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EDDIE EUROPEAN DISTRIBUTED DATA INFRASTRUCTURE FOR ENERGY

EDDIE

EUROPEAN DISTRIBUTED DATA INFRASTRUCTURE FOR ENERGY

D7.2

Conceptual, economic, human-centred, and regulatory knowledge about energy data-sharing infrastructures

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DEFINITIONS, ACRONYMS AND ABBREVIATIONS

Acronyms/ Abbreviations	Description
ACER	Agency for the Cooperation of Energy Regulators
AI	Artificial Intelligence
API	Application Programming Interface
BE	Behavioural Economics
BGP	Border Gateway Protocol
CCC	Climate Change Committee
CEDS	Common European Data Spaces
CEEDS	Common European Energy Data Space
CNN	Convolutional Neural Network
DA	Data Act
DERMS	Distributed Energy Resource Management System
DQN	Deep Q-Network
DL	Deep Learning
DLR	Dynamic Line Rating

DMD	Dedicated Measurement Devices
DMM	Data Management Model
DNN	Deep Neural Network
DSO	Distribution System Operator
DSR	Demand Side Response
DSSC	Data Spaces Support Centre
EC	European Commission
EDDIE	European Distributed Data Infrastructure for Energy
EDS	Energy Data Space
EEAB	External Expert Advisory Board
EMS	Energy Management System
EPBD	Energy Performance of Buildings Directive
EU	European Union
EV	Electric Vehicle
GDPR	General Data Protection Regulation
IADA	Interoperability Implementing Act on Data Access
IBR	Inverter-Based Resource
IEA	International Energy Agency

IoT	Internet of Things
ITU	International Telecommunication Union
JWG	Joint Working Group
KPI	Key Performance Indicator
LEC	Local Energy Community
LSTM	Long Short-Term Memory
ML	Machine Learning
NESO	National Energy System Operator
NIS2	Network and Information Systems Directive 2
NRA	National Regulatory Authority
OFDS	Open Fibre Data Standard
PPO	Proximal Policy Optimisation
RES	Renewable Energy Sources
RL	Reinforcement Learning
SDGs	Sustainable Development Goals
SDGDAA	SDG Digital Acceleration Agenda
SEDS	Single European Data Space
SQ	Sub-questions

ToU	Time-of-Use
TSO	Transmission System Operator
UN	United Nations
UNDP	United Nations Development Programme
UX	User Experience
WACC	Weighted Average Cost of Capital

EXECUTIVE SUMMARY

This deliverable presents the multidisciplinary results of Work Package 7 (WP7) of the EDDIE project. WP7 studies how energy data-sharing infrastructures can be designed to be economically sustainable, legally compliant, human-centred, and cyber-secure, thereby supporting the creation of a Common European Energy Data Space (CEEDS). The analysis combines economic theory, behavioural research, legal interpretation, regulatory insight, and cybersecurity assessment to build a coherent framework for data sharing in the energy sector.

Chapter 2 of this deliverable establishes conceptual and economic foundations of data spaces, explaining how digitalisation, interoperability, and AI-driven flexibility can enhance efficiency but also introduce new competition, cost allocation, and governance challenges.

Chapter 3 examines user experience and behavioural factors, drawing on empirical work and prototype evaluations to show how clear feedback and intuitive interfaces help improve energy literacy, engagement, and trust, while also addressing the systemic conditions under which such user-centred approaches can inform broader energy-data ecosystems.

Chapter 4 provides a comprehensive legal analysis of the EU framework governing the access to and sharing of electricity metering and consumption data. The analysis reveals an EU legal landscape that is still fragmented in some key respects, underscoring the need for clearer definitions, coordinated implementation, and interpretative guidance to ensure a coherent and consumer-oriented approach to energy data governance across the EU.

Chapter 5 discusses regulatory and governance models for data-sharing infrastructures, proposing transparent monitoring mechanisms that safeguard fairness while promoting innovation.

Chapter 6 assesses cybersecurity and safety, interpreting the NIS2 Directive in the context of energy data spaces and presenting a self-assessment questionnaire methodology for risk evaluation.

