi and Maggetti (2011) use a similar definition, in which describe independence as the institution that separates the government bureaucracy from the elected politicians

⁸The dimension aggregates measures of the obligation for (public) reporting imposed on the RA and the reporting obligation imposed on the market players by the RA.

This overview suggests that market reforms enhanced overall system efficiency but did not create market conditions that encouraged investment in renewable generation. Yet, the role of the sectoral governance regime on renewable generation has not been discussed. The following section analyzes the relationship between governance regimes and the electricity sector performance and proposes connections between governance regimes and renewable energy generation.

5.3.3 . Hypothesis formulation

NRAs' actions depend on the interaction between the agencies' preferences (principles and mandates), their internal resources, and the interests of governments and industry players. In this context, the agencies' governance regimes have a strong influence on their outcomes and, hence, on industry performance. Governance features such as decision-making autonomy, agency discretion, and the breadth of delegated powers are expected to influence performance differently.

The market reform aims at incentivizing industry players to invest in competitive and integrated electricity systems. To deploy new investments, potential investors need a guarantee about their expected returns. The reform envisioned independent NRAs as bureaucratic bodies able to monitor and steer the market in a stable and predictable mode and reduce the likelihood of short-term politicians' opportunistic policy deviation (Majone, 1996). Consequently, regimes with independent NRAs are expected to attract superior investment levels. In this regard, Cubbin and Stern (2006) finds a strong association between the presence of an independent regulator and superior electricity generation per capita. In some circumstances, the effect of independence is conditional on privatizing utilities. While Y.-F. Zhang et al. (2008)'s results indicate that *independence* characteristics are significantly associated with a higher generation per capital but only in the presence of private incumbents. This claim supports previous work by Y. Zhang et al. (2005), who show that privatization increases sector per capital output only when an independent regulator is established before the reform. Independence is significantly associated with other sector performance measures, such as investment and firm leverage. Égert (2009) rely on a cross-section of 13 countries and six utility sectors in 2008 to show that the setup of an independent regulator and the application of incentive price regulation reduce return risk and, therefore, foster investments. Moreover, Cambini and Rondi, 2017 highlight that establishing an independent regulator positively impacts investments in 80 EU utilities, including 37 energy firms in distribution and transmission. After controlling for political and institutional variables, they found significant investments from

the private sector increased between 1994 and 2004 because the setup of independent regulators enhanced policy credibility among investors.

The previous evidence supports the premise that independent NRAs commit to the reform's mandates, which has attracted investments that improved the overall system performance based primarily on monitorable sources. The inclusion of non-monitorable sources in the current market design stresses the system's efficiency by increasing its costs to match supply and demand⁹. When conflicted with increasing system costs of renewables, which could translate into higher prices to consumers and efficiency losses (especially in the capacity market), independent NRAs serve the overall system efficiency. Thus, we expect that:

- Hypothesis 1: More independence is associated with a lower share of renewables in the energy mix.

The NRAs' ability to interpret its mandates relies on the institutional design of the agency, societal demands, and the stakeholders' preferences about those demands. In the case of decarbonization needs, a particular group (e.g., citizens) could advocate for a more decarbonized energy mix, while another group (e.g., consumers) could express concerns about the impact of decarbonization on the rise of electricity prices. The NRA's conduct would depend on its preferences about the societal demand and the power distribution among groups. Therefore, we do not expect a significant effect of *discretion* on the electricity mix.

- Hypothesis 2: More discretion should not be associated with a higher share of renewables in the energy mix.

The breadth of delegated powers granted to a regulatory agency (monitor and steer competition in the industry) describes in practice the NRA's capacity to accomplish its goals. Brousseau and Gonzalez-Regalado (2022) distinguish NRA's powers between the ones used to supervise competition (scope of market monitoring) and the ones to supply information to the industry and reduce information asymmetries between operators, users, and public

⁹The "merit order" market design rewards generators in the queue line with marginal cost equal to or below the least efficient generation unit that entered the market. Assuming that the most efficient CO₂-generating units enter the queue, the CO₂ units with higher operational costs will provide capacity services in case of need. This implies that balancing costs increase under additional intermittent renewable units that demand superior balancing capacity.

authorities (transparency) ¹⁰. While political scientists have examined the reasons for governments to grant regulatory powers to NRAs (see Wassum and De Francesco (2020)), the effects of this breadth of powers on industry performance have been overlooked.

Several analyses have focused on the links between the breadth of NRA's powers and the agency's ability to conduct its work accurately. However, their results do not indicate the existence of a significant link. C. J. Hanretty et al. (2012) examine the correlation between accountability, which partially overlaps with the NRA's capacity to reduce information asymmetries, and the perceived regulatory quality in energy, telecommunication, and transport. A regulatory quality measure was derived from self-administered surveys about the NRA's performance. The authors found a positive but non-significant relationship between the two variables. Similarly, C. Hanretty and Koop (2018), using an ordered probit regression, did not find any correlation between accountability and regulatory quality (proxied by scores from the Global Competition Review) for 30 OECD competition authorities in 2005-2014.

These results indicate that regulatory powers do not affect the players' investment behavior. Principles, mandates, and policy commitment are determinants of investment decisions. As a result, we anticipate:

- Hypothesis 3: More market scope monitoring should not be associated with a higher share of renewables in the energy mix.
- Hypothesis 4: More transparency should not be associated with a higher share of renewables in the energy mix.

5.4 . Data and methodology

5.4.1 . Data

Because of data availability, our econometric analysis relies on 24 countries: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, Greece, Hungary, Ireland, Italy, Lux-

¹⁰Wassum and De Francesco (2020) contrast regulatory powers between “hard” and “soft” competencies. “Hard” competencies are related to direct intervention capacity, as in the case of setting prices or price controls, emitting licenses, and issuing sanctions and penalties. “Soft” competencies describe the capability of the NRA to modify behavior through non-binding actions. Examples of these competencies are issuing industry and consumer standards, guidelines, and codes of conduct and collecting information from industry players.

emburg, Lithuania, Latvia, the Netherlands, Poland, Portugal, Sweden, Slovenia, and Slovakia. We analyze the European electric systems for the period 2013-2018. The Annex ?? gives a detailed summary of the data used and statistical characteristics, particularly table 8.1.

The share of electricity produced from renewable sources was extracted from the Statistical Office of the European Union (EUROSTAT) database. The share, in the numerator, includes hydropower, wind, solar, biomass, bio-liquids, biogases, tide, wave, and ocean gross production. The denominator is the country's gross energy consumption in MWh ¹¹. Moreover, we constructed a second variable that captures the non-monitorable (i.e., solar and wind generation) sources' participation in the electricity mix to estimate whether the governance regimes conflict with these renewable sources.

To capture the NRAs' governance regime, i.e., independence, transparency (accountability), and Scope of action, we use the indicators computed by Brousseau and Gonzalez-Regalado (2022). The normalized scores range from 0 to 1 for each of these dimensions ¹². The metrics measure the evolution of the governance regime between 2013 and 2018.

Their metrics offer several advantages. First, they are derived from surveys on network sector governance regimes (electricity, gas, telecommunication, rail, and air transport) conducted by the OECD. The Organisation for Economic Co-operation and Development (2016) provides the most comprehensive dataset about regulatory governance to date for both periods. Second, the characteristics and number of dimensions were defined using text-analysis algorithms ¹³ (word co-occurrence) to uncover latent dimensions using the data variability without predefined assumptions about the most contrasting differences among regimes. Third, their metrics allow comparing regimes over time, enabling the evaluation of whether changes in governance have implications for the industry's output. Finally, the metrics summarize scores based on the data variation and not in a predefined weighting scheme.

To measure the extent and evolution of the liberalization reform, we con-

¹¹European Environmental agencies use this metric to track country decarbonization target performance

¹²The OECD estimates governance scores with the same survey (Casullo et al., 2019). However, scores are not comparable across time because of significant changes in their questionnaire. Brousseau and Gonzalez-Regalado (2022) NLP method allows bypassing this time-comparability issue

¹³Brousseau and Gonzalez-Regalado (2022) use a coding scheme to transform survey categorical responses into textual documents. Using topic modeling, textual sources uncover co-occurring clusters of terms named topics. Based on these clusters and their terms' semantic meaning dimensions are identified and defined.

structured a *market access* variable that captures to what extent legal provisions support entry in the generation and retail segments. The estimation method (see Annex ??) follows the approach proposed by Brousseau and Gonzalez-Regalado (2022). The metric was estimated using information from the OECD Product Market Regulation survey for 2013 and 2018 (Vitale et al., 2020). Similarly, we also utilize the OECD PMR index, which aggregates information on the industry entry barriers, market structure, vertical integration, and price controls. The data is available from 1975 to 2018.

In addition, our dataset considers national, sectoral, and institutional variables that affect the supply of renewable energy. Data on electricity consumption, production, and system capacity are obtained from EUROSTAT (2018) and International Energy Agency (2018), while the economic and demographic variables (GDP and population) from the Penn World Tables version 10 (Feenstra et al., 2015). The measures that capture the quality of institutions are gathered from various sources. The Freedom House Political Rights Score (Freedom House, 2018) accounts for political and institutional stability. Besides, the IHS-Market indicator and the Corruption Perception Index (CPI), from Transparency International (2018), measure the legal system's protection to prevent an arbitrary exercise of power. The society's preferences for environmental policies are estimated by the number of seats green parties hold in the legislative. The information is collected from the Comparative Political Data Set (Armingeon et al., 2023). To proxy for the most prominent firm's decision power in the sector, we use the market share of the largest generation firm available in Vitale et al. (2020). Finally, the measure of the industry's ability to innovate is gauged by the number of patents per millions of habitants and extracted from the International Renewable Energy Agency (2018) database.

In addition, we construct three variables that portray the support (or opposition) to renewable electricity generation. The first measure accounts for the (lobbying) power that non-renewable technologies would have to preserve the current mix structure. Technologies with larger market shares are expected to spend more resources to keep the status quo. We followed Pfeiffer and Mulder (2013) and estimated the Hirschman-Herfindahl (HH) index for non-renewable technologies¹⁴. The shares are extracted from EUROSTAT (2018). The second variable captures the extent to which lawmakers have produced public policies to support renewable generation. The variable is constructed by counting the years that particular policies or programs that support renewable generation (e.g., incentives or direct subsidies) have been in force¹⁵.

¹⁴The variable is estimated as follows: $lobbying_{it} = \sum_{i=1}^N share_i^2$

¹⁵We selected current active policies relevant to electricity generation at the national level.

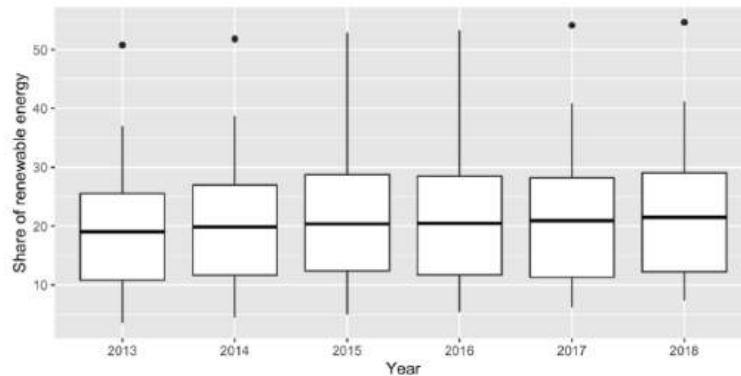
More extended promotion of green energy should trigger entry in the generation segment (Nicolli & Vona, 2019). The third index accounts exclusively for the importance of policies that provide direct financial incentives to generators. This importance is proxied by the percentage of policies granting subsidies, loans, and tax incentives as a share of total renewable support policies. We use the International Energy Agency (2018) Policy Database to identify the policies, type, status, and duration period.

To measure consumer electricity prices, we use end-use consumer year-averaged prices (for industrial and household customers, excluded VAT). The data is gathered from *Energy Prices and Taxes Statistics database* (International Energy Agency, 2018).

5.4.2 . Evolution of renewable shares, liberalization, and governance regimes

The shares of renewables have grown for our sample between 2013 and 2018. Figure 5.4 shows that disparities across countries remain over time despite this growth. This heterogeneity reflects differences in geographical location, national energy resources, and institutional and economic long-run conditions (Bourcet, 2020). As discussed in the following subsection, a fixed-effects model could account for these structural differences.

Figure 5.4: Distribution in the growth of renewable energies

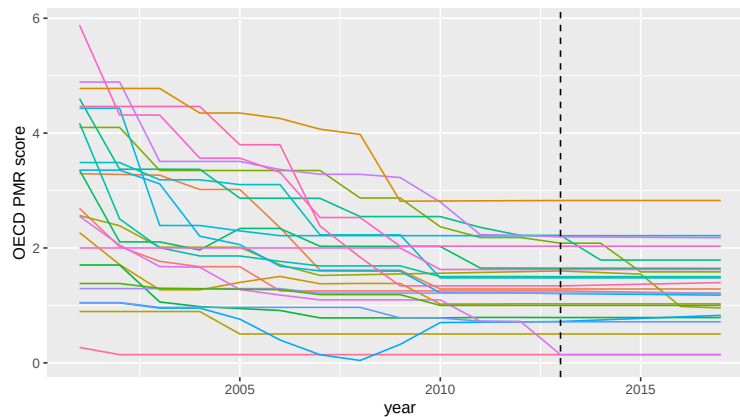


The liberalization reform that started in the early 1990s kept pace during the 2000s, although at different paces. Most European OECD countries reduced regulatory barriers to firm entry and competition and implemented pro-competition regulations in their regimes. Figure 5.5 shows the evolution of the electricity market reform implementation between 2000 and 2018, measured by the OECD PMR indicator (each line represents a country in our sample).

Policies that support consumers were not included in the indicator. If a policy has been active since 1976, in 2013, it was active for 37 years, while in 2018, it was active for 42 years.

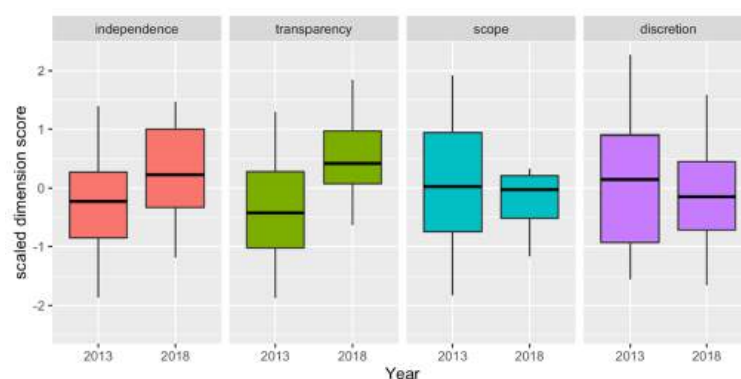
Since 2013, only a few countries have liberalized their markets further, while the majority have followed a steady trajectory.

Figure 5.5: Evolution of entry barriers in the European Electricity markets



In contrast, governance regimes experienced significant changes between 2013 and 2018. Figure 5.6 shows that NRAs are more independent (red) from the government and were granted higher levels of formality (reduced discretion in purple). However, regulators are still far from converging to a similar independence level. The variance of the score remains quite significant. In contrast, the transparency (green) and scope of market monitoring (blue) tasks increased their homogeneity over the period. Transparency increased while the scope of market monitoring remained similar to the previous period level.

Figure 5.6: Evolution of the IRA dimensions in Europe between 2013 and 2018



The NRA governance model is a fundamental part of the liberalization reform in the European Electricity markets, as explained in figure ???. This association challenges identifying the potential effects of governance on industry performance because changes in the governance regime might reflect

a deepening of the liberalization reform. The considerable changes in the governance regimes and the relatively modest evolution of the liberalization reform between 2013 and 2018 provide a possibility to isolate the governance effects on performance.

5.4.3 . Econometric model

The national electricity mix is the result of technical and political characteristics but also of various geographical, historical, and institutional factors that occasionally are unobserved for a researcher. The two-way fixed effect panel data model accounts for those unobserved factors that vary only over long periods. Besides, this model also controls for common shocks that could have affected electricity systems during specific periods ¹⁶.

$$\ln(performance_{i,t}) = \alpha + \beta_1 * govern_regime_{i,t} + \beta_2 * regulatory_regime_{i,t} + \beta_3 * controls_{i,t} + \mu_{i,t} \quad (5.1)$$

In equation 5.1, the share of renewable energy and electricity price are our outcome variables ($\ln(performance_{i,t})$). The effects of the governance dimensions ($govern_regime_{i,t}$), i.e., *independence*, *discretion*, *scope of market monitoring*, and *transparency*, on the outcome variables are captured by the term β_1 . Despite the liberalization reform's stability between 2013 and 2018, the term $regulatory_regime_{i,t}$ is introduced to capture the impact of any variation in the liberalization reform. The term β_2 captures the reform's effects.

Moreover, the error term structure $\mu_{i,t} = \delta_i + \nu_t + \gamma_{i,t}$ controls for unobserved electricity and renewable sector characteristics. The δ_i term captures time-invariant system and national characteristics (e.g., the lasting aspects of geography and institutional traditions). The ν_t captures unobserved common shocks that could have affected electricity systems during a particular period, and the $\gamma_{i,t}$ term is an idiosyncratic individual error term.

¹⁶We checked for significant individual and time effects by testing if, jointly, all individual and time intercepts are different from zero in an OLS regression. Our results suggest that the fixed-effects model should be selected. Our specification also assumes a constant effect of independence over countries and time. However, we tested whether the overrepresentation of negative heterogeneous treatment effects might artificially negatively bias our average estimates. We follow de Chaisemartin and D'Haultfœuille (2020) test to test if the effect direction comes from a true prior or is the result of overrepresentation. Our model is not driven by the issues presented on de Chaisemartin and D'Haultfœuille (2020).

In addition, we added a set of covariates $controls_{i,t}$ to account for other determinants of the energy mix, such as changes in demand (primary energy demand, income, energy security) and supply factors (policy support towards particular technologies, innovation, and specialization effects), and institutional quality (government effectiveness and the rule of law). The vector β_3 captures the effects of our control variables on system performance.

5.5 . Results

5.5.1 . Effect of governance regimes on renewable energy growth between 2013 and 2018

Table 5.2 shows the parameter estimates for the effects of the governance regime on the share of renewable energies. Models (1) to (4) test the individual effect of each dimension, while model (5) tests the overall regime effect.

Models (1) and (5) show a negative relationship between *independence* and the share of renewable energy after controlling for the rest of the dimensions. This estimate confirms the *Hypothesis 1*, which indicates that independent regulators are associated with a lower share of renewable electricity produced. At this point, we cannot explicitly distinguish between the independence granted to the regulator and its mandates (objectives). Therefore, we add a set of controls to account for other factors that might influence the share of renewables and the governance regime.

The rest of the dimensions do not seem to have a crucial influence on renewable generation. The effect of *discretion* is negative but is not statistically significant. Thus, we accept the *Hypothesis 2*. *Transparency* has a negative, but not significant, impact on renewable energy shares in models (2) and (5). In model (5), after controlling for the effects of the rest of the dimensions, the coefficient almost drops to zero. Thus, we accept *Hypothesis 3*. This result coincides with the one claimed by Koop and Hanretty (2018), where no strong associations are found between transparency and regulatory or industry performance. Finally, the *Scope of market monitoring* shows a positive but non-significant coefficient in models (4) and (5). These estimates confirm *Hypothesis 4*. The positive effects could indicate that regulators with market steering tools can organize markets that attract renewable generation better. However, more research is needed to support this connection.

Table 5.2: Fixed Effects: Impact of governance on renewable energies shares

	(1)	(2)	(3)	(4)	(5)
Independence	-0.817** (0.334)				-0.968* (0.531)
Discretion		-0.203 (0.317)			
Transparency			-0.371 (0.496)		0.098 (0.504)
Market				0.167 (0.682)	0.53 (0.683)
Liberalization	1.456** (0.616)	2.306** (0.864)	1.725* (0.902)	2.091** (0.787)	1.452** (0.583)
Inst. Stability	0.038*** (0.006)	0.041*** (0.008)	0.039*** (0.008)	0.040*** (0.008)	0.039*** (0.006)
Non-renew power	-1.039** (0.312)	-1.328** (0.351)	-1.148** (0.358)	-1.297** (0.371)	-1.084** (0.312)
Demand (GDP)	2.049** (0.861)	1.739* (0.843)	2.133** (0.977)	1.887** (0.910)	1.978** (0.852)
Wealth	-2.136** (0.921)	-1.926** (0.918)	-2.271** (1.029)	-2.067** (0.971)	-2.051** (0.934)
Trade balance	0.107 (0.105)	0.095 (0.118)	0.101 (0.113)	0.094 (0.115)	0.104 (0.113)
Years ren. laws	0.262*** (0.058)	0.319*** (0.085)	0.274*** (0.092)	0.309*** (0.087)	0.255*** (0.073)
Patenthundred	0.134** (0.056)	0.125* (0.067)	0.125* (0.067)	0.123* (0.070)	0.127** (0.053)
Individual effects	yes	yes	yes	yes	yes
Time effects	yes	yes	yes	yes	yes
adj. R ²	0.87	0.842	0.846	0.841	0.868
AIC	-141.4	-132.3	-133.5	-131.8	-139.5
Observations	48	48	48	48	48
F-statistic	33.137	18.331	23.049	24.334	36.048

Controls: *mkt access* level of market reform implementation related to granting new incumbents access to the natural monopoly segment of the industry, *inst. Stability*: freedom House political rights score. Extent to which political institutions are stable. *non-renew mkt power*: Proxy of lobbying power of non-renewable generators in the industry, *demand(GDP)*: masured in PPP USD of 2010, *wealth, income per capita*: In PPP USD 2010 per are set in logs., *patenthundred*: ratio of patents and the number of people in a country.. Discretion is excluded in model (5) due to multicollinearity with the other gov. dimensions. Heteroskedasticity robust standard errors in parentheses * p < 0.1, ** p < 0.05, *** p < 0.01.

Confounding factors and additional controls

We assess confounding factors that might affect the share of renewables and the governance regime in Table 5.2. First, we control for the effect of liberalization, which might influence the extent of the IRA model in a jurisdiction (Gilardi, 2005), and might foster renewable energies by removing entry barriers (Nicolli & Vona, 2019). The impact of market liberalization (*liberalization*) is positive and significant. Second, we consider the security of supply (*trade balance*). Countries with electricity deficits (more significant imports than exports) could be incentivized to set up independent regulators to foster investments. Besides, deficit countries might develop firm policies to support renewable generation since their territories might lack access to other generation capacities (hydro or nuclear plants), thus reducing their electricity deficit (Pollitt, 2019). We found that countries with positive trade balances (*trade balance*) are associated with larger renewable shares, yet all models' coefficients are insignificant. Finally, we control for the institutional environment and potential political capture following Baldwin et al. (2017). According to the authors, political capture threatens new investments by increasing the risk of expropriation. If political capture becomes large enough to hold up new investments, politicians set up independent regulatory agencies to attract new investments (Gilardi, 2005). In our specification, we use *Inst. Stability* variable to measure the institutional stability in a country (lower probability of investments being expropriated) and find that it is positively and significantly associated with larger renewable shares. In the robustness check section, we use alternative indicators to control for other institutional national characteristics, such as the rule of law and government quality.

We also controlled for the national efforts to support renewable generation. We measured this support by adding the years that different “green” policies have been in force (*years ren. laws*)¹⁷. The variable's coefficient is positive and significant (as expected), as presented in table 5.2, model (2). Moreover, we incorporated electricity demand controls such as consumption and national wealth (income per capita). Regarding electricity demand, proxied by nominal GDP, we find a positive and significant effect. In other words, more consumption is associated with more significant electricity generation from all sources, but in particular from renewables¹⁸). However, more pros-

¹⁷We use a second variable to control for policy support. We estimated the share of policies that support subsidies from all the policies implemented in national legislation. Results in Table 8.3 show no significant correlation between the variable and the share of renewable energy.

¹⁸We measure electricity consumption by using GDP instead of primary electricity consumption because of their high correlation (Pearson correlation coefficient = 0.98) and because of data availability.

perous countries seem to prefer an energy mix that relies on thermic generation. This finding aligns with the argument that developed countries prefer to spend on thermic systems because renewable generation might not meet unexpected demand increases (Cadoret & Padovano, 2016). Similarly, we account for the (lobbying) power that non-renewable generators have to preserve their rents. High non-renewable lobbying power (*IHH gen*) should limit the entry of renewable generators. Our variable is negatively correlated with the share of renewables. Innovation effects (*patenthundred*) are also positively correlated with a larger share of renewables.

In addition, we evaluated other market conditions associated with renewables, like electricity prices and market concentration. Systems where consumers face high prices might call for deeper regulatory reforms (including regulatory independence) or changes in the energy mix to reduce prices. Model (2) in table 8.2 indicates a positive but not significant association between prices and the renewable share. After adding prices to our specification, the coefficient of *independence* remains negative and significant.¹⁹ In markets with high concentration, the largest incumbent firm (through its market power) might attempt to maximize rents, either by capturing the NRA or by choosing a profitable energy source portfolio. Model (3) in table 8.2 shows a negative relationship between the share of the largest generator and the share of renewable energy, suggesting that more concentrated markets are connected to thermic generation. However, the coefficient size does not significantly change from the one in table 5.2, model (1)²⁰.

5.5.2 . Robustness check

Outliers

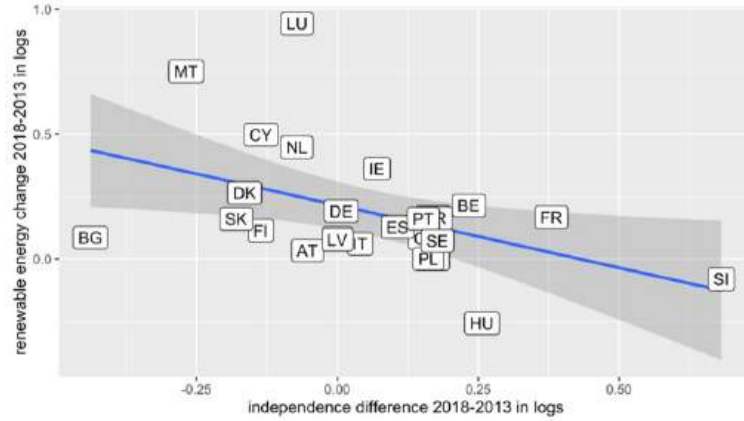
The distribution of our main variables indicates the presence of influential data points that might compromise our estimates. For instance, while the average share of renewable electricity lies around 20.1%, the share for Denmark stands more than two standard deviations away from the average. This issue is partially solved by our panel data specification that uses country within variation to identify the effect of governance regimes. However, some countries recorded significant changes (in our main variables) between 2013 and 2018, as shown in table 5.7. Countries like Malta (MT) and Luxembourg (LU) have considerably increased their shares of renewable generation, while Slovenia

¹⁹The model also considers industrial consumer prices and displays similar results. The results are not reported

²⁰The incumbent with the largest share was not included in the main specification because the sample size drops by three countries.

(SI) has improved its independence score performance compared to the rest of the sample ²¹.

Figure 5.7: Correlation between renewable energy share and independence



To verify the robustness of our estimates, we determine the extent to which they depend on those influential points by re-estimating model (1) in table 5.2, leaving out one country (data row) at a time ²². The results in table 5.8 show the *independence* coefficients do not significantly vary from each other after excluding one observation, and all are significant at 10% level ²³. These outcomes suggest that influential observations do not drive either the direction or the significance of our estimates.

Policy and institutional channels

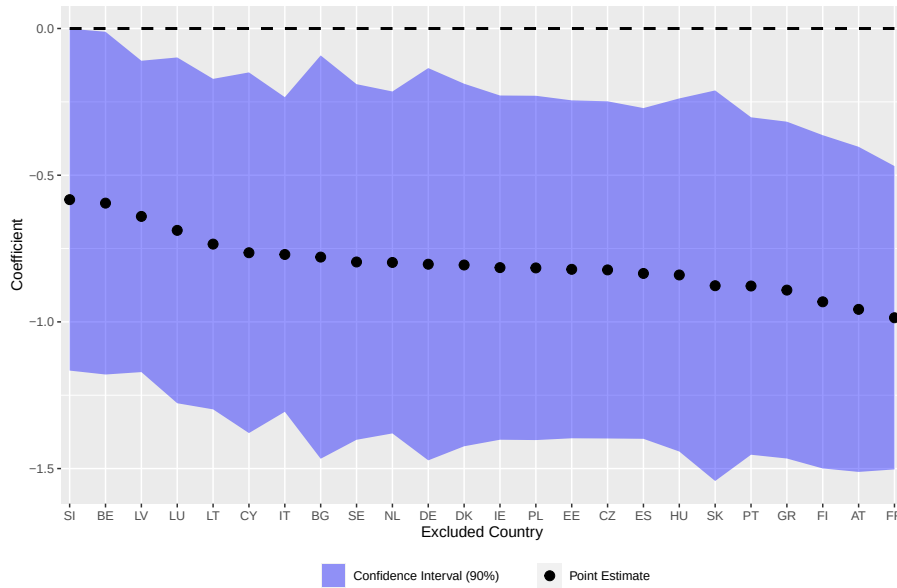
The policy and institutional environment (and its measures) might impact our results as well. Different aspects of national policies and institutions could

²¹On the vertical axis, we observe the change in the share of renewable energy (logs) from each country, while on the horizontal axis, we see the change in the independence score (logs). The figure highlights the presence of potential outlier observations that might drive our regression estimations.

²²Belsley et al. (1980) discuss the implications that outliers have depending on whether they are present in the outcome variable or independent variable. Variables that record extreme values in the dependent variable, as in the case of Malta, influence the regression intercept but do not affect the slope. The effects on the line from the independent variable observations like Slovenia or Bulgaria need more attention because they can alter the model slope and increase the occurrence of type 1 or type 2 errors. Following their argument, we removed one data row (country) from the model (1) to verify whether our estimates became insignificant.

²³In table 5.8, the y-axis displays the independence coefficient size, while the x-axis shows the excluded country. The blue area shows the coefficient confidence interval (90%) for each estimated model.

Figure 5.8: Effects of independence on renew. energy excl. one country



add uncertainty to our estimations. Table 5.3 shows the estimation results with other policy and institutional variables used in the literature on renewable share determinants (surveyed by Bourcet (2020)) to verify whether our estimates remain robust after using alternative policy and institutional measures.

Model (1) displays the coefficients of our baseline model. In model (2), we use the OECD PMR index to track changes in the market reform policies as an alternative to our *liberalization* variable. The independence coefficient varies slightly, but it becomes less significant²⁴. However, the reform's coefficient shows the expected negative sign (lower values of the PMR highlight a more liberalized market).

Model (3) accounts for national policy initiatives to reduce greenhouse gas emissions nationally. We use the variation of greenhouse gas emissions per capita growth rates as an effort proxy. The positive estimate suggests that countries with higher emissions growth rates tend to support higher renewable energy generation; however, the coefficient is not statistically significant at conventional levels. Social preferences might also play a role in supporting or limiting the implementation of decarbonization policies. In model (4), we add the variable *Green Party* to capture environmental preferences beyond

²⁴We omitted the OECD PMR in our main specification because not all countries had a score. Missing country data was obtained by imputation. We decided to keep the variable as a robustness check.

government policies. The coefficient remains robust (at a 10% level) and suggests that countries, where green parties have more delegates are associated with larger renewable preference shares. We did not include this variable in our main specification because it reduces estimation accuracy more than improving the model fitting, as pointed out by the Akaike Information Criterion (AIC) ²⁵.

Different aspects of institutions are able to influence renewable energy investments. In model (5), we use the Transparency International Corruption Perception Index (CPI) as a proxy for government quality. Lower corruption levels should translate into better-functioning public administration. The independence coefficient slightly varies compared to model (1), yet the CPI coefficient is not statistically significant. In model (6), we use the measure of “Rule of Law” constructed by the IHS-Market, which captures how investments are protected from expropriation. The independence coefficient changes in magnitude, but the effects’ direction and statistical significance remain. However, the IHS-Market coefficient becomes negative and non-significant, which is probably linked to the fact that countries in our sample tend to stick to EU standards. All the previous results conclude that our model is robust to different instruments to measure institutions.

Overlapping sample

Finally, we measure the share of renewables using the overlapping sample (22 countries from the price regression analysis presented in the discussion section (5.6) ²⁶) and the generation of solar and wind sources as a share of total electricity production ²⁷. In table 8.4 (in the appendix), the effect of independence in models (1) and (2) remains negative and significant at a 10% percent level. These parameter estimates suggest that the effect of the governance regime is present across different samples and renewable energy measures.

5.6 . Policy implications

The EU has reinforced its commitment to improving environmental performance by introducing the Clean Energy Package (CEP) in 2019. This leg-

²⁵In table 5.2, a lower value of AIC indicates a robust model. Model 1 has an AIC of -141.5, and model 2, -136.6

²⁶The price analysis includes Great Britain and Switzerland and excludes Bulgaria and Cyprus. Data availability drives this decision.

²⁷This measure is less sensitive to changes in electricity consumption patterns.

Table 5.3: Fixed Effects: Additional political and institutional covariates

	(1) Base	(2) PMR	(3) EGR	(4) Green	(5) Corrupt.I	(6) IHS-RL
Independence	-0.817** (0.334)	-0.736* (0.383)	-0.824** (0.329)	-0.860* (0.423)	-0.898** (0.363)	-1.309* (0.649)
OECD PMR		-0.0215* (0.0118)				
Em.GR			0.0117 (0.296)			
Green				0.0186** (0.00709)		
Corruption Index					0.0120 (0.00710)	
Rule Law						-0.693 (0.480)
Time effects	yes	yes	yes	yes	yes	yes
Controls	yes	yes	yes	yes	yes	yes
adj. R^2	0.870	0.862	0.866	0.855	0.837	0.833
AIC	-141.5	-138.9	-139.5	-136.6	-130.8	-129.6
Observations	48	48	48	48	48	48
F-statistic	33.14	100.2	30.49	43.16	11.96	16.27

Model (1) shows the coefficients of the equation in *Model(1)* - table 5.2. *OECD.PMR*: score of market reforms calculated by the OECD between 0 (fully liberalized) and 6 (vertically integrated - state-owned industry). *Em.EGR*: emissions per capita in percentage annual growth rate. *Green*: number of shares of the green party in the legislative per person. *FH political rights*: Freedom house political right score. *Corruption Index*: Transparency international corruption index where higher scores stand for more transparent and efficient government. *Rule of Law*: IHS rule of law score. It represents the protection of private investments in a country. Heteroskedasticity robust standard errors in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

isolation sets environmental principles and mandates to member states and, more recently, to regulators while preserving the current market structure. In this context, we ask whether the new CEP's environmental principles and mandates provided to NRAs are compatible with the current market design. Our work proposes that the new environmental mandates will conflict with the liberalization (and NRAs) commitments, and additional actions are needed to reconcile the previous and more recent rulings.

Policymakers should consider expanding the understanding of the conflict between liberalization, market designs, and environmental objectives (Pollitt, 2019). The first step is determining whether the conflict between the NRA's competition commitments (measured by independence) and renewable energy generation has slowed down current environmental targets. Most European member states achieved their environmental targets in 2020. According to the European Environmental Agency (2020), 22 Member States reached their 2020 targets, Belgium, Romania, and Slovenia remain close to meeting the target ($< 1\%$), and France and Poland were the countries furthest away from their 2020 target (over two percent below). At that stage, the conflict did not seem to affect the member states' decarbonization performance.

However, it is uncertain whether the conflict's effects will remain negligible as the shares of renewable electricity grow. Future climate change targets will become more stringent as an unprecedented transformation in the energy system is necessary to meet the 32% renewable energy target set for 2030 and full decarbonization for 2050. As the share of renewables grows to meet the targets, the need for investments to match electricity supply and demand will increase, similarly to consumer bills. Thus, we expect the NRA tension to grow with the risk of decelerating the decarbonization pace.

If NRAs are not accountable for environmental performance, the independence negative impact will become more significant over time. A possible solution could be to evaluate the current NRA governance model and reconcile it with the environmental principles and mandates included in the CEP. According to Bartle and Vass (2007), coordination mechanisms between economic NRAs, the government, and other environmental stakeholders should be established without compromising the agency's independence. The NRAs' expertise and specialized knowledge place them as central actors in integrating renewable energies. There are three areas in which coordination can help NRAs to support decarbonization. First, NRAs can support information exchange between industry actors and provide their economic expertise to policymakers. The information flow can help decision-makers at any level to consider other actors' points of view and design optimal solutions. For example, economic NRAs' could share their experience on the undesired effects

of policies. Second, NRAs may take an advisory role in policy elaboration. This should facilitate the detection of policy conflicts and the trade-off assessment between competition and environmental objectives. Finally, the information disclosure with stakeholders should be augmented beyond the economic scope of the NRAs' operation.

The proposed model "tweaks" have concerns. Investors could interpret NRA's involvement in environmental matters as a deviation threat from its competition principles and mandates. If the perceived threat is significant, some investors might decide to hold up their investments. Besides, the NRA's participation in non-economic advisory might reduce the levels of specialized knowledge and expertise that the agency can accumulate. Finally, agencies might fail legislative hearings and other types of evaluations because their performance assessment is currently based on economic results. NRA's accountability provisions should account for the tasks required to support environmental targets (Bartle & Vass, 2007).