Jointly, these analyses support that EDDIE’s decentralised, open-source architecture can strengthen an interoperable European energy data ecosystem that balances innovation, competition, privacy, and resilience.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Purpose of the Document

The purpose of this deliverable is to consolidate the multidisciplinary knowledge generated in the four tasks of EDDIE's WP7 Multi-disciplinary analysis of EDDIE. WP7 supports the technical work of EDDIE by analysing the economic, behavioural, legal, regulatory, and cybersecurity dimensions of data-sharing infrastructures for the energy sector. EDDIE aims to create a decentralised, open-source, and interoperable framework that enables trustworthy exchange and use of energy data across Europe. Deliverable D7.2 contributes to this aim by identifying the conceptual principles, institutional requirements, and human factors necessary for the success of a European distributed data-sharing infrastructure for energy.

The results of D7.2 inform the evaluation of demonstrators developed in WP6 and provide the analytical foundation for the policy and exploitation work carried out in WP8.

1.2 Scope and Intended Audience

The deliverable addresses five complementary aspects of energy-data sharing:

- Conceptual and economic analysis of energy data-sharing, including the roles of digitalisation and interoperability, and the challenges brought by cost allocation and AI.
- User-experience and behaviour, exploring how individuals perceive, understand, and act on energy consumption data.
- Legal framework, covering the rights and obligations related to metering, data access, and data protection.
- Regulatory and governance models, ensuring sustainable and fair operation of data spaces.
- Cybersecurity and safety, ensuring integrity, availability, and trust in energy-data infrastructures.

Because the dissemination level of D7.2 is Public (PU), its audience includes:

- The European Commission and CINEA, as granting authority.
- Energy regulators, DSOs, TSOs, and policy makers, contributing to EU standardisation and data space governance.
- Industry and service providers exploring new business opportunities in energy data.

- Researchers and civil society stakeholders engaged in digitalisation, energy transition, and data governance.

1.3 Structure of the Document

This deliverable reflects the multidisciplinary nature of WP7. Several complementary methodologies are applied across the different chapters (including conceptual reasoning, literature synthesis, quantitative modelling and qualitative interviews, among others) and each of them is described in the relevant chapter.

The rest of the deliverable is organised as follows. Chapter 2 develops the conceptual and economic framework for energy data-sharing infrastructures, combining theoretical analysis with illustrative modelling. Chapter 3 presents empirical findings on user experience and behavioural aspects, based on participatory design, field studies, and survey research. Chapter 4 examines the European legal framework for metering and consumption-data sharing through a comparative legal-analysis methodology. Chapter 5 analyses the economic-regulatory models and governance options for sustainable data spaces, drawing on interviews and case studies. Chapter 6 addresses cybersecurity and safety, applying a risk-assessment and questionnaire-based approach consistent with the NIS2 Directive. Chapter 7 summarises the main cross-disciplinary conclusions.

2 CONCEPTUALISATION AND ECONOMIC PROPERTIES FOR ENERGY DATA-SHARING INFRASTRUCTURE

2.1 Introduction

The increasing digitalisation of the European energy system is changing the way electricity is generated, managed, and utilised. The rollout of smart meters, network expansion, and increase of distributed renewable resources is creating large and complex flows of data. Something that used to be just a by-product of energy production is now a valuable resource, changing how energy systems grow and how services are delivered to people and companies. Secure and interoperable access to energy data has therefore become an essential foundation for achieving Europe's climate and energy objectives, for enhancing competitiveness and innovation, and for ensuring that the benefits of the green and digital transitions are shared widely.

In this context, the EDDIE project seeks to establish a decentralised, open-source framework that enables trustworthy exchange and use of energy data across Europe. The project reflects the wider vision of a CEEDS, where technical interoperability and governance frameworks together create an ecosystem for data sharing. The work presented in this chapter explores the conceptual and economic properties of such a system. The analysis has mainly three objectives. First, it provides a conceptual understanding of energy data as a good that has both public and private dimensions. Second, it analyses the economic mechanisms through which digitalisation reshapes competition, market structures and innovation, focusing particularly on issues such as interoperability, cost allocation, and the role of artificial intelligence in energy markets. Third, it considers the conditions under which a data-sharing infrastructure can function efficiently, remain economically viable and deliver broader social value. These considerations are not purely technical or financial. They also relate to how trust is built among actors, how new business models emerge, and how regulation can support a fair and transparent data economy.