5.7 . Conclusions

In light of the challenges to achieve carbon neutrality in 2050, and the new "economic logic" that renewable energies have on current electric systems. This paper assessed the impact of the institutional context in which policymakers operate, particularly focusing on analyzing the impact of *independence*, and other three indicators of NRAs governance regimes (*discretion*, *transparency*, and *scope of Market Monitoring*) on the growth of renewable energies between 2013 and 2018. Our results show that NRA's *independence* negatively correlates with the growth of renewable energy share. In addition, we found that *transparency* is negatively correlated with electricity tariffs for industrial users.

The central argument of our work relies on the documented assumption that independent regulators were mandated to implement competition, reduce incumbent rents in favor of consumers, and ultimately trigger system reliability. Our findings suggest that independent regulators remained committed to their competition and efficiency mandates. This commitment conflicts with introducing renewables in the system because additional renewables increase system costs, e.g., excess power in the capacity market, which impacts competition, efficiency, and market stability.

Our main contribution is to provide robust quantitative evidence that between 2013 and 2018, the *independence* of NRAs decelerated the adoption

of renewable power in the electric sector. Finally, we discuss the current and future consequences of not reconciling the current governance model and new environmental legislation. We found many arguments supporting that future climate targets should become a part of the NRA mandates.

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6 - Conclusions

This dissertation set out to answer a critical question: *How should EVs be coordinated with electricity systems to become a tool to mitigate GHG emissions?* While technical challenges in V2G implementation are gradually being addressed through standardization and the introduction of V2G-capable vehicles, the commercialization of V2G and smart charging remains hindered by business model uncertainties, user adoption barriers, and fragmented perspectives among industry stakeholders.

Our research demonstrates that the integration of EVs into electricity systems is not merely a technical challenge but a complex interplay of information flow structures, user participation frameworks, and the alignment of economic and environmental objectives. The success of V2G and other smart grid applications depends not only on technological feasibility but also on how effectively EV users are integrated into grid operations and market mechanisms. Governance structures, regulatory frameworks, and market dynamics all shape the incentives and barriers for participation, influencing the scalability and effectiveness of smart grid coordination.

By reframing the coordination challenge as one of information complexity, governance, and systemic design, this dissertation provides a foundation for a more holistic and scalable approach to integrating V2G and renewable energy into the energy transition. Future research should examine how evolving regulatory frameworks, technological advancements, and market structures impact consumer participation. Additionally, a deeper exploration of transparency, standardization, automation, and market power will offer critical insights into optimizing governance models for residential prosumer integration and ensuring that smart grid systems support both economic efficiency and decarbonization objectives.

6.1 . Key Contributions

6.1.1 . Information Flow and Scalability Matter for Smart Grid Coordination

The effectiveness of smart grid applications, including V2G, is not solely dependent on algorithmic sophistication but also on how information is gath-

ered, structured, and exchanged. Our findings suggest that a failure to consider information flow complexity can result in operational inefficiencies, limiting the scalability of even the most advanced optimization algorithms. By introducing an assessment method based on scaling and information theory, we demonstrated that the structural design of the information network plays a crucial role in determining the minimum computation cost and its distribution as V2G applications scale.

6.1.2 . The Coordination of EVs in Power Systems is Shaped by Distinct Design Archetypes

Through a systematic review and empirical analysis, we identified four fundamental design archetypes for smart grid applications: *Hierarchical Design*, *Exponential*, *2.7-7.4*, and *1.7-2.7*. Each archetype reflects different approaches to information flow and system connectivity, offering distinct trade-offs in terms of complexity, scalability, and computational requirements. This insight challenges the prevailing assumption in the literature that data gathering and information structure are neutral factors in smart grid optimization. Instead, our research underscores that these factors fundamentally shape the effectiveness of EV-power system coordination.

6.1.3 . Green Information Systems and the Role of Inter-Organizational Information Sharing

Beyond technical and market challenges, the role of Green Information Systems (Green IS) in integrating EVs with electricity systems through V2G services is critical. By leveraging a simulation framework that introduces uncertainty from resilience engineering, we demonstrated how different Inter-Organizational Information System (IOIS) configurations impact the profitability and GHG reduction potential of a V2G aggregator operating in power markets. Our results show that while current industry standards provide a baseline for interoperability, they may not fully capture the potential value of information exchange, leading to suboptimal decision-making and missed economic and environmental opportunities. In particular, our study suggests that aggregators could significantly enhance their profitability—potentially doubling it—by integrating more detailed mobility information, such as future travel needs and departure times. This insight highlights the necessity of considering IOIS beyond existing communication protocols and encourages the development of more advanced IOIS architectures that foster collaboration rather than creating data silos.

6.1.4 . Governance Structures Influence the Success of Smart Grid Integration

This research extends beyond EVs to examine residential prosumer integration in smart grids. By developing a conceptual framework based on Transaction Cost Theory (TCT), we analyzed monitoring and switching costs, identifying four governance models that shape prosumer participation. Through comparative case studies, we demonstrated how different governance structures influence control mechanisms, interoperability, and economic incentives. Ultimately, successful smart grid coordination requires well-designed governance structures that align economic incentives, technological capabilities, and policy objectives.

6.1.5 . Regulatory Independence and Renewable Energy Growth

In light of the challenges to achieving carbon neutrality by 2050 and the economic transformation brought by renewable energies, our research also assessed the impact of institutional contexts on renewable energy growth. Specifically, we analyzed how the independence of National Regulatory Authorities (NRAs) and three other governance indicators—*discretion*, *transparency*, and *scope of market monitoring*—influenced the expansion of renewable energy between 2013 and 2018. Our results show that the independence of NRAs negatively correlates with the growth of renewable energy share. This highlights the tension between existing regulatory mandates and evolving climate policies. Independent regulators have historically prioritized competition and efficiency, but the rapid expansion of renewables introduces new system costs that challenge these priorities. Our research underscores the importance of reconciling the current governance model with new environmental legislation. Moving forward, climate targets should become an explicit part of NRA mandates to align economic incentives with sustainability goals.

6.1.6 . Reconceptualizing “Good Coordination” in V2G and Smart Grid Systems

The concept of "good coordination" in integrating electric vehicles (EVs) with power systems and smart grid applications is not solely about technological innovation but also about how information is structured and exchanged across a broad network of stakeholders. Our findings show that existing V2G research often overlooks the complexities of information flow and system design, which can hinder the scalability and efficiency of coordination strategies. Instead of focusing only on algorithmic optimization, we emphasize

the need for a broader systems perspective that considers how coordination archetypes—such as hierarchical and exponential designs—interact and complement each other. The complexity paradigm allows for a deeper understanding of the trade-offs involved in coordinating EVs, which the underlying information networks and governance structures can influence. By integrating insights from technology and governance, we can overcome the fragmentation observed in industry practices and regulatory frameworks, paving the way for more effective policy development and market design. This approach could be crucial for shaping future research agendas on smart grid governance, ensuring a more integrated and sustainable deployment of V2G technologies.

6.2 . Future Directions

6.2.1 . How complex can smart grids be?

Addressing this question will provide deeper insights into the limits of scalability and efficiency in V2G applications, helping system operators, policymakers, and industry stakeholders design better coordination mechanisms for integrating EVs and prosumers into electricity networks. Furthermore, understanding how different coordination structures interact will be crucial for advancing smart grid applications and ensuring that V2G systems deliver on their promise to decarbonize electricity grids effectively.

6.2.2 . How does competition for information influence the effectiveness of V2G systems?

Further research is needed to explore the economics of information competition among aggregators, the behavioral aspects of EV owners' relationships with aggregator information systems, and the governance trade-offs in prosumer integration. These factors will play a crucial role in shaping the business models and adoption dynamics of V2G technology and distributed energy systems.

6.2.3 . 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.

6.2.4 . 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.

6.2.5 . 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 cyberse-

curity, 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.

6.2.6 . 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.

6.2.7 . How to align economic and environmental objectives in electricity systems?

Furthermore, regulatory frameworks must evolve to better support renewable energy integration. Our findings suggest that regulatory independence, while essential for market stability, may conflict with aggressive renewable deployment goals. A new balance must be struck between competition, efficiency, and sustainability, ensuring that climate targets are embedded in regulatory decision-making.

7 - Additional work on Carbon Capture Storage Technologies

7.1 . Modeling CO₂ Pipeline Systems: An Analytical Lens for CCS Regulation

In this paper I was a second author. The paper was co-written with Adrien Nicolle (First Author), Olivier Massol, and Emma Jagu Schippers

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Abstract

Carbon Capture and Storage (CCS) is regularly depicted as a crucial technology to reduce the social cost of achieving carbon neutrality. However, its deployment critically depends on the installation of CO₂ infrastructures. As the regulatory procedures governing their provision are yet to be clarified, this paper aims to assess the social and environmental impacts of such regulations. We show how the engineering equations of a CO₂ pipeline implicitly define a Cobb-Douglas production function. We then infer that the resulting cost function exhibits economies of scale and verifies the technological condition for a natural monopoly. As the possible exertion of market power is a concern, we evaluate the social distortion of the unregulated monopoly and the average-cost pricing solution, which we compare to the outcomes of the welfare-maximizing solution. While the deadweight loss obtained under average-cost pricing remains lower than 5% compared to the first best solution, our findings indicate that allocative efficiency is an issue, with more than a quarter of the CO₂ emissions not being transported. This analysis will usefully inform the emerging regulatory policy debates on CCS by providing the first analytically determined cost function of a CO₂ pipeline.

7.1.1 . Introduction

The perception of Carbon Capture Storage (CCS) as a relevant technology to achieve global climate targets has fluctuated substantially over time, alternating between periods of high hopes and disillusionment. In the 2000s, mitigation scenarios envisioned a widespread and rapid deployment of CCS, a

technology then presented as promising and cost-effective (IPCC, 2005). For instance, the International Energy Agency (IEA) emphasized that renouncing this technology might increase social mitigation costs by 70% (IEA, 2009). However, in the 2010s, the meager progress observed in CCS implementation triggered a growing skepticism (von Hirschhausen et al., 2012), questioning the feasibility of previous deployment targets. At present, CCS is again gaining momentum as new policies – e.g., the Inflation Reduction Act (117th Congress, 2022) and the Net Zero Industry Act (European Commission, 2023) – ambition to accelerate its deployment by lowering administrative barriers and closing the financial gap with generous subsidies. Nevertheless, one can wonder whether they will be sufficient to unlock the emergence of CCS as recent reports call for new policy approaches to reduce the institutional uncertainties surrounding that technology (IEA, 2021; IPCC, 2022).

Choosing the right policy instrument is challenging because it must simultaneously address issues about the supply and demand of CCS. From the supply-side, attracting investors to develop CCS transportation infrastructures is challenging because of the high sunk costs and the need to gather a critical volume of captured CO₂ in the projected infrastructure. That volume has significant implications for the sizing of the infrastructure and its cost. Thus, investors need more certainty on the expected volume of CO₂ emissions to be transported (Cai et al., 2014). From the demand-side, emitting firms are cautious about investing in a capture unit, as they face uncertainties from a possible range of future carbon prices and options to mitigate their emissions (Heydari et al., 2012). Moreover, both sides face uncertainty in the prices for transporting the captured emissions. As the pipeline operator will presumably be monopolistic, its pricing behavior (i.e., pricing levels, tariff structure) may be prone to regulatory oversight. If the actions taken by the governmental agency that creates and enforces sectoral regulations are uncertain, so are both the consumer surplus obtained by the emitters that adopt carbon capture and the ability of the pipeline operator to recoup its cost. Hence, absent a clear regulatory signal, neither emitters nor pipeline operators will engage in CCS deployment.

The purpose of this paper is thus the following: How does the regulation of CCS pipeline transportation impact social welfare? Our study aims to provide insights into the impact of CCS transport regulation, with the broader goal of quantifying the social cost of decarbonization. From a policymaking perspective, we aim to provide the CCS pipeline infrastructure's regulator with the first analytical cost function to reduce the informational asymmetry between the regulated firm and itself. Bridging this informational gap will help the regulator identify the required pricing scheme to maximize the social welfare of CCS pipeline infrastructures.

From a methodological perspective, this paper adapts the theoretical lens of engineering economics applied to natural gas pipelines, which shows the substitution effects between capital and energy (Chenery, 1949; Massol, 2011; Perrotton & Massol, 2018; Yépez, 2008). Through this technical representation, we describe the microeconomic behavior of a CO₂ pipeline operator that transports the emissions through a single point-to-point pipeline system. By assuming a cost-minimizing operator, we quantify the impact of regulation on the level of capital investment analytically, the quantity of CO₂ that the pipeline operator agrees to transport – i.e., the supply for the transportation service – the pipeline operator’s profit, and the social welfare.

Our analysis conveys a series of new findings. We show that the technology of a point-to-point CO₂ trunk pipeline system can be represented using a Cobb-Douglas production function with two inputs: capital and energy. We prove that this system exhibits pronounced economies of scale, that the long-run total cost function is subadditive, and that it thus verifies the theoretical condition for a natural monopoly. This finding has important policy implications, as it suggests that some form of regulatory intervention may be necessary to alleviate the adverse effects resulting from the exertion of monopolistic power. We show how this could create an underutilization of the CCS transportation system, thus undermining eventual environmental objectives. Following these results, we discuss some assumptions of our model and suggest future avenues of research.

Our technological representation departs from the usual representations of CCS pipeline transportation in Integrated Assessment Models (IAMs) and the economic literature. In IAMs, these representations have been criticized for lacking transparency and precision (Butnar et al., 2020; Luderer et al., 2022). In the economic literature, the cost functions for CCS transportation do not account for the specificity of CO₂ (Knoope et al., 2013), with most studies considering the physics of natural gas transportation instead. In this perspective, Viebahn and Chappin (2018) stress in their literature review that CCS is a complex technology that requires interdisciplinary approaches. This perspective has inspired the present technological representation, which brings together economic and engineering models that have so far developed independently. With few exceptions (e.g., Massol et al. (2015)), economists use a simplified representation of the technology of a CO₂ pipeline, typically a total cost function with a linear (sometimes piecewise linear) specification. Hence, our approach substantially departs from the network optimization studies (d’Amore & Bezzo, 2017; Holz et al., 2021; Jagu Schippers & Massol, 2022; Kemp & Sola Kasim, 2010; Klock et al., 2010; Mendelevitch et al., 2010; Middleton & Bielicki, 2009; Morbee et al., 2012; Oei & Mendelevitch, 2016; Oei et al., 2014; Tutton, 2018; Waxman et al., 2021; Zhang et

al., 2018). The merits of these numerical studies are that they capture the network interactions among multiple sources and sinks. However, they rely on optimization models solved numerically and de facto embed a simplified (typically linear) cost function representation. In the present manuscript, we thus abstract from analyzing the interactions among multiple sources and aim to concentrate on an analytical approach capable of revealing essential features of the technology of a simple point-to-point CO₂ pipeline infrastructure. These models are used extensively to guide policymaking but consistently overlook the underlying engineering problems in developing pipeline systems. By contrast, the engineering literature focuses on the complex physics governing CO₂ pipeline transportation but does little to explore the economic implications (McCoy, 2008; McCoy & Rubin, 2005).

This paper's first main contribution is its technical representation of the CO₂ pipeline technology, bridging the gap between engineering and economics. Second, this paper contributes to the growing literature that identifies and provides policy insights to overcome barriers faced by the large-scale deployment of CCS infrastructures. Through our novel technical representation of the CO₂ pipeline system, this paper is the first quantitative contribution to the economic regulation literature of CCS pipeline infrastructures. A portion of the economic literature seeks the causes behind the failure of large-scale deployment, but few papers provide substantial regulatory insights.

Our paper is organized as follows. Section 7.1.2 provides an overview of the regulatory approaches envisioned for CO₂ infrastructures. Section 7.1.3 presents the engineering-based production function and its properties. The implications are discussed in Section 7.1.4. The last section 7.1.5 concludes.

7.1.2 . Background and motivation

CO₂ pipeline systems: an infrastructure sector in need of regulation

CCS is experiencing an upward momentum. In 2022, the annual capacity of the CCS projects under development attained 244 million tons of CO₂, which is 45% larger than the 2021 inventory . Most of these projects focus on the emissions from industrial plants (e.g., cement, iron and steel, gas treatment, petrochemical plants) and are located in the US, the UK, Norway, and the EU, in which public authorities recently unveiled ambitious development plans.¹

¹Namely: the US Inflation Reduction Act of 2022 (117th Congress, 2022), the UK's CCUS Infrastructure Fund (BEIS, 2021), the Net Zero Industry Act (European Commission, 2023), the State Support Agreements defining the participation of the Norwegian state in the Longship CCS project in Norway (Norwegian Ministry of Petroleum and Energy, 2022), the

These projects heavily rely on the installation of a CO₂ pipeline system connecting a carbon capture facility to a storage site. These transportation infrastructures are expected to grow organically to connect several emitters and form a network that could ultimately reach a continental scale.² However, deploying a CO₂ pipeline infrastructure critically depends on the institutional framework governing its provision.

Infrastructure sectors, such as CCS pipeline infrastructures, are commonly designated as “natural monopolies” as it is more cost-efficient when a single firm, the monopolist, supplies the market. Indeed, the cost functions of network infrastructures typically exhibit substantial economies of scale, declining average costs, and subadditivity. Furthermore, these sectors are capital-intensive, with high upfront sunk costs. However, even if there are efficiencies from having a monopoly operating infrastructures, it also creates the risk of market power abuse. In this case, the monopoly would reduce social efficiency by increasing consumer prices, which calls for regulatory intervention.

The contemporary regulatory frameworks governing CO₂ pipeline systems

Table 7.1 summarizes the institutional approaches and practices retained in early-adopter regions: the US, the UK, Norway, and the EU.

Danish Carbon Capture scheme (Danish Energy Agency, 2022), or the Dutch Sustainable Energy Transition Subsidy Scheme “SDE++” (Dutch Ministry of Economic Affairs and Climate Policy, 2023).

²For example, the European CO₂ pipeline system modeled in Oei and Mendelevitch (2016) runs 45,000 km by 2050. In the US, the full economy decarbonization scenario examined by Larson et al. (2020) requires the installing installation of 21,000 km of trunk lines and 85,000 km of spur lines by 2050.

	UK	U.S. Interstate	U.S. Intrastate	Norway	EU
Regulatory agency for rates and access	Ofgem likely to be appointed (BEIS, 2022)	Unclear regulatory mandate for pipelines crossing some federal lands and for pipelines not crossing federal lands	No agency, except for common carriers in Texas and Colorado	No agency but the state intervenes as a project leader and as a stakeholder in the transportation infrastructure (Gassnova SF, 2022)	Silent legislation
Non-discriminatory access prices	Yes	Mandatory for common carriers	Generally mandatory for common carriers	Yes (informational discussion)	Yes
Pricing scheme	Rate-of-return regulation combined with performance incentives (BEIS, 2022)	Project-dependent (STB intervenes in case of a dispute)	Project-dependent	Two-tariff structure: (i) a user-specific maritime component based on distance, and (ii) a non-discriminatory access charge to the Norwegian onshore receiving terminal, the offshore pipeline, and the storage site	Silent regulation

Table 7.1: Review of regulatory initiatives in early-adopter regions for CCS pipeline infrastructures

From Table 7.1, these jurisdictions tend to advocate third-party access to these infrastructures. That said, we observe essential variations in the governance and pricing schemes imposed on CCS pipelines. We distinguish here three types. The first type is the explicit approach retained in the UK. It provides Ofgem – the independent regulatory agency in charge of natural gas and power infrastructures – with an enlarged mandate that makes it responsible for regulating CO₂ infrastructures. Accordingly, the CCS chain is subject to a vertical unbundling, whereby a dedicated infrastructure operator must provide transportation under price control (BEIS, 2022). Consistent with Ofgem’s conventional approach to the regulation of natural gas networks, the regulator sets and administers the allowed revenue by defining: (i) a regulated asset base comprising the allowed capital expenditures, (ii) an allowed rate of return, (iii) the operating expenditures that the operator can recoup, and (iv) a series of performance targets to be defined.

The second approach involves some degree of state participation, as in Norway’s Longship project. Two Norwegian industrial sites (a cement plant and waste-to-energy facility) will capture their CO₂ emissions, which the

Northern Lights consortium will transport and store.³ The state intervenes at several levels: it leads the Longship project via its state-owned enterprise Gassnova (Gassnova SF, 2022), has signed separate agreements with firms participating in the CCS value chain (Norwegian Ministry of Petroleum and Energy, 2022), and is an equal shareholder – together with Total and Shell – of the Northern Lights consortium through the state-owned company Equinor (Whitmore, 2021). From informal discussions with stakeholders, we understand that the pipeline system operator is supposed to charge cost-reflective non-discriminatory prices. In contrast, no obligations are set on the price charged for maritime shipments, which can thus vary according to the emitter's willingness. So far, it is unclear whether Northern Lights will be subject to some form of economic regulation after the first decade of operations.

The third type of approach depends on the federal setting of the governance regime, which is the case of the EU and the US. A fuzzy approach prevails, which echoes the non-exclusive powers of the Federal/EU jurisdictions concerning CO₂ pipelining and can accommodate the diversity of approaches prevailing at the lower (i.e., state or national) level.⁴⁵ However, this approach has not boosted the emergence of significant changes in the governance regime of CCS, which remains unclear in most parts .

Overall, the contours of the regulation imposed on CO₂ pipeline systems look poorly defined. Regulatory mandates are uncertain in most cases, suggesting that public authorities have not grasped the monopolistic nature of the pipeline operator and the consequences that this may have (as seems to be the case in the US and the EU). Where a mandate exists, as in the UK, the regulatory framework seems to be strongly inspired by the case of natural gas. This choice might be due to the lack of data on the cost function of CO₂ pipeline systems, forcing the regulator to draw on the natural gas case and apply the same policy instruments. In light of this observation, it is urgent to clarify (i) whether the CO₂ pipeline system verifies the conditions of a natural monopoly and, if so, (ii) to determine the associated cost function, thus reducing the information asymmetry with the regulated firm.

³Northern Lights has two activities: (i) it ships the CO₂ to an onshore reception terminal and, from there, (ii) transports the CO₂ by pipeline to a subsea storage.

⁴In Europe, the EU authorities stress the obligation to grant third-party access, but they remain silent on important issues such as: the nature of the vertical unbundling imposed on the CCS chain, the pricing provisions (i.e., to what extent can prices depart from purely uniform charges?), and the type of price controls imposed on the pipeline operator.

⁵In the US, while it is likely that some form of rate of return regulation will be implemented on an interstate level – an approach already applied to other infrastructure sectors (Viscusi et al., 2000) – the allowed rate of return and thus the allowed revenue obtained by the operator still needs to be clarified.

To our knowledge, the literature on CCS largely ignores these issues. Only a handful of papers mention the possibility that the pipeline operator is a natural monopoly (Krahé et al., 2013; Massol et al., 2015; Roggenkamp & Haan-Kamminga, 2010) but do not provide evidence of this claim nor present a quantitative discussion of the associated social impacts. In the extensive gray literature, only a few policy briefs and reports mention the industry's lack of economic regulation (Elkerbout & Bryhn, 2019; Whitmore, 2021).

Possible regulatory approaches to model the economics of CO₂ pipelines

Recall that regulators must find a pricing scheme that maximizes social surplus under incomplete information (Laffont & Tirole, 1986, 1994). The regulator faces many informational gaps, but the incomplete knowledge of the regulated firm's costs is the most relevant (Joskow, 1999).⁶ In other words, the economic regulator needs to make a preliminary assessment of the cost function of the regulated firm through auditing – requiring the regulated firm to produce reports – or benchmarking. Indeed, firms might seize this information gap to maximize their profits given the constraints imposed by the regulatory process (Wolak, 1994). More recently, Glachant et al. (2013) explained how bounded regulatory commissions can select regulation tools according to the type of investments and decisions they must undertake, considering their capacities for actions and means. Given their bounded capacities, having analytical tools capable of mimicking a regulated firm's investment and operation decisions is necessary for designing effective regulatory frameworks. Knowledge of the cost function and the technology at hand (i.e., the relations between the output of the infrastructure and the inputs) is particularly relevant in this context.

Regulatory economics apply three different methodological approaches to gain insights into the technology of an infrastructure sector. The first category gathers the studies based on frontier-based benchmarking techniques developed in the vein of Data Envelopment Analysis (DEA). DEA uses piecewise linear programming to calculate the efficient frontier of a sample (Färe et al., 2013). This nonparametric method determines the efficient performance frontier from best industry practices and represents a popular benchmarking tool in the electricity sector (Jamasb et al., 2004). The second category involves the econometric estimation of a flexible functional form – usually a translog specification – to obtain an approximate cost function. Regulation of natural gas pipelines in North America has widely applied this method (Ellig &

⁶Other sources of informational asymmetry concern budget constraints and governance weaknesses

Giberson, 1993; Gordon et al., 2003; Oliver, 2015). The third category gathers the process models that derive analytical production and cost functions from technological information. That approach has its theoretical roots in the pioneering works of (Chenery, 1949, 1952), Leontief and his associates (Leontief, 1953) and Smith (1959, 1961). Studies have used this method to deal with regulatory issues of natural gas pipeline (Callen, 1978; Massol, 2011; Perrotton & Massol, 2018; Thompson et al., 1972; Yépez, 2008).

By nature, frontier-oriented benchmarking and econometric methods have an empirical nature and thus require a sample of observations. This feature is a concern when the infrastructure sector under scrutiny is emerging and only gathers a handful of projects, such as CO₂ pipelining. The industrial organization retained for the few existing CCS projects is also problematic: So far, these demonstration projects were vertically integrated supply chains with a firm possessing the capture plant and its transportation system (GCCSI, 2021). To our knowledge, none of these projects publishes detailed accounting data, which makes it possible to decompose the cost of each component. This context contrasts sharply with other network infrastructures, whose regulation intervened for existing and well-known infrastructures. Interestingly, cost functions in the academic literature do not provide any help to regulators either, as reported by Knoope et al. (2013): only a few models account for the costs of the pumping station, and most models rely on the empirical cost data of the natural gas industry instead of considering the impact of CO₂'s physical properties on the cost function. Against this background, the present paper opts for the third approach and examines how the specification of a process model can provide regulators with valuable insights.

7.1.3 . An engineering-based analytical cost function for CO₂ pipelining

Modeling a CO₂ pipeline cost function

Inspired by Chenery (1949) and Yépez (2008), we consider a CO₂ pipeline system consisting of a point-to-point pipeline and a pumping station. This system is the simplest possible CO₂ transportation infrastructure connecting one entry node (e.g., a cluster of industrial emitters with carbon capture capabilities) to one sink (e.g., a neighboring storage site as in emerging CCS projects: Northern Lights in Norway or Net Zero Teesside in the UK).⁷ By

⁷Northern Lights collects CO₂ emissions through shipping and stores the aggregated CO₂ emissions in an intermediate storage site before transporting them to the storage site through an offshore CO₂ pipeline. For Net Zero Teesside, CO₂ emissions are first collected through feeder pipelines. An offshore point-to-point trunkline then transports the emissions to the offshore storage site.

nature, this basic system can also provide valuable knowledge on more complex infrastructures with a modular type. For example, a trunkline system can be decomposed into a collection of such basic infrastructures that are serially associated with enabling long-distance transportation.⁸ Similarly, the extensive network systems envisioned at the national or continental scale can also be decomposed into a collection of such elementary infrastructures.

We considered three engineering variables (the pumping power, the mass flow or output, and the inside diameter of the pipe) and a system of three engineering equations (a pumping equation, a flow equation, and a mechanical stability equation; see the details in Table ??) govern the simple infrastructure at hand. Remarking that the infrastructure uses two economic inputs – namely the capital immobilized K , and the energy needed for powering the pumping equipment E – and has a single output Q (i.e., the flow of CO₂ to be transported) and clarifying the relations between these economic variables and the engineering ones, we show that the system of engineering equations at hand defines the following Cobb-Douglas production function :

$$Q^\beta = K^\alpha E^{(1-\alpha)} \quad (7.1)$$

where the values of the technical coefficients $\beta = 9/11$, and $\alpha = 8/11$ are directly obtained from the engineering analysis. The production function (7.1) allows smooth substitutions between the two input variables.

Given the prevailing energy and capital market prices (denoted by e and r respectively), the least-cost combination of inputs required to transport a given flow is the solution to the long-run cost-minimization problem. Solving, one obtains the following long-run total cost function :

$$C(Q) = \frac{r^\alpha e^{1-\alpha}}{\alpha^\alpha (1-\alpha)^{1-\alpha}} Q^\beta \quad (7.2)$$

Observe that $\beta < 1$. The long-run cost function is strictly concave and thus strictly subadditive (Sharkey, 1982). It is cheaper to transport CO₂ from

⁸Although the candidate topology of pipeline systems retained in network optimization studies allows a potentially meshed structure, the structure of the resulting least-cost solutions exhibits a conventional star/tree network topologies with no mesh properties – see the solutions obtained for the cases of California Middleton and Bielicki (2009), Europe (Morbee et al., 2012), Spain (Massol et al., 2018), Norway (Klokk et al., 2010), the UK (Kemp & Sola Kasim, 2010) or Sweden (Jagu Schippers & Massol, 2022). Hence, such networks can be decomposed into elementary modules such as the one under scrutiny in this paper.

point to point within an infrastructure operated by a single firm than by any collection of independent pipeline systems. Therefore, the CO₂ pipeline system verifies the technical definition of a natural monopoly (P. L. Joskow, 2007). This result raises the question of allocative efficiency.

Market outcomes

Using the cost function above, we adopt the regulator's perspective to address the following two issues: (i) the magnitude of the associated social cost from the lack of economic regulation and (ii) the effect of a regulatory setting on the monopolist's decisions, and thus on social welfare. We consider the market outcomes obtained under the three standard cases of a regulator with complete information : (i) the marginal cost-pricing organization (superscripted *), (ii) the unregulated private monopoly (superscripted *M*), and (iii) the average cost-pricing solution, where the net social welfare is maximized while allowing the infrastructure operator to break even (superscripted *avg*).

We assume that the demand for pipeline transportation originates from a collection of large stationary emitters equipped with carbon capture capabilities that can connect to the infrastructure. For concision, we overlook their decision problems and state that their aggregate demand for CO₂ transportation services can be modeled using a simple inverse demand function: $P(Q) = A \cdot Q^{-\epsilon}$ where $1/\epsilon$ is the absolute price elasticity of demand and A the demand coefficient. We also retain the technical assumptions: $\epsilon < 1$ so that without any output, the monopolist's total revenue is zero, and $\epsilon > 1 - \beta$. Using these assumptions, we determine the closed-form expressions of the solutions to the three standard cases above .

To compare the market outcomes, we use performance ratios that have closed-forms expressions and are determined by the technology parameters (i.e., α and β) and the demand elasticity. They are invariant with the relative input prices and the demand coefficient A . We opt for a numerical approach and consider a realistic value for the price elasticity parameter. In the sequel, we take -1.25 for the price elasticity of demand and conduct a sensitivity analysis around that reference.⁹ The results are presented in Table 7.2.

⁹The -1.25 figure was obtained from the econometric estimation of a simple isoelastic inverse demand specification using data representing the volume and marginal willingness to pay for transportation services in Sweden. That willingness-to-pay was computed using the capture cost data in Johnsson et al. (2020)), a reference carbon price of 100€ per ton of CO₂ and the carbon storage cost data in IEAGHG and ZEP (2011).

	1.13	1.19	$1/\varepsilon$ 1.25	1.31	1.38
Output ratio					
$\frac{Q^M}{Q^*}$	0.046	0.062	0.074	0.084	0.093
$\frac{Q^{avg}}{Q^*}$	0.752	0.737	0.723	0.708	0.691
Capital ratio					
$\frac{K^M}{K^*}$	0.081	0.102	0.119	0.132	0.143
$\frac{K^{avg}}{K^*}$	0.792	0.779	0.767	0.754	0.739
Profit ratio					
$\frac{\Pi(Q^*)}{P(Q^*)Q^*}$	-0.222	-0.222	-0.222	-0.222	-0.222
$\frac{\Pi(Q^M)}{P(Q^*)Q^*}$	0.603	0.516	0.449	0.395	0.345
$\frac{\Pi(Q^{avg})}{P(Q^*)Q^*}$	0.000	0.000	0.000	0.000	0.000
Welfare ratio					
$\frac{W(Q)}{W(Q^*)}$	0.804	0.772	0.748	0.729	0.711
$\frac{W(Q^{avg})}{W(Q^*)}$	0.996	0.995	0.992	0.990	0.987

Table 7.2: Numerical results of the performance ratios.

Absent any form of regulation, a private monopoly transports less than 10% of Q^* , the socially desirable quantity of CO_2 . This rationing is also apparent in the operator's investment decisions K^M . With the price elasticity figures at hand, the monopolist installs less than 15% of the capital stock K^* installed by a benevolent social planner. Unsurprisingly, the monopolist obtains hefty profits $\Pi(Q^M)$ and that organization brings a considerable dead-weight loss representing between 19% and 29% of the maximal net social welfare $W(Q^*)$. These results show the necessity of protecting consumers from the monopoly pricing behavior of a private pipeline operator.

To correct this market failure, one can suggest imposing the marginal cost-

pricing solution by transporting Q^* , as it maximizes social welfare. This decision supports a classic microeconomic result indicating that pricing at marginal cost maximizes social welfare and is the first-best solution. Similarly, microeconomic textbook results suggest that this socially desirable organization does not allow the monopolist to recover its costs. Indeed, the corresponding loss is substantial as $\Pi(Q^*)$ represents -22.2% of the total revenue $P(Q^*)Q^*$. Absent any subsidy, this solution does not allow the pipeline operator to break even.

The average cost pricing rule alleviates this issue by ensuring a non-negative profit for the pipeline operator and minimizing social welfare losses (i.e., it is the second-best solution). Compared with the socially desirable benchmark, this second-best organization achieves a high level of net social welfare $W(Q^{avg})$ that represents at least 98% of the theoretical reference level $W(Q^*)$.

7.1.4 . Discussion and policy implications

We organize our discussion in two parts. First, we discuss the advantages of considering the physical characteristics of CO₂ emissions. Then, we adopt the perspective of the economic regulator and analyze how other factors – environmental policy and advanced knowledge of the demand of emitters – could influence its approach and how our model could incorporate such aspects.

Providing a first analytical cost function to CCS pipeline transportation

In contrast to most earlier studies that rely on natural gas cost data to infer the economics of CO₂ pipelining (Knoope et al., 2013), the present analysis accounts for the technical properties of the CO₂ fluid. Calculating the marginal to average cost ratio, we find that it is less than one, which proves that there are substantial economies of scale in CO₂ pipelining. We also proved that the CO₂ pipeline system verifies the technological condition for a natural monopoly as the cost function is strictly subadditive.¹⁰ This critical finding provides a scientific justification for an assumption repeatedly retained but so far unproven.

Aside from this analytical result, our model is a practical analytical tool for policymakers governing CCS transportation infrastructures. Indeed, our technological representation allows the regulator to determine the operator's

¹⁰Here $\beta = 0.81$, which is slightly greater than the 0.61 figure obtained in the empirical analysis conducted on natural gas pipelines by Massol (2011)

long-run total costs and the substitution effects between the pipeline's dimensions and the pumps. From a practical point of view, our considerations improves the technological understanding of the CO₂ pipeline system as it clarifies the links between the diameter of the pipeline and the amount of capital immobilized.¹¹ As measuring a diameter is straightforward, that relation provides the regulator with observable data to assess and track whether the capital expenditures made by the pipeline operator are justified for efficient transportation. Consequently, this technological representation reduces the information asymmetry between the regulator and the pipeline operator. It can help prevent some regulatory distortions (e.g., the Averch-Johnson effect, which is the tendency of the regulated firm subjected to rate-of-return regulation to overcapitalize). Hence, it can usefully assist a regulator bounded in its allocation of resources.

Insights for regulation

Using the previous technological representation, we test the impact of different pricing schemes for the CCS transportation network on generic benchmark strategies of economic regulation. We assume the regulator is fully informed of the firm's cost function. We find that imposing average cost pricing on a CO₂ pipeline operator yields only a slight deadweight loss while allowing the pipeline operator to break even.¹² However, while this pricing scheme allows investors to break even compared to marginal pricing, its pernicious consequences on the social cost of achieving environmental targets might be substantial. Indeed, under average cost pricing, the network transports (and thus captures and sequesters) fewer CO₂ emissions: the volume Q^{avg} comprises between 69% and 75% of the socially desirable benchmark Q^* (see Table 7.2), which indicates that at least a quarter of the volume is not captured. The corresponding efficiency gap ($Q^* - Q^{avg}$) emanates from emitters with a marginal willingness-to-pay for a transportation service that is both: (i) greater than the marginal cost to provide the service, and (ii) smaller than the average cost price. The monopolist also installs a capital stock comprised of between 74% and 79% of the theoretical reference K^* .

We see from the above that economic regulation is inseparable from en-

¹¹The capital is linked to the squared diameter D as $K = p_s w_s L \pi D^2 (a + a^2)$, where p_s denotes the unit price of steel, w_s denotes the weight of steel per unit of volume and a a fraction of the pipeline diameter.