These complementary perspectives provide the conceptual and analytical basis for understanding how a distributed European energy data infrastructure can contribute to Europe's wider goals of sustainability, digital sovereignty, and social welfare. The intention is not only to examine the economics of data but also to situate a CEEDS within a wider transformation of the energy sector: one that increasingly relies on openness, cooperation and innovation to deliver a secure and sustainable energy future.

2.2 Methodology

The analysis presented in this chapter follows a mixed-methods approach, combining conceptual reasoning with qualitative and quantitative techniques to capture the complexity of data-driven energy systems. The topic lies at the intersection of economics, technology and policy, and therefore benefits from an approach that draws together insights from several disciplines rather than relying on a single perspective.

The work builds on existing research on digitalisation, data governance, and network industries, which provides the conceptual basis for understanding how energy data creates value. This background helps to clarify that energy data differs from most other goods: it can be shared and reused by many actors, while access to it is often shaped by legal, technical or commercial conditions.

A large part of this chapter involves developing an integrated economic perspective to interpret how digitalisation and data availability are transforming the organisation and incentives of the energy sector. This conceptual analysis draws on ideas from information economics, industrial organisation, and public policy to understand how new technologies and data flows interact with market design, competition, and regulation. The resulting perspective provides a foundation for assessing the economic logic and practical challenges of energy data spaces.

To complement this conceptual work, examples from recent European initiatives on energy data spaces are briefly presented to illustrate emerging approaches and experiences. These examples are used to situate the analysis within the wider European context and to identify lessons for issues such as interoperability, governance, and cost allocation. The intention is not to undertake a detailed comparison, but to draw on relevant developments that highlight alternative design and governance options.

In addition, illustrative economic modelling and simplified simulations are used to explore how pricing mechanisms, market incentives, and the use of artificial intelligence may influence market efficiency, innovation, and consumer behaviour. These exercises are not intended to produce forecasts, but to highlight key feedback loops, adaptive behaviours, and network effects that characterise data-driven energy ecosystems.

This mixed-methods approach provides a consistent analytical framework for examining how energy data spaces create and distribute value, promote innovation and efficiency, and contribute to a fair and sustainable energy system.

2.3 Economic Perspectives on Granular Energy Data

2.3.1 Introduction

The all-encompassing digitalisation of key parts of the economy[1] has reached the energy sector (Sioshansi et al., 2020).[2] While digitalisation is widely expected to increase the efficiency of the energy system, it brings the need to re-conceptualise the economics of the green energy transition. This requires the development of a logical mapping that starts from the new technological possibilities opened by the digitalisation of the energy sector and matches them into information economic concepts. This mapping is then used to frame the emerging policy trade-offs posed by this process and to provide a new perspective needed to identify the new energy system actors, understand the changing roles of the existing players, and analyse the shifts in their incentive structures, in the digitalisation era. The aim is to discover processes that might reinforce competitive advantages for actors such as energy retailers and aggregators and improve their ability to design targeted, profiled, and bundled supply contracts, whose accuracy becomes unmatchable by entrants or competitors not having the same access to such data. This perspective becomes an imperative when assessing the market and distributional effects of these processes.

The possibilities due to the digitalisation of the electricity system also pose new challenges. First, grid operators need efficient economic signals and regulatory incentives and frameworks to adopt digital solutions.[3] Second, consumers should benefit from the adoption of end-point digital tools such as smart meters so that their incentives are aligned with the societal goals of electrification and decarbonisation. Third, interoperability, as the ability of

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[1] In Europe, the share of businesses that provided fully digitalised products and services increased from 34% to 50% during the COVID-19 lockdown. This was also related to the use of cloud computing services, which increased from 24% in 2019 to 41% in 2021 (European Commission, 2022a).

[2] Digitalisation shaped the fourth industrial revolution (Schwab, 2016) relying on computational innovations brought out by the combined developments in the fields of Artificial Intelligence (AI) and quantum computing.