¹²The purpose of this paper is not to discuss the challenges faced in the implementation of that second-best solution, something that can be found elsewhere. We refer to P. L. Joskow (2007) for a comprehensive discussion of the challenging implementation of that pricing rule which requires a perfect knowledge of both the costs and the price elasticity of demand.

vironmental regulation.¹³ We now argue that our study can be extended to account for specific environmental policies by modifying the elasticity of demand. Indeed, our study could be adapted to study the impact of CCS regulation in combination with other environmental policies. For example, if a state adopts a CO₂ emission price, this will affect the overall elasticity of transport demand. If the price is high enough, emitting sites will prefer to capture their emissions, and their elasticity will be low (and will be close to 1). Our study allows us to quantify such effects (and in such cases, the ratio of the monopolist's welfare over the first-best welfare is almost equal to 1), but specifying the link between the CO₂ emission price and elasticity is left to future research.¹⁴

We assumed an aggregate demand from emitters without acknowledging their differences. However, the demand for transportation is heterogeneous because of the plurality of emitters' profiles: industrial emitters do not have the same emission profiles, whether in terms of volumes, seasonality, or substitutes to carbon capture (Garðarsdóttir et al., 2018; Johnsson et al., 2020). Regions could adopt price discrimination depending on the nature of the heterogeneity to maximize the industry's social welfare. Indeed, economic theory suggests that it is a suitable option if the regulated firm can identify different submarkets with various willingness-to-pay or different demand elasticities. From this perspective, Norway already seems to depart from the non-discriminatory tradition. It adapts its tariffication to the heterogeneous demand: although promoting non-discriminatory access, Northern Lights seems to have to arbitrate between future users due to the limited capacity of its infrastructure. Indeed, of the 1.5 MtCO₂/y of planned capacity in the first phase, already 0.8 MtCO₂/y is reserved for the first two users. In short, access to Northern Lights appears to be similar to third-degree price discrimination. Overall, our study suggests that a closer look at the demand for transportation could incentivize more specific forms of regulation, such as price discrimination. We leave these aspects to further research.

7.1.5 . Conclusions

There are both high hopes and concerns over the future deployment of CCS. CCS is gaining unprecedented momentum, and mitigation scenarios expect it to become a relevant technology to achieve global climate targets

¹³Through a game-theoretic perspective, Jagu Schippers and Massol (2022) explore the impact of carbon removal accounting on the CO₂ infrastructure development for CCS and BECCS.

¹⁴Similarly, the existence of an emission allowance market will necessarily impact demand, which can be partially reflected through the elasticity of demand.

efficiently, especially within industries where CO₂ mitigation alternatives are limited or too expensive to implement. However, little attention is devoted to CCS pipeline infrastructures, although the deployment of the CCS industry is contingent upon these infrastructures. Thus, the fundamental policy issue addressed in this paper is to examine and quantify the economic effects that the regulatory framework imposed on a CCS pipeline system has on the social cost of achieving climate targets. The existing regulatory frameworks imposed on CO₂ pipelining remain unclear and vary significantly from one region to another. Our study questions whether regulators have genuinely grasped the monopolistic character of these infrastructures and the risk that the exhibition of market power can represent. Since part of the difficulty in regulating lies in the information asymmetry between the pipeline operator and the regulator, our paper aims to reduce this gap by determining the cost function of the former.

We propose a new representation of CO₂ pipeline systems that captures their essential engineering features: a Cobb-Douglas production function that allows substitution between two inputs (capital and energy), which verifies the technological condition of a natural monopoly. Our representation analytically validates the widely accepted – but rarely demonstrated – hypothesis that the CO₂ pipeline system exhibits economies of scale. We believe that this representation provides an observable and simple analytical understanding of the CO₂ pipeline system for policymakers, thus reducing the informational asymmetry between the regulator and the regulated firm. In practice, regulators most likely do not have complete information on the pipeline operator's cost function as these infrastructures are still emerging. Our model thus provides a framework for analyzing their economics and should thus be helpful to academics, regulators, and policymakers interested in their deployment.

Our work could also enrich cost functions retained in partial equilibrium models of the CCS industry thanks to its technical accuracy and economic interpretability. We examine the market outcomes and show that the dead-weight loss can be substantial without regulation. Our findings indicate that average cost pricing performs well regarding social welfare but yields a critical environmental issue, as allocative efficiency is not achieved. Nevertheless, the efficiency gap identified in this study critically relies on the posited use of a uniform, non-discriminatory price.

Future research could consider a more detailed analysis of the emitters' demand and explore alternative pricing forms. Adapting our model to accommodate different categories of emitters based on their respective willingness-to-pay and price elasticity is a possible research avenue. From a temporal point of view, future research could also integrate our technical representa-

tion in a dynamic version, including the rates the monopoly charges over time. This representation could also inform emerging policy discussions, such as the need for optimally oversized transportation infrastructures (see, e.g., Nicolle and Massol (2023) for a preliminary discussion), the debates on the timing of future regulatory interventions, or whether regulation should be ex-ante or ex-post.

From a spatial point of view, our study essentially focuses on regulating a hypothetical pipeline project and thus omits spatial considerations regarding the regulation of transnational infrastructures. Likewise, our study does not discuss social issues such as public acceptance or right-of-way. Defining a clear regulatory framework and coordination among stakeholders (Jagu Schippers et al., 2022) is mandatory, and we believe that our CO₂ pipeline system representation can serve to quantify these purposes. Exploring these aspects would provide the CCS infrastructures' regulator with a better knowledge to assist the emergence of this industry, foster its large-scale deployment, and reduce the social cost of achieving carbon neutrality.

7.1.6 . References

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7.2 . Kickstarting Carbon Capture and Storage Adoption: Tailoring

Subsidies to Emitters' Needs

In this paper, I am a third author, the paper has been co-written with Adrien Nicolle (first author), and David Lowing.

This paper is under review in Energy Economics.

Abstract

Despite being an essential technology in industrial decarbonization scenarios, CCS struggles to achieve large-scale deployment. Indeed, emitters face a coordination problem, which prevents them from forming the critical mass the transportation operator needs to develop a network that leverages economies of scale. In response, many public entities have multiplied financing mechanisms to support CCS adoption. However, current subsidy mechanisms overlook the network infrastructure and do not acknowledge the heterogeneity of emitters. This paper introduces a methodology for distributing subsidies among industrial emitters based on their capture costs and network cost contribution while accounting for potential budgetary constraints. Firstly, we evaluate each emitter's contribution to the network cost through the Shapley value. Secondly, we define each emitter's subsidy claim by combining results from the first step with their capture cost. We then distribute the subsidies according to the Proportional bankruptcy solution. We justify this solution based on properties (axioms) we desire our subsidy distribution to verify. A key feature of our methodology is its flexibility. Indeed, each step can be adapted to suit the normative framework that a future study or policymaker wishes to posit. We apply our methodology to CCS deployment in France and compare our results to the conservative case where subsidies are distributed without considering the network. Our case study shows that our methodology leads to a more favorable subsidy distribution to upstream emitters, which are the most influential in CCS adoption.

7.2.1 . Introduction

Carbon capture and storage (CCS) is gaining strong momentum, with more than 200 projects announced in the past year (IEA, 2024). This recent enthusiasm contrasts with a roll-out that has so far been doomed, with less than a quarter of the announced large projects entering operation (Wang et al., 2021). Furthermore, even if all these projects were to proceed, the cumulative capture capacity would only reach 400 million tons of CO₂ per year (MtCO₂/y), far from the expected 1.6 GtCO₂/y by 2030 (IEA, 2021) or 3 GtCO₂/y by 2050 in the industrial sector only (IPCC, 2018).

Reaching the above figures requires building a costly CCS network infrastructure connecting emitters to storage sites. As in other networks, CCS pipeline transportation exhibits strong economies of scale and is the most cost-efficient transportation option in the long run (Oeuvray et al., 2024). To harness these economies of scale, it is therefore necessary to create industrial clusters in which emitters share the transportation and storage (T&S) infrastructure (Brownsort et al., 2016). Forming CCS clusters can be challenging as an industrial emitter waits for the T&S infrastructure before investing into carbon capture and, conversely, the T&S operator builds a T&S network only if a critical mass of emitters is willing to connect to it. Thus, CCS deployment faces a chicken-and-egg dilemma (European Commission et al., 2023; Herzog, 2011). As an illustration of this challenge, current projects mainly operate as vertically integrated systems (Fattouh et al., 2024) - thus overlooking potential economies of scale of a shared T&S infrastructure.

We identify two main underlying problems to the CCS chicken-and-egg dilemma. The first issue is the lack of a clear regulatory framework for T&S tariffs. Because poorly designed future regulations could prevent the T&S operator from recovering its costs, it prefers not to invest in the T&S network. Similarly, an emitter could be exposed to monopoly tariffs without regulation, making its investment in capture more costly than emitting CO₂ directly into the atmosphere. Thus, without a clear regulatory framework, neither party commits to CCS. In this perspective, the CCS community perceived the lack of a clear regulatory framework as the main obstacle to reaching commercial-scale deployment (Davies et al., 2013). A decade later, regulation of T&S tariffs is still fuzzy and unclear in practice (Nicolle et al., 2023). However, studies by Massol et al. (2015, 2018) have addressed this issue by considering the impact of regulated T&S tariffs on carbon capture adoption by industrial emitters.

The second issue is the coordination of heterogeneous emitters to attain a critical mass. Indeed, due to the various industrial processes (Leeson et al., 2017; Roussanaly et al., 2021) and purity of the flows (Naims, 2016), emitters face different capture costs. Moreover, some industries have a lack of alternatives to reduce their emissions while others have various options (Gerres et al., 2019). Consequently, under a similar economic incentive (such as the EU-ETS allowance price), emitters do not have the same willingness to join the CCS infrastructure. Thus, emitters face a coordination problem as described in Sákovics and Steiner (2012). According to the authors, public intervention in the form of appropriately distributed subsidies can overcome the coordination problem and avoid additional costs. In the case of CCS, appropriate subsidies could encourage enough emitters to invest in carbon capture simultaneously, thereby forming the critical mass needed for a T&S

operator to invest in a network leveraging economies of scale.

In the literature, the coordination of heterogeneous emitters through subsidies has yet to receive attention. The study by Comello and Reichelstein (2014) identifies the subsidy path required by natural gas power plants to adopt carbon capture and meet an emissions' standard. While their study identifies the minimal subsidy budget to overcome the coordination problem, they consider homogeneous agents and overlook the T&S network in the distribution of subsidies. A second body of literature based on cooperative game theory (Massol et al., 2015, 2018) and mixed complementarity problems (Mendelevitch, 2014) addresses the investment and operational decisions of heterogeneous industrial emitters. These studies include T&S aspects in the emitters' investment decisions. However, both studies incentivize CCS through a unique CO₂ price, thus ignoring dedicated subsidies to overcome the emitters' coordination problem. In contrast, a last strand of literature relying on real options detail the investment decision of a single emitter by considering subsidies (see the literature review by Agaton (2021)). However, these studies adopt a project-by-project approach (i.e., a single emitter), thus overlooking potential synergies between projects.

In practice, public entities have multiplied financing mechanisms to support CCS in the past years to encourage investment, but they seem to follow the same flaws as the literature. Indeed, subsidies are generally provided project-by-project, do not unveil the rationale behind the subsidy distribution, and do not acknowledge the heterogeneity of industrial emitters (see Fattouh et al. (2024) and GCCSI (2023) for a description of current funding mechanisms). Moreover, most subsidy mechanisms target only one stage of the CCS infrastructure. As a result, for a CCS project to be subsidized and thus viable, emitters must turn to one subsidy fund, while the T&S operator must turn to another. In the worst case, the CCS project can be abandoned because one of the agents did not receive the hoped-for subsidy.

Overall, the literature has not dealt with the emitters' coordination problem underlying the CCS chicken-and-egg dilemma and has not provided a general framework for distributing subsidies to industrial emitters. Thus, our research question is: How should CCS subsidies be distributed among emitters to kickstart CCS adoption?

To address this question, we develop a two-step methodology. In the first step, based on emitters' capture cost and a T&S network plan, our methodology assesses each emitter's funding need, hereafter referred to as each emitter's claim. Since T&S tariffs are unclear in the general case, we define an emitter's claim as the sum of its annual capture costs and network cost con-

tribution - i.e., not the sum of its capture cost and the T&S tariff charged by a T&S operator. Because this first stage primarily consists of allocating the network cost among emitters, it relies on elements of game theory such as the Shapley value (Shapley, 1953). Before proceeding with the second step, we assume that the sum of the claims exceeds the budget allocated to the public entity in charge of kickstarting CCS. Thus, we define a simple claims problem as detailed by O'Neill (1982). This seminal paper has given rise to a literature that identifies distribution rules (so-called bankruptcy solutions) for solving claims problems (Thomson, 2003, 2015). A particular strength of bankruptcy solutions is that they can be disaggregated into axioms (see Thomson (2015) for a survey on axiomatic characterizations of popular bankruptcy solutions). In this context, selecting one bankruptcy solution over another implies selecting the axioms that the user desires the resulting allocation to respect. Consequently, in the second step of our methodology, we start by selecting axioms relevant to the CCS context. These axioms define the Proportional solution, which distributes subsidies proportionally to emitters' claims. This solution is generally considered as the definition of fairness (Thomson, 2003). In the Appendix, we suggest other relevant desirable axioms - and thus bankruptcy solutions.

We apply our methodology to the case of France, whose government wishes to support CCS deployment through subsidies over the next decade (Comité national de l'industrie, 2023). We compare our results to the case where the emitters' claims are solely defined based on capture costs, similar to existing support mechanisms in Denmark (Agency, 2023; European Commission, 2023) and the Netherlands (Ministry of Economic Affairs and Climate Policy, 2023). Although the T&S network represents a small share of the CCS costs (less than 15% in our case), including it in the emitters' claims disrupts the distribution of subsidies, thus implying that policymakers should not overlook it when designing the subsidy distribution. In particular, we find that an emitter whose emissions pass through a large part of the network receives 40% more subsidies than in cases where claims are based solely on capture. Indeed, these upstream emitters reduce the transportation cost of other emitters.

The contributions of our paper are two-fold. First, we highlight the emitters' coordination problem and the need for public intervention through dedicated subsidies, which have yet to receive attention from policymakers and the CCS literature. From a policymaking perspective, we provide a subsidy distribution that acknowledges emitters' heterogeneity, avoids strategic behavior, and incorporates all the components of a CCS infrastructure. Secondly, we present a methodology that formalizes the design of CCS subsidy mechanisms. Indeed, our methodology provides a flexible framework in which

future studies can adapt the approach of each step: in the first step, future studies could replace the Shapley value with prevailing regulated T&S tariffs; in the second step, due to the axiomatic characterization of bankruptcy solutions, future studies could select axioms different from those retained in this study, thus obtaining a new distribution rule. Therefore, our methodology is part of a flexible normative framework that can be adjusted case-by-case.

The paper is organized as follows: in Section 7.2.2 we introduce the theoretical background, in Section 7.2.3, we present the methodology for the cooperative game and the bankruptcy approaches. In Section 7.2.4 we illustrate our methodology with the case of CCS deployment in France. We discuss our results in Section 7.2.7. Lastly, we conclude our paper in section 7.2.8.

7.2.2 . Theoretical background

In this section, we introduce key concepts for our methodology. First, in Subsection 7.2.2, we provide some preliminaries on cooperative game theory, a research field well-known for addressing economic allocation problems where agents can benefit from coordinating with each other. Next, Subsection 7.2.2 discusses bankruptcy theory, another research field within game theory that studies resource allocation under budget constraints. Finally, Subsection 7.2.2 introduces the formalism of graph theory.

In the rest of the paper, we let $N \subset \mathbb{N}$ be a finite and countable set of objects. The cardinality of N , i.e., the number of elements of N is denoted by $|N|$. For each real-valued vector $x \in \mathbb{R}^{|N|}$, the sum of the coordinates of x is denoted by the norm $\|x\| = \sum_{i \in N} x_i$.

Cooperative game theory

Consider a non-empty and finite set $N \subset \mathbb{N}$ of economic agents referred to as **players**. Any subset $E \in 2^N$ is called a **coalition**, representing a group of cooperating players. The grand coalition N represents the scenario where all players cooperate, while the empty coalition $\emptyset$ depicts a situation with no cooperation. A transferable utility game, abbreviated as a **TU-game**, is defined as a pair (N, v) consisting of a finite player set $N \subset \mathbb{N}$ and a **characteristic function** $v : 2^N \rightarrow \mathbb{R}$, with $v(\emptyset) = 0$. The real number $v(E)$ can be interpreted as the cost generated by the players in coalition E when they collaborate. The class of TU-games with a finite set of players is denoted by $\mathbb{G}$. A TU-game $(N, v) \in \mathbb{G}$ is **submodular** if $v(E) + v(T) \geq v(E \cup T) + v(E \cap T)$ for any two $E, T \in 2^N$. A submodular game is a game in which it is highly

beneficial for players to cooperate with each others.¹⁵

A fundamental concern in TU-game theory revolves around the distribution of the grand coalition's cost $v(N)$ among the players. This concern is addressed by **single-valued solutions** for TU-games. In a TU-game $(N, v) \in \mathbb{G}$, each player $i \in N$ may obtain a payoff. A payoff vector $x \in \mathbb{R}^{|N|}$ is a $|N|$ -dimensional vector assigning a payoff $x_i \in \mathbb{R}$ to each player $i \in N$. A single-valued solution, or a value, is a mapping $f : \mathbb{G} \rightarrow \mathbb{R}$ that assigns a unique payoff vector $f(N, v)$ to each $(N, v) \in \mathbb{G}$.

The **Shapley value**, introduced by Shapley (1953), stands out as arguably the most prominent single-valued solution for TU-games. Its definition unfolds as follows. Imagine the grand coalition forming step by step, starting from the empty coalition $\emptyset$. At each step, a player joins the coalition, and this formation process follows a linear order $\theta \in \Theta_N$ defined over the player set N , where Θ_N represents the set of all possible linear orders over N . The step $\theta(i)$ denotes the step when player $i \in N$ enters. Upon a player's entry, there is a positive or negative impact on the coalition's cost. This impact is termed the **marginal contribution** of a player $i \in N$ to a coalition $E \in 2^{N \setminus \{i\}}$ within a game $(N, v) \in \mathbb{G}$ and is expressed as $v(E \cup \{i\}) - v(E)$. The Shapley value assigns to each player its average contribution to coalitions, assuming that the linear orders in Θ_N occur with equal probability.

[Shapley value] The Shapley value is the value Sh on $\mathbb{G}$ defined, for each $(N, v) \in \mathbb{G}$, as

$$\forall i \in N, \quad Sh_i(N, v) = \frac{1}{|\Theta_N|} \sum_{\theta \in \Theta_N} [v(E^{\theta, i} \cup \{i\}) - v(E^{\theta, i})],$$

where $E^{\theta, i} = \{j \in N : \theta(j) < \theta(i)\}$ is the set of predecessors of $i \in N$ with respect to θ .

The Shapley value always prescribes **efficient** payoff vectors, meaning that, for each $(N, v) \in \mathbb{G}$, it holds that $\|Sh_i(N, v)\| = v(N)$. The value is known to satisfy a number of other interesting properties with economic interpretations (see Winter (2002) and Algaba et al. (2019)) that emphasize its appeal. Among these properties, it is well-known that the Shapley value prescribes **coalition rational** payoff vectors on submodular TU-games. A payoff vector $x \in \mathbb{R}^{|N|}$ is coalition rational if no coalition of players has an interest to split off from cooperation, i.e., $\sum_{i \in E} x_i \geq v(E)$ for each $E \in 2^N$.

¹⁵Note that submodularity is considered a desirable property in our context, particularly when coalitions incur costs. In other contexts where coalitions generate positive utilities, submodularity may be less desirable, and one might prefer the property of supermodularity, which is the converse of submodularity.

The set of efficient and coalition rational payoff vectors associated with a game is known as its **Core**. The Core of a game can be interpreted as the set of stable payoff vectors, meaning that payoff vectors within this set incentivize players to participate in cooperation. [Core] For each $(N, v) \in \mathbb{G}$, the Core $C(N, v)$ of (N, v) is defined as the set of efficient and coalition rational payoff vectors. Obviously, if a TU-game is submodular, then the Shapley prescribes a payoff vector in the Core. Consequently, on submodular games, the Shapley value always prescribes payoffs that incentivize players to cooperate.¹⁶

Bankruptcy theory

An endowment $\mathcal{E} \in \mathbb{R}_+$ has to be divided among a set N of agents with claims adding up to more than $\mathcal{E}$. For each $i \in N$, let $c_i \in \mathbb{R}_+$ denote agent i 's claim, and $c = (c_i)_{i \in N}$ the vector of claims. Altogether, a bankruptcy problem is a tuple $(N, c, \mathcal{E})$ such that $\sum_{i \in N} c_i \geq \mathcal{E}$. Let $\mathbb{B}$ denote the class of all bankruptcy problems. A solution for bankruptcy problems is a function that associates, to each $(N, c, \mathcal{E}) \in \mathbb{B}$, an award vector $f(N, c, \mathcal{E}) \in \mathbb{R}^{|N|}$ whose coordinates add up to $\mathcal{E}$ and satisfy the inequality $0 \leq f_i(N, c, \mathcal{E}) \leq c_i$ for each $i \in N$. In this paper, we consider the Proportional solution to conduct our study. The Proportional solution assigns an award to each claimant proportional to their (relative) personal claim.

Consider any $(N, c, \mathcal{E}) \in \mathbb{B}$. The **Proportional** solution P is defined as

$$\forall i \in N, \quad P_i(N, c, \mathcal{E}) = \frac{c_i}{\sum_{j \in N} c_j} \mathcal{E}.$$

On the full domain of bankruptcy problems $\mathbb{B}$, the Proportional solution can be characterized by a combination of desirable properties, called axioms. This result is due to Moreno-Ternero (2006) and it invokes two axioms. We provide the formal expression of these axioms along with their (general) economic interpretations.

1. **Claim monotonicity:** for each $(N, c, \mathcal{E}) \in \mathbb{B}$, each $\lambda \in \mathbb{R}_{++}$ and each $i \in N$, $f_i(N, \mathcal{E}, c + \lambda e_i) \geq f_i(N, c, \mathcal{E})$.
2. **Non-manipulability:** for each $(N, c, \mathcal{E}), (N', c', \mathcal{E}) \in \mathbb{B}$ with $N' \subset N$, if there is a $i \in N'$ such that $c'_i = c_i + \sum_{j \in N \setminus N'} c_j$ and $(c'_j)_{j \in N \setminus i} =$

¹⁶This result is also formulated in terms of supermodularity, a concept opposite to submodularity, in contexts where coalitions generate positive utilities.

$(c_j)_{j \in M \setminus i}$, then

$$f_i(N', c', \mathcal{E}) = f_i(N, c, \mathcal{E}) + \sum_{j \in N \setminus N'} f_j(N, c, \mathcal{E}).$$

Claim monotonicity states that if an agent's claim increases, *ceteris paribus*, then they should receive at least as much as they did initially. Non-manipulability prevents strategic behavior. It states that if there is no incentive for a group of claimants to merge their claims into a single one or for a single agent to represent their claim as a collection of several claims.

[Moreno-Ternero (2006)] A solution f on $\mathbb{B}$ is the P solution if and only if it satisfies Claim monotonicity and Non-manipulability.

Graph theory

Let $M \subset \mathbb{N}$ be a finite set of objects. A **directed graph** on M is a pair (M, P) where elements of M are the nodes and $P : M \rightarrow 2^M$ is a map describing the links between the nodes. We assume that $i \notin P(i)$ for any $i \in M$. In the following, we denote a directed graph (M, P) just by P . For each $i \in M$, the nodes in $P(i)$ are called the successors of i . The nodes in $P^{-1}(i) = \{i' \in M : i \in P(i')\}$ are called the predecessors of i . A **directed path** from $i \in M$ to $i' \in M$ is a sequence of nodes $i = h_1, h_2, \dots, h_k = i'$ such that $h_k \in P(h_{k-1}), \dots, h_2 \in P(h_1)$. The transitive closure of a directed graph P is a directed graph $\hat{P}$, such that, for each $i \in M$, $i' \in \hat{P}(i)$ if and only if there exists a path from $i \in M$ to $i' \in M$. The nodes in $\hat{P}(i)$ are called the subordinates of i in P , and the nodes in $\hat{P}^{-1}(i)$ are called the superiors of i in P . Similarly, the set $\hat{P}(E)$ represents the subordinates of the nodes in $E \subseteq M$ and the set $\hat{P}^{-1}(E)$ represents the superiors of the nodes in $E \subseteq M$.

A directed graph is a **tree graph** if and only if there is a unique sink $i_0 \in M$ such that (a) the sink has no successor, i.e., $P(i_0) = \emptyset$, (b) the superiors of the sink are all the other nodes, i.e., $\hat{P}^{-1}(i_0) = M \setminus \{i_0\}$, and (c), each node aside from the sink has exactly one successor, i.e., $|P(i)| = 1$ for each $i \in M \setminus \{i_0\}$.

7.2.3 . Methodology

In this section, we present our methodology for distributing a subsidy among industrial CO₂ emitters. First, Subsection 7.2.3 formalizes our research question by introducing all the inputs and by defining the scope of our

problem. It then provides a brief overview of the two steps of our methodology. Subsection 7.2.3 and Subsection 7.2.3 delve deeper into the explanation of our methodology, expanding upon the theoretical background covered in the previous section.

Problem formulation

Inputs: Let $\mathcal{E} \in \mathbb{R}_+$ be the **subsidy budget** a public entity can afford to distribute. Let $N = \{a, b, \dots, n\}$ be a finite set of industrial **emitters**. Each emitter $i \in N$ is endowed with a real $x_i \in \mathbb{R}_+$ corresponding to its **capture cost**. The vector $x \in \mathbb{R}_+^n$ collects all capture costs. Let i_0 denote the storage. Constructing and managing a transportation network to link the emitters to storage is costly. To maximize economies of scale, it is necessary for emitters to cooperate in order to build an optimal network that minimizes transportation costs. In this paper, we use a Mixed Integer Linear Program (MILP) to determine such a **cost-optimal network**. Consequently, we obtain a tree graph $(N \cup \{i_0\}, P)$, or P for short, representing the (cost-optimal) transportation network. In this graph, nodes correspond to emitters, links represent pipelines, and the storage node serves as the sink. In addition, each pipeline is endowed with a real number $y_{ij} \in \mathbb{R}_+$, where $i, j \in N \cup \{i_0\}$ such that $P(i) = j$. This y_{ij} corresponds to the **transportation cost** generated by the pipeline linking emitters i and j . The vector of all transportation costs is given by $y \in \mathbb{R}_+^n$. For the rest of this paper, $\mathcal{E}$, N , x , P and y are treated as inputs.

Problematic: We consider a public entity that wishes to kickstart the adoption of CCS by subsidizing industrial emitters. However, the subsidy budget the entity can afford to distribute does not cover the total costs faced by the emitters, i.e., $\mathcal{E} \leq \|x\| + \|y\|$. In fact, the subsidy budget does not even cover capture costs, i.e., $\mathcal{E} \leq \|x\|$. The problem addressed in this paper is to determine a fair and relevant methodology to distribute $\mathcal{E}$ among the emitters according to their capture costs and their location on the network. We denote this type of problems by a tuple $(\mathcal{E}, N, x, P, y)$, and their domain by $\mathbb{E}$.

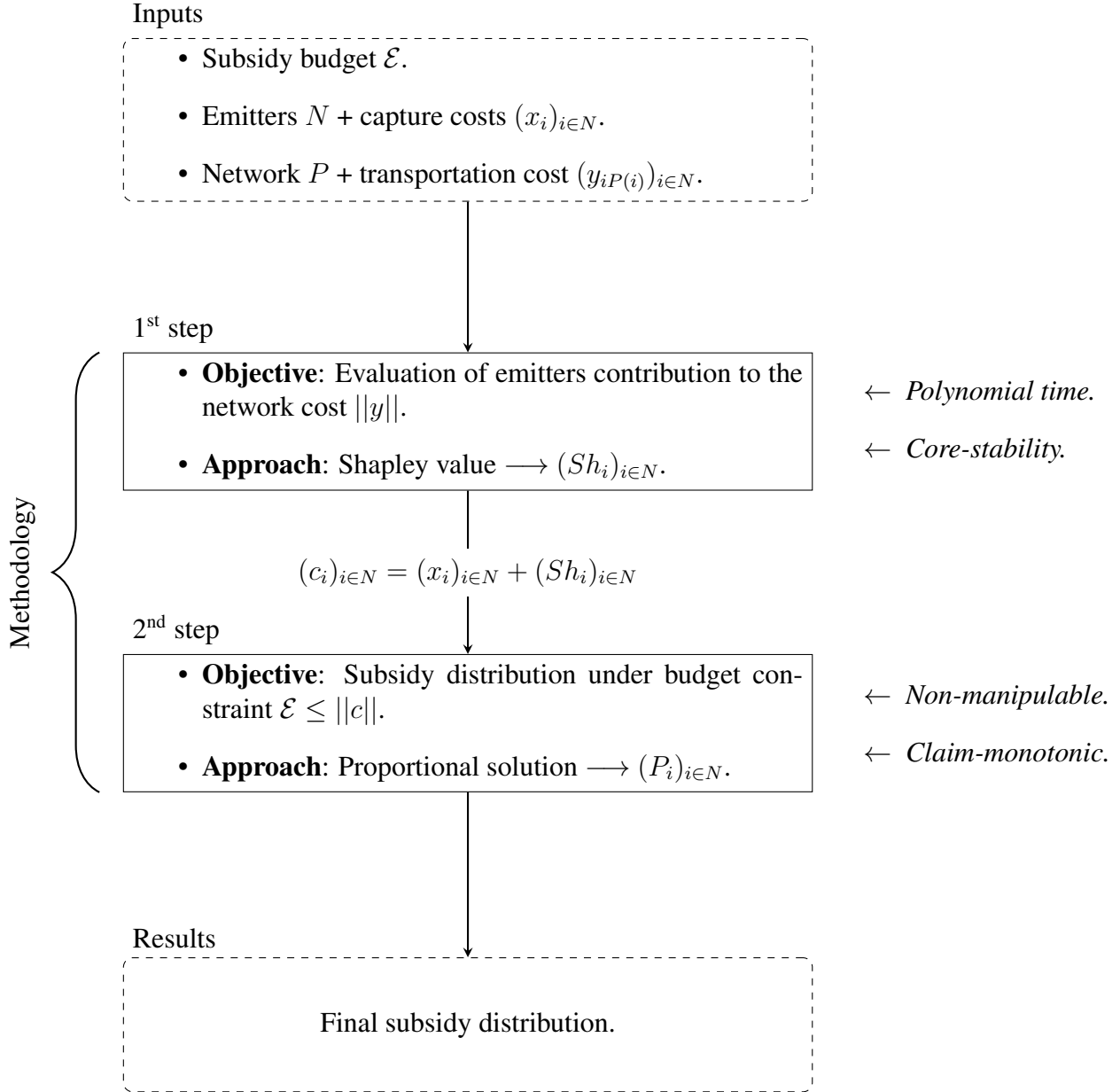


Figure 7.1: Two-steps methodology

Methodology: We propose a two-step methodology as illustrated by Figure 7.1. In the **first step**, we evaluate the contribution to the network cost $||y||$ of each emitter. This step is grounded in cooperative game theory and is based on the Shapley value. Doing so, we obtain for each emitter $i \in N$ a contribution to network cost Sh_i . This step has two advantages: (i) due to the specific structure of our problem, the Shapley value can be computed in polynomial

time (see Algorithm 3); (ii) it appears that the Shapley value satisfies a form of Core-stability in our context, meaning that no emitter has an incentive to leave the coalition. Combining the capture cost x_i of emitter i with its contribution to the network cost Sh_i , we obtain the claim c_i of i , which corresponds to the theoretical cost this emitter faces in the coordination problem. In the **second step** of the methodology, we operate the actual subsidy distribution. As the public budget $\mathcal{E}$ is insufficient to cover all emitters' claims, i.e. $\|c\|$, we use the Proportional solution from bankruptcy theory. The two axioms characterizing the solution, i.e., Non-manipulability and Claim monotonicity, have meaningful interpretations in our context. This second step results in a subsidy distribution that partially covers each emitter's subsidy claim. Thus, we assume that an emitter receiving partial subsidies closes the remaining financing gap through its own finances.

First step: dividing network cost

In this step, we divide network cost among the emitters so that an emitter's share reflects its contribution to the total cost of the network. In economic literature, numerous studies have addressed the problem of dividing costs among a set of agents situated on a fixed tree graph (see, for instance, Littlechild and Owen (1973), Ni and Wang (2007), Dong et al. (2012), van den Brink et al. (2018), and Oishi et al. (2023)). In these studies, the authors often apply the Shapley value to a specific TU-game that incorporates information about the costs and the tree graph. This approach allows for a fair division of costs among agents. We follow their approach and define TU-games that capture the economic characteristics of a transportation network. We call them **network games** and provide the following definition.

Pick any problem $(\mathcal{E}, N, x, P, y) \in \mathbb{E}$. The corresponding network game is the couple (N, v^P) , where $v^P : 2^N \rightarrow \mathbb{R}$ is defined as

$$\forall E \in 2^N, \quad v^P(E) = \sum_{i \in \hat{P}(E) \cup E} y_{iP(i)}.$$

The network game associates, to each coalition of emitters E , the cost of a hypothetical sub-network sufficient to connect these emitters to the sink. Obviously, it holds that $v^P(N) = \|y\|$ and $v^P(\emptyset) = 0$. The class of all network games obtainable from problems in $\mathbb{E}$ is denoted by $\mathbb{G}(\mathbb{E})$. Dividing network cost among emitters is equivalent to dividing the cost of the grand coalition $v^P(N)$.

We evaluate the emitters' contributions to the network cost by applying

the Shapley value to network games. On $\mathbb{G}(\mathbb{E})$, the computation of the Shapley value differs from its original expression for general TU-games (see Definition 7.2.2). The value becomes easier to compute and can be interpreted differently.

The Shapley value can be expressed, for each $(N, v^P) \in \mathbb{G}(\mathbb{E})$, as

$$\forall i \in N, \quad Sh_i(N, v^P) = \sum_{j \in \hat{P}(i) \cup \{i\}} \frac{y_{jP(j)}}{|\hat{P}^{-1}(j) \cup \{j\}|}$$

Proof. See ??.

□

On network games, the Shapley value assigns a fair portion of the costs incurred by the network pipelines connecting each emitter to the sink. More precisely, it distributes the cost of each pipeline equally among the emitters located upstream of it. In addition, it is clear that the typically computationally challenging Shapley value can be computed in polynomial time on network games according to the algorithm below.

Algorithm 3 First step of the methodology

Emitters N , graph P , pipelines costs y . $Sh \leftarrow (0, \dots, 0)$

for $j \in N$ **do**

for $i \in N$ **do** $i \in \hat{P}^{-1}(j) \cup \{j\}$ $Sh_i \leftarrow Sh_i + \frac{y_{jP(j)}}{|\hat{P}^{-1}(j) \cup \{j\}|}$

$Sh_i \leftarrow \varphi_i \quad Sh$

Finally, it is important to note that network games are always submodular. As a result, the Shapley value of a network game always belongs to its Core, making it a stable cost division method. This implies that the first step of our methodology ensures that each emitter's network cost contribution is smaller than the cost of connecting itself directly to the storage.

For each $(N, v^P) \in \mathbb{G}(\mathbb{E})$, $Sh(N, v^P) \in C(N, v^P)$.

This concludes the first step of our methodology. We have obtained an efficient way to evaluate the contribution to the network cost of each emitter. Next, we will combine these contributions with capture costs to devise fair subsidy distributions.

Second step: subsidy distribution

To fairly distribute a subsidy among emitters, a public entity must assess the subsidy claim of each emitter. In this paper, we compute the claim c_i of an emitter $i \in N$ as the sum of its capture cost and its contribution to network cost, i.e., $c_i = x_i + Sh_i(N, v^P)$. By efficiency of the Shapley value and by definition of a network game, it holds that $\|Sh_i(N, v^P)\| = \|y\|$. Consequently, there is not enough subsidy to cover the claims of the emitters, i.e., $\mathcal{E} \leq \|c\|$. Therefore, to distribute the subsidy, we turn to bankruptcy theory.

For each $(\mathcal{E}, N, x, P, y) \in \mathbb{E}$, we can define an associated bankruptcy problem $(N, \mathcal{E}, c)$. In our framework, the endowment to be shared is the subsidy $\mathcal{E}$. The agents and their claims correspond to our emitters and their claims. The sum of the claims surpasses the subsidy. Finally, an award vector corresponds to a possible subsidy distribution. From here, one can apply any solution concept from bankruptcy theory. We decide to focus on the Proportional (P) solution.

Indeed, by applying the Proportional solution (P), the subsidy distribution is immune to strategic behavior since the distribution is independent of the underlying merging or splitting of the emitters (Non-manipulability). This means that emitters cannot form alliances or split their activity in order to gain more subsidy. In addition, the Proportional solution (P) guarantees that the distributed amount is increasing with respect to one's claim (Claim monotonicity). This means that the subsidy allocated to an emitter will increase with respect to both its capture cost and its distance to the storage site.