[3] The European Commission (EC) considers that EUR 584 billions of investment in electricity grids will be required until 2030, where digitalisation and grid real-time monitoring investments are relevant (European Commission, 2023f).

different data systems to exchange information, becomes a necessary condition to remove entry barriers and increase market competition (Reif and Meeus, 2022).[4]

This brings us to the debate on themes such as decentralised versus centralised architecture of Data Management Models (DMM).[5] This requires exploring the options to bring transparency and openness of energy data to the network edges while still relying on a common 'centralised' framework to maintain trust, an essential element in enabling common data spaces, where data infrastructures and governance frameworks are brought together to form a federated data ecosystem based on shared policies and rules (European Commission, 2024b).

Finally, digitalisation endogenises consumer demand, as it provides the information necessary to choose and move across alternative tariffs and retailers, increasing demand flexibility and providing new bundling possibilities. The main factors influencing demand-side behaviours are the time-profiled economic incentives, made possible by the new granular data, which, however, often require refined cognitive abilities and digital and numerical literacies, for users to access and process massive quantities of real-time microdata.

These processes present new technical and regulatory challenges for achieving an efficient, equitable, and timely digitalisation of the sector, which is too often neglected in the current energy policy literature. We address these knowledge gaps by creating a logical framework that connects the new technological possibilities introduced by the digitalisation of the energy sector with relevant concepts in information economics. Based on this mapping, we conclude this section exploring policies addressing digitalisation and energy infrastructures, encompassing a strategic incentive-based analysis of the economic problems posed. While exploring the different dimensions of digitalisation in energy spaces, we discuss solutions to similar issues that have been developed for the Internet sector, where digital interconnection choices and incentives have been addressed since its inception. Our analysis addresses how these issues affect economies of scale, cross-platform benefits, and market entry incentives, while also considering the new impacts and the economic value of personal data generated through the digitalisation of energy systems.

[4] The EC considers data interoperability and standards as a lever to facilitate grid investments and cost savings (European Commission, 2022b).

[5] This debate is similar to the one on integrated (i.e., coordination) vs separated (i.e., competition) information and data management and electricity grid operation. For a discussion of the trade-offs between these options and the proposal of a novel governance approach, see (Brandstätt et al., 2017).

2.3.2 Energy transition and digitalisation

The EC predicts a 60% increase in electricity consumption by 2030 (European Commission, 2023f). Digitalisation is a key enabler for an integrated energy system that addresses the energy trilemma, namely, energy security, energy equity, and environmental sustainability (Cambini et al., 2020; Jamasb and Llorca, 2019). These constitute three key elements for the achievement of the wider United Nations (UN) Sustainable Development Goals (SDGs) (Jamasb et al., 2024). In 2023, the UN Development Programme (UNDP) and the International Telecommunications Union (ITU) launched the SDG Digital Acceleration Agenda (SDGDAA), a global analysis of the links between digital technologies and sustainable development, providing a roadmap for governments' digital transformation. The SDGDAA includes diverse examples of how digital technologies help this process (ITU and UNDP, 2023).

In line with SDG 7, to "Provide affordable, reliable, sustainable energy for all by 2030," the SDGDAA showcases digital solutions, including simulation-based software for mini-grids electricity demand and a community engagement platform to explore their own long-term demand growth and usage behaviour ("Comet," implemented in Malaysia, Indonesia, Myanmar, Somaliland, India, Nepal, and Fiji).

In 2022, the EC launched the EU Action Plan for the Digitalisation of the Energy System (European Commission, 2022b; 2023c). This plan includes smart buildings, smart metering systems, EVs, the Internet of Things (IoT), and other devices to provide key information to monitor energy consumption, boost data sharing, increase Renewable Energy Sources (RES) integration, and reduce costs for consumers. Moreover, the EC considers that innovative data services, apps, and Energy Management Systems (EMS) have a large untapped potential for energy users, but they need further boost and policy support measures to become ubiquitous. Indeed, connecting large amounts of RES in a short time requires innovative digital solutions to anticipate and possibly solve future technical and operational needs. Simultaneously, consumers should be empowered to make informed decisions using the new information at their disposal.

The International Energy Agency (IEA) also emphasises the importance of digitalisation in enhancing energy efficiency and driving innovation in the sector (IEA, 2017). To achieve these aims, a new perspective on Energy Data Spaces (EDS) is needed, one that should consider the effects of digitalisation on the energy system's incentives and efficiency. Interoperability and standardisation of the EDS are crucial for seamless integration and communication among diverse components within the energy infrastructure, as well as for cost-effective integration of RES into the system (Digital4Grids, 2023).

A European, decentralised, and open-source EDS solution to structure electricity generation, transport, and distribution networks, as well as consumption, has been advocated (European Commission, 2019), which sets the rights to non-discriminatory and transparent access to metering as well as production and consumption data for customers and third parties of their choice. However, while energy policies identify both the digitalisation opportunities and potential risks, they often do not capture a fundamental economic dimension of digitalisation: its potential to be a radical transformer of existing market structures, due to the competitive relevance of granular user data.

This competitive impact, results from two conflicting effects: the ability of digitalisation to reduce market entry costs for potential entrants, and digitalisation's role in entrenching incumbents' market power. This last effect is related to the potential of digitalisation to monetise and generate economic value and to create and link new markets for novel commodities and services, for instance, through bundling practices, such as leasing EVs, providing electricity to charge them, and, possibly, repurchasing such stored electricity from EV or behind-the-meter household batteries at different times of the day, when this might be more valuable.

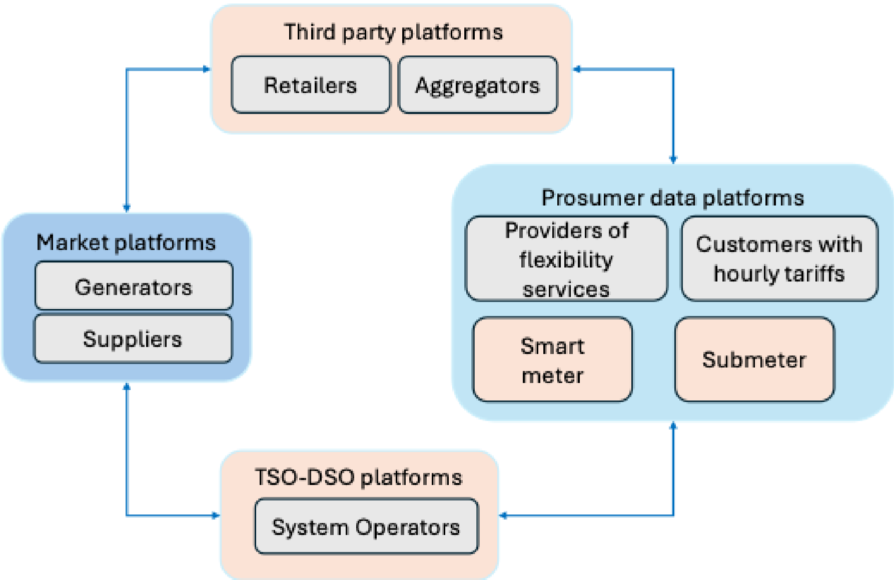

Figure 2.1: Information exchanges between the main agents in the power system.
Source: Own elaboration.

Figure 2.1, shows a simplified version of the energy system, used as a reference when discussing pros and cons of policies across the fields of digitalisation and energy infrastructures, whose joint study too often lacks a clear, strategic interaction-based analysis of the key public economic problems posed. Transmission System Operator (TSO)–Distribution System Operator (DSO) platforms, represent the own data exchanges platforms from grid operators. Market platforms match the energy bids from generators and customers (retailers), or flexibility needs from grid operators are matched with flexibility bids (aggregators). Prosumer platforms include all the systems and infrastructure essential to meter energy consumption data (smart meter), or flexibility provided by flexible resources (submetering). Finally, third party platforms include the (energy) retailers and aggregators (flexibility).

2.3.3 Digitalisation and grid operation

An efficient integration of large volumes of variable RES requires addressing new operational challenges, as they include Inverter-Based Resources (IBR) with limited operational capability compared to the rotating synchronous generators in replaced thermal plants. Overloads (congestions), voltage issues, or inertia problems primarily pose operational challenges. In many cases, grid operators should curtail the scheduled RES in the markets to ensure power system reliability, which clearly represents an inefficiency (Davi-Arderius et al., 2024; 2025).