7.2.4 . Case study

In this section, we apply our methodology to the case of CCS deployment in France. Subsection 7.2.5 describes the context of CCS in France, presents our data, and displays the cost-minimizing pipeline network connecting industrial emitters to liquefaction terminals (i.e., storage sites). Subsection 7.2.6 applies our methodology. We discuss these results and highlight noteworthy observations.

7.2.5 . Data

CCS context in France

In June 2023, the French government launched a public consultation on policies to support CCS deployment (Comité national de l'industrie, 2023).

This consultation also sets out a phased strategy for CCS deployment in industry up to 2050. Indeed, the report envisions the capture of between 4 and 8.5 MtCO₂/year by 2030 and between 15 and 20 MtCO₂/year by 2050 in six major industrial clusters. Because CO₂ storage capacities and locations are still theoretical, the consultation calls for a survey of storage potential in sedimentary basins, and expects initial injection tests to start in 2025. To remedy eventual lack of storage capacity, the report also identifies liquefaction terminals for exporting CO₂ to storage sites abroad. In our study, we will assume that these liquefaction terminals are the only exit points for CO₂. We exclude subsequent shipping and storage from our study. The report estimates that the carbon capture and transportation infrastructure will cost between 11 and 18 billion euros (b€). From exchanges with stakeholders, we know that the French government will provide around 5b€ through subsidies to emitters through an auction mechanism. Thus, the government will entail a part of the total costs, but not its entirety.

Capture data

For our case study, we rely on data of the Climate Trace database, which provides the location and annual emissions of all industrial emitters. We retain large emitters of industrial sectors for which carbon capture is the main lever for decarbonization.¹⁷ We use emitters' 2022 emissions as a benchmark for their annual emissions. We map liquefaction terminals accordingly to France's CCUS consultation report (Figure 7.2). In total, we have 42 emitters and 6 CO₂ terminals.

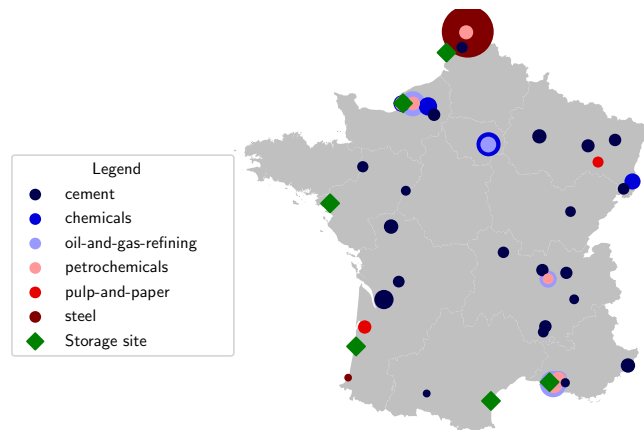


Figure 7.2: Map of emitters and CO₂ terminals.
Size of dots are proportional to annual emissions.

¹⁷We consider an emitter as "large" if it emits more than 10,000 tons of CO₂ annually.

For each industrial sector, we define its capture cost in euros per ton of CO₂ avoided [€/tCO_{2,avoided}] and its capture rate, as shown in Table 7.3. These parameters greatly depend on the industrial site and the capture technology under consideration.

Industrial sector	Carbon avoided cost [€/tCO _{2,avoided}]	Capture rate [-]
Ammonia	20	0.8
Cement	50	0.9
Steel	60	0.9
Pulp & paper	60	0.9
Refineries and petrochemicals	100	0.7

Table 7.3: Carbon capture assumptions by sector.

Transport data

Secondly, we identify potential pipelines that could link the emitting sites to the storage sites.¹⁸ For sake of simplicity, we assume that pipelines can connect two emitters to each other or connect an emitter to a storage site. With 48 nodes - 42 nodes emitters and 6 liquefaction terminals- considering all possible connections would be computationally challenging. Following Morbee et al. (2012), we apply Delaunay (1934) triangulation, which reduces the number of potential pipelines that can be built. Excluding pipelines crossing countries other than France, we obtain the potential transport routes shown in Figure 7.3.

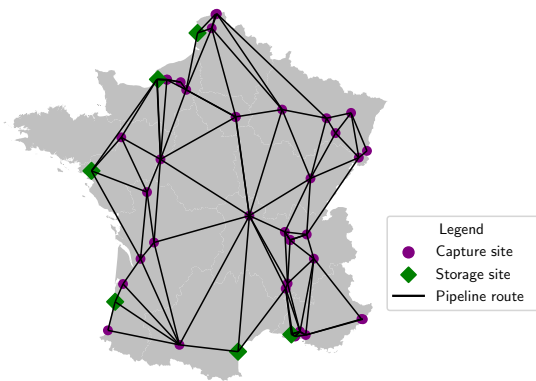


Figure 7.3: Potential pipeline routes from Delaunay triangulation.

¹⁸We exclude other types of transportation, as recent developments confirm that transport by pipeline is the most cost-efficient solution for CCS transport (Ouvray et al., 2024)

Numerous studies quantify the cost of transporting CO₂ by pipeline, but there are wide disparities as shown by Knoope et al. (2013, 2014) and Roussanaly et al. (2014). In network optimization models, studies tend to discretize available pipeline capacities in order to exploit economies of scale (d’Amore & Bezzo, 2017). Here, we adopt the investment cost function calculated in Morbee et al. (2012), which provides the investment cost of a pipeline as a function of length, volumes and terrain factors, thus simplifying the MILP. We then convert this cost into an annualized investment fix cost $C^{inv,fix}$ and an annualized variable cost $C^{inv,var}$, as our model deals with a single representative year. Aside from the investment cost, we consider operation and maintenance cost C^{om} , see Table 7.4.

Transport Cost	Value	Source
$C^{inv,fix}$ [M€/ (km·y)]	0.0401	Adapted from Morbee et al. (2012)
$C^{inv,var}$ [M€/ (MtCO ₂ ·km·y)]	0.0014	Adapted from Morbee et al. (2012)
C^{om} [M€/ (km·MtCO ₂)]	0.01	Oei et al. (2014)

Table 7.4: Transportation costs

Cost-minimizing network

Through a MILP, we obtain the cost-minimizing pipeline network presented in Figure 7.4. To illustrate our methodology, we choose to focus on the northern part of the south east cluster, which is highlighted by the blue box in Figure 7.4.

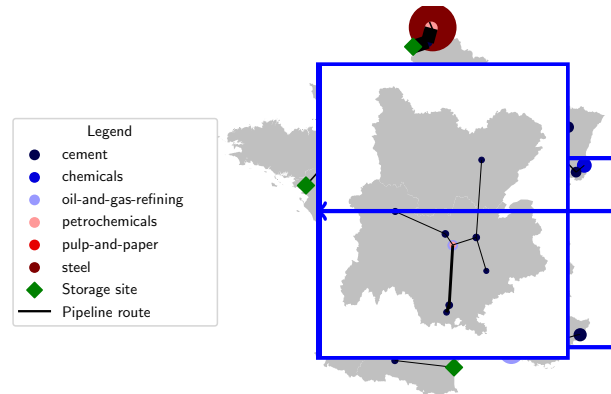


Figure 7.4: Map of France and northern sites of south-east cluster

Notably, the model’s output corresponds to the clusters described in the

French governmental report (Comité national de l'industrie, 2023). A main difference lies in the connection of the eastern Zone Grand Est cluster to the western Le Havre cluster. Indeed, the governmental study assumes that on-shore pipelines can transport CO₂ to Germany, unlike our model that can export CO₂ through liquefaction terminals in the West or South of France only.

7.2.6 . Results

South-East Cluster. For our case study, we apply our methodology to a portion of the south-east cluster. Let us formalize this case study by the problem $(\mathcal{E}, N, x, P, y) \in \mathbb{E}$. Without loss of generality, we fix the subsidy budget to $\mathcal{E} = 170$ and the sink is denoted by i_0 . The other inputs of the model are summarized in Table 7.5.

$i \in N$	$C22$	$C8$	$C33$	$C25$	$C29$	$C26$	$C37$	$C35$
x_i	18.83	60.55	21.51	18.44	15.44	18.18	10.75	13.13
$P(i)$	i_0	$C22$	$C8$	$C33$	$C25$	$C33$	$C26$	$C26$
$y_{iP(i)}$	1.03	7.64	0.04	1.21	4.56	2.34	2.84	6.4

Table 7.5: Inputs of the case study (in M€/year)

Figure 7.5 is an illustration of our network to better visualize the tree graph structure and the pipelines' costs.

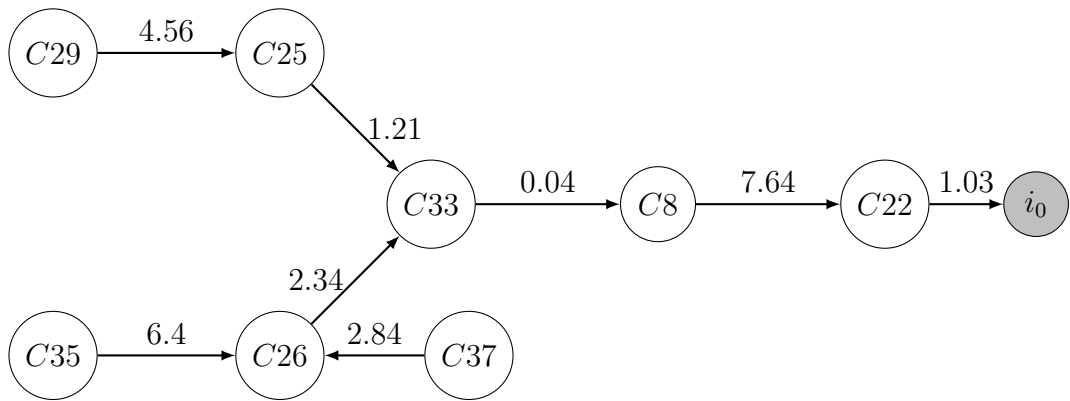


Figure 7.5: Network and pipelines' costs

Two-step methodology.

Step 1: Compute the Shapley value of the network game (N, v^P) associated with our case study problem. According to Proposition 7.2.3, the Shapley value divides the cost of each pipeline equally among its upstream emitters. For instance, the cost $y_{C26C33} = 2.34$ is equally divided among $C26, C35$ and $C37$. Applying this reasoning to each pipeline, i.e., following Algorithm 3, we obtain the Shapley value of the network game, which is given by the second line of Table 7.6.

$i \in N$	$C22$	$C8$	$C33$	$C25$	$C29$	$C26$	$C37$	$C35$
$Sh_i(N, v^P)$	0.128	1.219	1.226	1.831	6.391	2.006	4.846	8.406
c_i	20.305	61.769	22.736	20.271	21.831	20.186	15.596	21.536

Table 7.6: First step's results (in M€/y)

Step 2: From the Shapley value obtained in Step 1, we can derive the vector of needs $c \in \mathbb{R}^8$ (see the third line of Table 7.6). Each coordinate c_i , $i \in N$, of this vector is obtained by summing the capture cost x_i and the Shapley value $Sh_i(N, v^P)$ for i . We have the necessary components to construct the bankruptcy problem $(N, c, \mathcal{E})$. Consequently, we can apply solutions to bankruptcy problems to determine subsidy distributions. Additionally, we formulate an alternative bankruptcy problem $(N, x, \mathcal{E})$ where the network cost are not factored in; specifically, the emitters' needs are represented solely by their capture costs. This enables us to compare two scenarios: one considering the network and one without, allowing some discussions.

Interpretations of the results. Observe from Figure 7.6 that emitters whose emissions pass through many pipelines (upstream emitters) in the transportation network receive more subsidies if their contribution to network cost is considered (i.e., $(N, c, \mathcal{E})$) compared to the situation where only their capture cost is accounted for (i.e., $(N, x, \mathcal{E})$). For instance, the distant emitter $C35$ receives 42% more subsidies in situation $(N, c, \mathcal{E})$ compared to situation $(N, x, \mathcal{E})$ through the P solution. Indeed, our methodology favors emitters who are far upstream in the transportation network, as serving them with a pipeline reduces the transportation costs of other emitters.

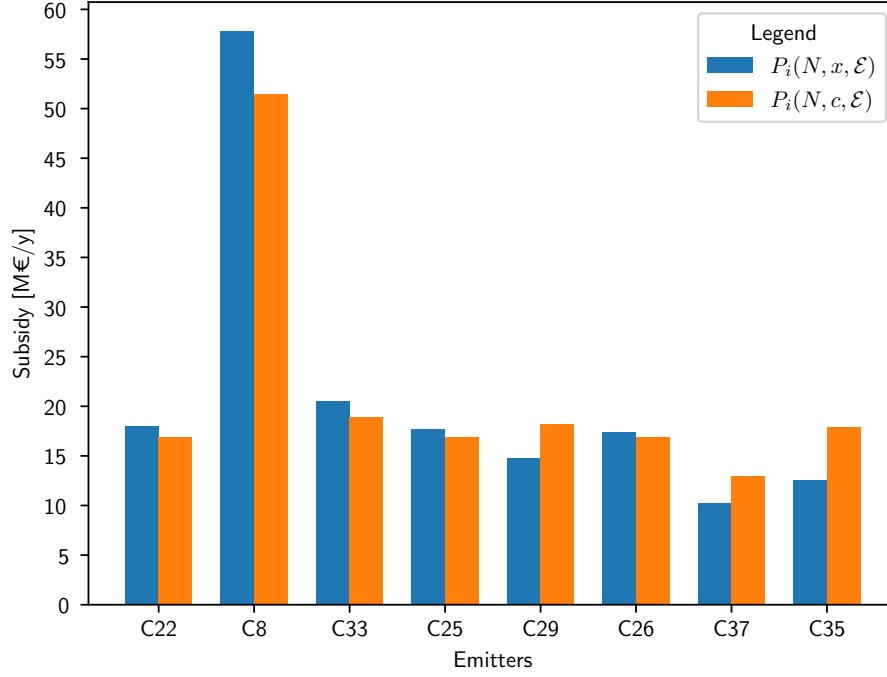


Figure 7.6: P results in base case $(N, c, \mathcal{E})$ and without considering the network $(N, x, \mathcal{E})$.

7.2.7 . Discussion

In this section, we discuss some advantages and drawbacks of our methodology. First, in subsection 7.2.7, we discuss alternative approaches for our methodology's first and second steps. Second, in subsection 7.2.7, we suggest future research avenues to study different mechanism designs to implement our methodology.

Methodology modification for future research

For each step of our methodology, we suggest an approach relevant to the current deployment of CCS: for the first stage, we rely on the Shapley value, and for the second stage, we use the Proportional bankruptcy solution. Beyond the approaches applied for each step, our study provides a flexible normative framework for designing a CCS subsidy distribution mechanism. Indeed, alternative approaches are possible for each methodology step, which we detail below.

In the second step, a promising direction for further research is to in-

investigate alternative axioms, leading to different bankruptcy solutions. The choice of an axiom could be motivated by the case study or additional normative considerations. We refer to Thomson (2003) and Thomson (2015) for a deep analysis of bankruptcy solutions and their axiomatic characterizations. For the first step, future studies could replace the Shapley value with their case study's prevailing T&S tariff. Another possibility consists of applying the Shapley value to minimum cost spanning tree games (see, for instance, Bird (1976), Kar (2002) Bergantiños and Lorenzo-Freire (2008), Bergantiños and Kar (2010), Bogomolnaia and Moulin (2010), Bergantiños and Vidal-Puga, 2010, Trudeau and Vidal-Puga (2019)) and Bergantiños and Vidal-Puga (2021) instead of network games (see Definition 7.2.3). The key distinction between network games and minimum cost-spanning tree games lies in their definitions and structures. An exogenously defined cost-minimizing network characterizes a network game. In contrast, a minimum cost-spanning tree game is defined based on the collection of all cost-minimizing networks that sub-coalitions of emitters can generate. Minimum cost-spanning tree games allow for considering counterfactuals in which some coalition of emitters connect themselves to the storage without cooperating with the other emitters (see, for instance, Granot and Huberman (1981), Granot and Huberman (1984) and Granot (1986)). This framework is relevant for studying strategic interaction between emitters and addressing stability issues (see, for instance, Granot and Huberman (1984) and Estévez-Fernández and Reijnierse (2014)). While applying the Shapley value to minimum cost spanning tree games may yield interesting results, the main drawback of this approach is that it becomes harder to compute, as demonstrated by Ando (2012). Other alternative approaches for the first step can be found in Hougaard (2018). More recently, some studies have proposed decomposing the network cost into several components to account for the heterogeneous requirements of infrastructure users (see Van Beek et al. (2024)) or decomposing agents' demands (or claims) into multiple stages to address differences in emission volume and their impact on network design (see Lowing (2024)).

Implementation of our methodology

A key assumption of this paper is that the public entity distributing the subsidies has perfect information on every emitter's claim. Under this assumption, the role of the public entity is to distribute subsidies efficiently based on its perfect knowledge of emitters' capture cost and location. Thus, in our paper, the public entity does not face the preliminary issue of estimating the capture cost of each emitter in order to determine the minimal subsidy budget to support CCS adoption. In this context, the public entity with imper-

fect information must develop a mechanism to incentivize emitters to reveal their capture cost. This mechanism will necessarily influence the effectiveness of the subsidy distribution. In this perspective, the Dutch government subsidizes industrial emitters through an auction mechanism. Each emitter's auction corresponds to its subsidy demand per ton of CO₂ (subsidy intensity) corrected by an emissions intensity factor. The government ranks the auctions in ascending order and subsidizes emitters until the subsidy budget is empty. A greedy emitter could request a higher bid than it claims (by requesting a higher subsidy intensity), but it runs the risk of not being selected. In this way, each emitter is (supposedly) incentivized to submit a bid corresponding to its claim -i.e., its capture cost.

Alternatively, a public entity could roughly estimate capture costs without setting up a mechanism to reveal emitters' costs. For instance, the Norwegian government runs its CCS flagship project through its company, Gassnova, and is part of the Northern Lights consortium, which manages transportation and storage. In addition to its direct involvement, the Norwegian government has covered 80% of Northern Lights' costs via state aid agreements (Fattouh et al., 2024). Similarly, Danish emitters can apply to the national CCUS Fund and the NECCS Fund. Depending on its budget and storage target, the government selects emitters through a tendering procedure (European Commission, 2023). In both countries, some grey areas remain: neither country has publicly disclosed the rationale behind the allocation of subsidies.¹⁹ These grey areas do not promote a clear and transparent funding mechanism for future CCS projects. However, transparency in subsidy distribution (i.e., public spending) is a central criterion for the large-scale development of this technology. In this respect, the study by Rode et al. (2023) sets out six principles to guide the development of large-scale CCS. Among these, the fourth principle calls for transparent commitments by government and policymakers.²⁰

In light of these examples, setting up a transparent mechanism to reveal emitters' costs seems desirable to kickstart CCS adoption. Future research could address the impact of gathering information (in auction mechanisms or not) on the efficiency of our methodology. In particular, future research could analyze the efficiency of the subsidy distribution in the investment decision considering the asymmetry of information between emitters and the public entity.