Digitalisation enables the implementation of advanced operational solutions to anticipate and solve these new operational challenges (Di Silvestre et al., 2018). Most of these solutions use data from monitoring energy flows through the grid or smart meter systems. Among others, they include Distributed Energy Resource Management Systems (DERMS) to operate large volumes of small RES or Dynamic Line Rating (DLR) that consider weather conditions when defining the maximum load of each line (Degefa et al., 2014).

Digitalisation and AI can also help reduce interruption times and improve the quality of supply (Barja-Martinez et al., 2021; InnoGrid, 2023). However, this is not straightforward, and grid operators need advanced tools using big data analytics. Some studies have quantified that DSOs in EU-27+UK would need to invest between EUR 25 and 30 billion between 2020 and 2030 to achieve the decarbonisation targets, with investments in the digitalisation of the low-voltage network level at which most of the small customers are connected (Monitor Deloitte, 2021).

These efficiency-enhancing processes are implemented in parallel with important developments in technologies and data processing. They include the establishment of (energy intensive) data centres hosting cloud solutions to store increasingly large and distributed amounts of data, the development of appropriate algorithms for big data analytics to obtain added value from multiple sources (e.g., historical metering data, real-time monitoring data, or weather forecasts), continuous development of AI solutions, often based on natural language processing tools, to improve customer service (day-to-day processes, customer call centres or claims management), edge computing to decentralise data processing (primary or secondary substations), and possibly quantum computing to expand computational power and address the needs of big data requirements (Masanet et al., 2020; Charbonnier et al., 2022).

In many cases, addressing the new operational challenges of RES integration requires specific consumers (or generators) to modify their consumption (generation) pattern to change energy flows in the network. This, however, involves implementing flexibility services and transforming traditional passive consumers into active consumers by allowing aggregators to control their end-use devices or batteries (Chaves-Avila et al., 2024). Participants in these flexibility services receive economic compensation for modifying their consumption or generation at the request of the grid operator (Nouicer et al., 2023).

To explore the potentials of flexible consumption from households, the UK's National Energy System Operator (NESO),[6] launched a study into the potential mechanisms to influence the households' flexibility (e.g., technology and tariff structure) and to guide the development of markets for flexibility services.[7]

However, implementing digitalisation solutions by grid operators is not straightforward and requires properly designed regulatory frameworks for their investments. Digitalisation investments differ from conventional investments in lines, cables, or transformers. Table 2.1 provides a summary of the key differences between traditional investments in electrical assets and investments in digitalisation made by grid operators. These differences increase the complexity of how regulators approve, incentivise, and supervise investments in digitalisation made by grid operators. This concern is especially relevant when grid digitalisation capital needs are high, and the investment benefits might differ across the grid. For instance, a more congested grid might need a higher level of monitoring than the rest. This issue is also related to the anticipatory grid investments defined in the EU Grid Action Plan (European Commission, 2023f), which are essential in facilitating connection of new RES. Moreover, the ambitious grid investments declared in the EU Grid Action Plan require setting an attractive Weighted Average Cost of Capital (WACC) for the digitalisation investments.[8]

[6] https://www.nationalgrideso.com/
[7] See the press release "Energy consortium launches the UK's largest domestic flexibility study" at https://www.nationalgrideso.com/document/212851/download.
[8] WACC reflects the rate of return that regulators allow grid operators to recover on their investments.

	Electrical asset investments	Digitalisation investments
Useful life of investments	Long-term capital investments (40 or more years)	Short-term capital investments (10 or less years)
Standardisation of investments	Wide number of international standards and regulations. High standardisation of grid investments: cables, transformers, substations. Easy to set benchmark costs by National Regulatory Authority (NRA).	Few international standards and regulations because of recent and constantly innovative solutions. Mid/low standardisation of digitalisation investments related to innovative solutions. Difficult to set benchmark costs by NRA.
Criteria to audit investment by Regulators	NRA sets short list of network design criteria for grid operators	NRA might set digitalisation design criteria for some activities (smart meters), but not for others (IT communications, characteristics of monitoring devices). Digitalisation design criteria are more complex and highly

		dependent on a variety of standardisation, cybersecurity, interoperability and existing solutions in each company.
NRA replicability and assessment of the optimal investment volumes	Easy replicable by NRA with the grid structural information and the network design criteria.	More difficult to replicate by NRA. Difficult to define and compare digitalisation structural information between grid operators. Relevance of using Digital twins for replicability. NRA should use Key Performance Indicators (KPI) to compare efficiencies from different grid operators.
Implementation of economic incentives to grid operators	Easy to implement incentives to make investments below benchmark costs.	Benchmark costs are more difficult to be set, and digitalisation grid investments might not be easily comparable. Difficult to calculate profitability of investment, as this depends

		upon faster obsolesce, and results depending on different types of network externalities, the dynamic of which might be highly path dependent (David, 1997; 2007)

Table 2.1: Comparison between traditional investments in electrical assets and investments in digitalisation by grid operators.

2.3.4 Centralised vs decentralised data management models

Historically, the usefulness of many energy solutions has been dependent on the ability to upscale or downscale technologies. In the 1990s, Combined Cycle Gas Turbines experienced technological progress that enabled the building of new, less costly plants. These developments facilitated the entry of independent power producers into newly liberalised electricity markets, removing some pre-existing barriers to competition (Elia et al., 2021). Progress in RES technologies was accelerated by allowing the emergence of initially small wind turbines, then gradually leading to the entry of ever larger installations. Recently, some innovative solutions, such as local energy communities or community-based projects, which share generators or storage devices between some customers, have been proposed (Otamendi-Irizar et al., 2022). [9] These mechanisms empower customers and local economies. Nevertheless, data exchange processes are essential for the success and development of those energy communities.[10]

The development of early electricity and town gas systems in the 1800s already posed key policy questions around centralised vs. decentralised infrastructure models. The early

[9] For instance, the Swaffham Prior Heat Network project led the way in the UK, to be the first village to develop a rural heat network. The mix of air source and ground source heat pumps have capacity to supply 1.7MW of heat to 300 homes. This allowed to address energy poverty and local environmental issues caused by the village's reliance on heating oil. https://www.cambridgeshire.gov.uk/residents/climate-change-energy-and-environment/climate-change-action/low-carbon-energy/community-heating/swaffham-prior-heat-network/about-swaffham-priors-heat-network.

[10] https://www.iea.org/commentaries/empowering-people-the-role-of-local-energy-communities-in-clean-energy-transitions

systems were mainly the result of local private or public initiatives. National and central systems only emerged later, as the need for technical standardisation and operational coordination grew. For instance, in the UK, at the time of the establishment of the national electricity grid in 1926, there were over 600 electricity distribution networks that operated at different voltage levels. A national system was needed for the technical standardisation of assets and harmonisation of system operations (Jamasb and Pollitt, 2007).

Often, centralisation may promote efficiencies or achieve better regulation since it is a means for achieving technical and non-technical 'standardisation.' Standardisation is, in turn, important for the promotion of innovation. Markets alone cannot be relied on to provide these elements in an efficient way due to the specific 'public' nature of the service provided (network infrastructure). Economic theory suggests that markets do not supply sufficient public goods, and the elements of energy systems mentioned above exhibit characteristics of public goods, leading to private underinvestment due to incentives for free riding (Atkinson and Stern, 1974). Public goods emerge due to non-excludable and non-rivalrous elements of the energy infrastructure, for instance, due to information asymmetry linked to data on individual usage of the shared grid.

However, centralised solutions may not always be the most efficient, particularly when certain components were previously developed separately on different platforms. This attribute aligns with the idea of coordinating and using existing energy data systems to form an energy data space. In these cases, existing decentralised and interconnected solutions might be more efficient, less costly, and easier to apply than centralised solutions.

A useful example of an integrated decentralised network is provided by the Internet, a network of networks of different scales and sizes, interconnected, and able to deliver universal end-to-end connectivity. In this sector, the establishment of Internet Exchange Points (Schwab, 2016) provided an alternative form of "Localised centralisation" of traffic exchanges, often based on not-for-profit governance, reducing overall costs of access (ITU, 2021). These changes also resulted in a more decentralised hierarchy of the global Internet, enabling it to reap broader benefits from its original technical interoperability. However, the Internet is also exposed to threats to universal connectivity due to many proprietary sub-ecosystems, for instance, mobile social networks that require additional elements/memberships/apps to be accessible by users.