¹⁹Likewise, Northern Lights' remuneration after the first decade of operation is unclear (Nicolle et al., 2023).

²⁰Our study aligns with this criterion and directly addresses the second principle, which recommends investing in a common infrastructure.

7.2.8 . Conclusions

In summary, this paper introduces a flexible methodology for distributing subsidies to kickstart the adoption of Carbon Capture and Storage (CCS). By leveraging cooperative game theory and bankruptcy theory, our method efficiently allocates subsidies within budget constraints. Compared to the literature, this methodology has two major advantages. On one hand, the novelty of our methodology lies in considering both the heterogeneous capture costs of emitters and their network locations. On the other hand, future studies or policymakers can customize it according to their normative considerations and their specific case study. Applying this methodology to CCS deployment in France reveals a favorable distribution of subsidies to influential upstream emitters, which is crucial for accelerating CCS adoption. Further research is necessary to validate and refine this methodology for broader application in industrial decarbonization efforts.

7.2.9 . References

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8 - Annexes

8.1 . Annex 1: Example of Algorithmic Complexity

We can use the following example to fix ideas on the definition of algorithmic complexity and how it builds on the main concepts of information theory. Let us consider three bit-strings, each representing the message of an actor communicating the constraints of a hypothetical system:

$A = 11111111111111111111$,
 $B = 10101010101010101010$,
 $C = 11101010011011101010$

All of them have the same length, 20 bits. However, A and B are distinguishably different than C because they have patterns.

Let $A' = 110100$ and $B' = 101010$, each with a length of 6, be the program that can compress these patterns, given the assumption that a Turing machine has a worktape to understand A' and B' . The work tape says, “Read the 1 bit, copy this value of the first bit into the next bit, count, stop if the count is 10100 (twenty in binary), repeat. Bit-string B' can use a similar work program: “Read first 10 bits, copy the value into the next bits, count, stop if the count is 1010 (10 in binary), repeat”. In these compressions of A and B , we can see that the number of steps a Turing machine has to perform does not depend on the size of the recursive program but on how we can compress the original bit string according to their patterns. Furthermore, let us consider the example of C . In this case, at least 20 computation steps are required for the computer to decompress C in its calculations before being able to provide its output because there is no pattern on C . More formally, we can introduce some mathematical notation to compute the algorithmic complexity using the above examples.

Let us define $P(C)$ as the probability that C can be written given a program if each square of the program tape is filled with a 0 or a 1 by a separate coin toss: $P(C) = 1/2^{2*length(C)+1} = 1/2^{2*20+1}$.

From $P(C)$ we can obtain $H(C)$, Shannon (1948) entropy, by taking their negative base-two logarithm, $H(C) = -\log_2 P(C) = 20$.

Furthermore, let us introduce Shannon (1948) information measure: $I(C) = H(C) - H(C') = 0$, because there is no C' different from C that can be used to compress C . A generalization, of this indicator, would be $I(x) = H_{max}(x) - H_{min}(x')$. Therefore, we can calculate $I(A) = I(B) = 14$ and specify the general form $H_{min}(x')$. Indeed, the algorithmic complexity of A, B , and C is 6, 6 and 20 bits, respectively.

8.2 . Annex 2: Data description and additional controls

Table 8.1: Descriptive summary of variables used in the empiric analysis

Type	Variable name	Description (units)	Source	Min	Mean	Max	SD
Main dependent variables	Sh. renew-ables	Share of renewable energy (%)	EUROSTAT	3.499	20.1	54.7	12.38
	Ind. electric	Tariff charged for consumption of a KWh by hou. (log(EUR/KWh))		4.245	4.8	5.47	0.272
Secondary dependent variables	Sh. wind-gen	Share of renewable energy wind (%)	EUROSTAT	0.021	9.5	45.8	10.75
	Sh. solar	Share of renewable energy solar (%)		0	2.15	7.82	2.194
	Hou. elecprice	Tariff charged for consumption of a KWh by households (log(EUR/KWh))		4.879	5.44	5.96	0.267
Governance and reform variables	Independence	Independence index (0 – 1)	Brousseau & Gonzalez, 2020)	0.185	0.3	0.37	0.043
	Scope	Market coord. Gov. index (0 – 1)		0.216	0.27	0.32	0.027
	Transparency	Transparency index (0 – 1)		0.167	0.25	0.35	0.052
	Discretion OECD PMR	Discretion index (0-1) OECD PMR (1 - 6)	OECD-PMR Constructed PMR survey	0.144	0.24	0.34	0.048
	TA mkt access	Market access index (0 - 1)		0.11	0.15	0.2	0.023
Electricity supply, demand, and security controls	Elec gen.	Total electricity supply (log GWh)	IEA OECD database	7.688	11	13.4	1.398
	Elec cons	Total electricity supply (log GWh)		15.27	17.3	19.6	1.211
	Trade balance GDP	Elec. exports – imports (log GWh) GDP in const. (log 2017 million USD)	PWT ver10	5.367	8.14	9.15	0.718
	Income PC	GDP per capita (log USD/population)		24.3	26.6	29	1.318
Renewable's support controls	Years lawren	Policy time that supports renewable generation (log years)	Constructed IEA policy database	2.485	4.19	5.66	0.773
	Green Party	Green party seat in the Legislative	Comparative Political Dataset	0	2.34	12.4	3.28
	1-IHH sshare	Diversification of elec. generation sources (0 – 1)	Constructed IEA-OECD database	-0.441	0.47	0.72	0.248
	1-IHH sshare NR	Diversification of elec. generation non-renewable sources (0 – 1)		0.082	0.58	0.95	0.214
	GHG em. grate	Greenhouse gas emissions growth rate (%)		-28.72	0.10	38.10	9.49
Institutions and government efficiency controls	FH civil law	Freedom House civil law scores (0-60)	Freedom in the World Report, 2021	44	55.9	60	3.471
	FH pol rights	Freedom House pol. rights scores (0-40)		28	38.1	40	2.29
	FH index	Freedom House total scores (0-100)		72	93.9	100	5.567
	IHS RL	IHS rule of law index (0-1)	IHS Markit	0.67	0.86	1	0.092
	TI CPI	Transp. International corruption perception index (0-100)	Transparency International	43	67.4	91	14.07

To measure the intensity of market reform, we assessed the regulatory environment using survey questions from the OECD PMR (Vitale et al., 2020). Instead of using the categorical content of the survey, we tracked changes

in replies by assessing the textual information embedded in the survey. We applied the following steps to the data.

1. We created a set of documents using the textual information from the survey. The textual information comes from the words used to express country replies. In the following question, "Are market prices regulated?", we registered "market prices are regulated" for a positive answer, and "prices are unregulated" for a negative one in our database.
2. We constructed text documents for every country and time with the previous information. Based on co-occurring terms in every document, we fit a topic model (LDA) and identify four groups of terms that describe the country's market reform, as shown in figure: textanalysisresults.

Figure 8.1: Text Analysis of market regulation dimensions

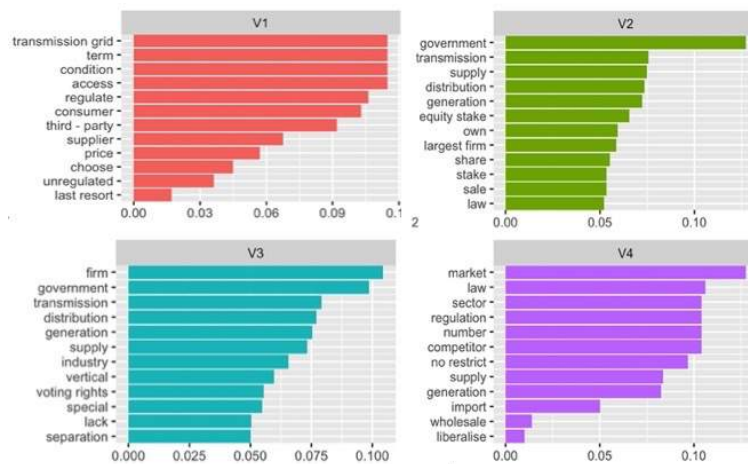


Table 8.2: Additional controls

	(1)	(2)	(3)
Independence	-0.817** (0.334)	-0.861** (0.365)	-0.861** (0.324)
Household Elec.Price		0.259 (0.223)	
Share L.incumbent			-0.293*** (0.049)
Individual effects	yes	yes	yes
Time effects	yes	yes	yes
Controls	yes	yes	yes
adj. R^2	0.87	0.854	0.948
AIC	-141.475	-126.115	-161.093
Observations	48	44	42
F-statistic	33.137	39.885	240.344

Model (1) of table:reestimatesgov is used in all specifications. *Household Elec.Price*: electricity prices paid by residential consumers in EUR per GWh. *Share L.incumbent*: share of the largest electricity producer in percent points. Heteroskedasticity robust standard errors in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8.3: Different support mechanisms

	(1)	(2)
Independence	-0.817** (0.334)	-0.994* (0.545)
Years ren. laws	0.262*** (0.058)	
Share Subsidies		-0.142 (0.149)
Time effects	yes	yes
Controls	yes	yes
adj. R^2	0.87	0.833
AIC	-141.475	-118.835
Observations	48	42
F-statistic	33.137	26.951

Model (1) of table:regestimatesgov is used in all specifications. *Share Subsidies*: Share in percentage points (logs) of the legislation that grants subsidies to renewable energy generators over the total number of legal instruments that support green electricity. Heteroskedasticity robust standard errors in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8.4: Alternative dependent variable and overlapping sample

	(1) Base	(2) Wind-Solar.SH
Independence	-0.764* (0.413)	-0.130* (0.065)
Liberalization	1.585** (0.719)	-0.269 (0.183)
Inst. Stability	0.037*** (0.006)	0.002*** (0.001)
Non-renew power	-1.035** (0.311)	-0.409** (0.051)
Demand (GDP)	2.122** (0.866)	-0.172 (0.126)
Wealth	-2.209** (0.928)	0.18 (0.132)
Trade balance	0.102 (0.107)	0.025 (0.015)
Years ren. laws	0.209** (0.080)	-0.026* (0.013)
Patenthundred	0.129** (0.058)	0.003 (0.011)
Individual effects	yes	yes
Time effects	yes	yes
adj. R^2	0.85	0.938
AIC	-125.413	-291.447
Observations	44	44
F-statistic	32.819	59.566

Model (1) of table:regestimatesgov is used in all specifications. The dependent variable *Wind-Solar.SH* in model (2) is the sum of wind and solar shares as part of the total electricity produced in GWh. The value varies between 0 and 1. Heteroskedasticity robust standard errors in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8.5: Fixed Effects estimation: Impact of governance regime in electricity price – complete table

	(1)	(2)	(3)	(4)	(5)
Independence	-0.116 (0.291)				0.225 (0.438)
Transparency		-0.512* (0.298)			-0.767* (0.410)
Scope			0.387 (0.639)		0.727 (0.563)
Discretion				0.31 (0.303)	
Liberalization	0.91 (1.176)	0.626 (1.280)	1.069 (1.179)	0.8 (1.440)	0.761 (1.286)
Inst. Stability	-0.009 (0.011)	-0.0104 (0.011)	-0.0103 (0.013)	-0.0076 (0.011)	-0.0144 (0.0145)
Wealth	-0.57*** (0.176)	-0.60*** (0.174)	-0.57*** (0.184)	-0.60*** (0.176)	-0.61*** (0.184)
Elec. Supply	0.243 (0.183)	0.297 (0.198)	0.184 (0.197)	0.249 (0.208)	0.221 (0.200)
Non-renew power	-0.013 (0.106)	0.006 (0.112)	-0.073 (0.152)	0.025 (0.135)	-0.094 (0.148)
Individual effects	yes	yes	yes	yes	yes
Time effects	yes	yes	yes	yes	yes
adj. R ²	0.828	0.845	0.83	0.834	0.851
AIC	-144.5	-149.5	-145.1	-146.1	-149.8
Observations	48	48	48	48	48
F-statistic	27.87	32.1	32.96	30.59	28.66

Model (1) of table:reestimatesgov is used in all specifications. Heteroskedasticity robust standard errors in parentheses * p < 0.1, ** p < 0.05, *** p < 0.01.

9 - Appendices

9.1 . Curriculum Vitae

Contact Information:

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Personal Details:

Born in Lima – Nationality: Peruvian – Married

Professional proficiency in Spanish (Native), English (Written and Oral), French (Oral)

I am passionate about addressing challenges related to adopting technologies that enhance societal well-being, focusing on the energy sector, climate change policy, and digitalization. I am currently a PhD CIFRE at Stellantis, where my research centers on analyzing the value of information for Vehicle-to-Grid (V2G) technology, enabling electric vehicles to serve as grid storage. The expertise that I have gained from this research lies in understanding how digitalization can drive organizational sustainability by changing how digital objects can be used, in this case, electric vehicles. With eight years of experience as a climate change and energy policy consultant in Latin America, I bring a strong project management and entrepreneurship background. I am fluent in Spanish, English, and French.

Professional Experience

STELLANTIS – ECOLE CENTRALE SUPELEC	Paris, France
Ph.D. CIFRE	2022/05 – to date

My Ph.D focuses on how electric vehicles (EVs) can be decentralized energy storage through Vehicle-to-Grid (V2G) technology. Collaborated with Stellantis divisions on decarbonization strategies, contributing to a white paper positioning the company as an electricity retailer and a report on CO2 emissions measurement from EVs. Represent Stellantis on the advisory board of the SCALE project, the largest European initiative on V2G, a role I initiated through international conference participation and networking.

ESSEC BUSINESS SCHOOL/ ECOLE CENTRALE SUPELEC/ DAUPHINE

Paris, France

Research Assistant

2021/09 – 2021/09

At ESSEC, I contributed to a case study on the organizational processes behind the Citroen AMI. I led "The Architectures of V2G" project at Ecole Centrale Supélec, analyzing the V2G value chain. At Université Paris Dauphine, co-organized a working group on decentralized electricity and mobility, facilitating weekly knowledge-sharing meetings.

INDEPENDENT CONSULTANT

Chile and Peru

Climate Change and Energy Expert

2020/07 – 2021/09

Provided expertise in carbon markets for the Ministry of Environment and the Ministry of Energy and Mines of Peru, assessing their 2050 carbon neutrality strategy and conducting technical studies on CO2 emissions measurement. Also acted as a negotiator for an NGO, facilitating the sale of carbon credits in voluntary markets.

2 DEGREES INVESTING INITIATIVE

Paris, France

Professional intern

2020/01 - 2020/07

Completed a six-month internship focused on evaluating institutional investors' alignment with Paris Agreement climate scenarios. Authored two reports on the investment portfolios of Latin American insurance companies and developed a model to simulate the financial impact of a carbon tax on firms with generation assets in the Colombian electric grid.

DEUMAN Consulting

Peru, Chile, and Ecuador

Technical Manager - Partner

2014/01 - 2020/01

Progressed from intern to Country Manager of Peru, eventually taking on global responsibilities and becoming a partner. During my tenure leading the Peruvian office from 2017 to 2019, we doubled the sales and expanded the team from 3 to 12 consultants. Since 2019, I oversee the technical quality of methodologies and reports across Deuman's offices in Ecuador, Peru, and Chile. Managed over 30 consultancy projects related to Energy, Sustainability, Finance, Environmental Quality, and Business Development while engaging high-level stakeholders to develop policies, negotiate processes, and lead project execution.

Relevant Academic Research

- Citroën AMI (A) - Internal Disruption in the Automotive Industry. [Case

Center] (with Jane Lepoutre) – Published in 2024

- Modeling CO2 pipeline systems: An analytical lens for CCS regulation. [Economics of Energy and Environmental Policy] (with Adrien Nicolle, Olivier Massol, and Emma Jagu) – Published in 2023.
- Kickstarting CCS Adoption: Tailoring Subsidies to Emitters' Needs. (with Adrien Nicolle and David Lowig) – Working Paper
- Impact of Regulatory Governance Regimes on Renewable Energies: An Empirical Analysis of European National Regulatory Agencies (NRAs) from 2013 to 2018. (with Eric Brousseau and Carlos Gonzalez, 2023) – Working Paper
- Evaluating the design of smart grid information flows: the impact of scale and complexity in vehicle-to-grid applications (with Jan Lepoutre and Yannick Perez, 2023) – Working Paper
- The value of data sharing in smart grids: A simulation of inter-organizational strategies for vehicle-to-grid aggregators. (with Jan Lepoutre, Yannick Perez, 2023) – Working Paper

Relevant Technical Reports

- The Economic Interest of Vehicle-to-Grid: Case Study on Electricity Arbitrage in the "Day Ahead" Market. Study performed for the members of AVERE France in 2024.
- Transition Risks Assessment by Latin American Financial Institutions and the Use of Scenario Analysis. [Inter-American Development Bank] (with Laura Ramírez, and Jacob Thomä) – Published in 2020.
- Analysis of Climate Scenarios and Exposure to Transition Risks: Investment Portfolio of the Colombian Insurance Sector.[FASECOLDA] (with Laura Ramírez, and Clare Murray) – Published in 2020.

Relevant Consultancies

- Assessment of the Carbon Neutrality Strategy of Peru 2050 Plan for the Ministry of Environment of Peru (2020)

- Evaluation of Peru's measures to improve the generation of non-conventional renewable energies (2017)
- Analysis of Chile's carbon tax offset using Clean Development Mechanism (CDM) carbon credits (2017)

Education

- Ph.D. in Engineering - Economics (2022-2025) Ecole Centrale Supélec, Université Paris-Saclay, France
- Master 2 in Industries des Réseaux et Économie Numérique (IREN) (2020-2021) Université Dauphine, Ecole Polytechnique, Centrale Supélec, Telecom Paris, Université Paris-Saclay, France.
- Master in Theoretical Economics (2016-2017) Universidad Del Pacífico, Peru
- Bachelor's in environmental engineering (2009-2014) Universidad Nacional Agraria La Molina, Peru

Other Interests, Achievements, and Skills

- **Sports:** Sailing- Peruvian national champion, bronze medal in the Laser South American championship, and sportsmanship award in the Sunfish Youth World Championship. Rock climbing - Brand ambassador of a clothing brand for three years. Alpinism, Surfing, and Basketball.
- **Programming languages:** Proficient in R and Python.
- **Journalism:** I went to Tibet to report on an international climbing expedition to Shisha Pangma.
- **Associations:** 2009 President of the Peruvian Association of Laser Class Sailing.