The current approach by the European Regulators (ACER, 2022) prioritises implementing a "single and common-front door" for the independent aggregators in the flexibility registers. This solution enables several decentralised data platforms to act as a unique (centralised) platform by the third parties, i.e., independent aggregators, suppliers or customers. Similar solutions are already implemented with some DSO-shared platforms such as Datadis for the metering of consumption data in Spain or SIORD for monitoring RES and future flexibility resources (Datadis, 2023; Canales Laso et al., 2023).

As previously discussed, centralisation is neither necessary nor sufficient for standardisation and harmonisation of an interoperable network of networks and implementing a single and common front-door can be a feasible and efficient solution. From technological and business perspectives, in the last decade, many companies have dedicated large resources to centralising their data processes through cloud migration (Hasan et al., 2023), with data coming from many decentralised physical servers. This approach reduces costs and increases security and accessibility, among other benefits, while aiming to maximise the system's efficiency by leveraging its positive network externalities.

The diffusion of edge computing is currently driving a new trend towards decentralisation. This implies moving from a central cloud platform that operates and makes decisions for all the network assets towards multiple small edge devices that take their own decisions and operate decentralised assets. This decentralisation trend provides relevant benefits, as it reduces data flows, simplifies computational needs, reduces vulnerabilities in the power system, reduces computation latency, and increases reliability. Currently, their implementation in the power system is in an incipient stage, but future developments are expected in the next years, mostly related to the operational challenges due to renewables (Charbonnier et al., 2022).

Similarly, decentralisation on the Internet is exemplified by the emerging trend of dense interconnections among small and medium-sized regional networks, a practice known as "doughnut peering," (Faratin et al., 2008; ITU-T, 2025) which is used to bypass the largest central players and create a "doughnut hole" architecture.

However, decentralisation also has the potential unintended consequence of increasing the market power of initially external operators, becoming able to leverage their existing market position in contiguous markets, such as edge computing in the retail energy market.

2.3.5 Data interoperability and standardisation

A key success element for exploiting potential economic benefits from digitalisation is to set interoperability measures that seamlessly enable data exchange and communication across a sector – and even at a cross-sectoral level – and lower barriers to participating in the flexibility services previously defined in 2.3.3 (Reif and Meeus, 2022; Davi-Arderius et al., 2024).[11]

The physical configuration of the DMM, and the rules and regulations governing these systems provide a key example of the relevance of interoperability between different data resources.

By focusing, again, on the Internet experience, this network evolved around the development of a unified communication protocol (TCP-IP), allowing universal interoperability across many different international networks, whereby cross-network digital exchanges were managed by Border Gateway Protocols (BGP) (D'Ignazio et al., 2006).[12] However, notwithstanding technical interoperability, the governance of digital interconnection and[13] This standard provides a framework for collecting, sharing, and utilising data related to fibre optic infrastructure in a consistent, interoperable manner. The OFDS improves transparency and reduces information asymmetry by standardising the collection and sharing of data about fibre networks. Hence, in this case, interoperability among the many relevant dimensions of these networks is necessary in ensuring that data can be shared and integrated across different platforms and systems.

Refocusing on energy systems, digitalisation provides added value by combining data from different sources, i.e., energy resources or end-use devices. This requires their design to use common standards and be interoperable. Standardisation lays the groundwork for interoperability. From a technical perspective, data interoperability is one of the components of the technology building blocks in data spaces.[14] In this context, achieving full interoperability requires the adoption of common standards in the form of compatible data

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[11] 'Interoperability,' which will be discussed in more detail in Section 2.4, means the ability of different energy or communication networks, systems, devices, applications, or components to interwork to exchange and use information. Standards aim to ensure interoperability and safety, reduce costs, and facilitate companies' integration in the value chain and trade. European Standards are under the responsibility of the European Standardisation Organisations such as CEN, CENELEC or ETSI (European Commission, 2019; European Commission, 2023f).

[12] Still, national governments and corporations managed to create spaces outside universal connectivity (intranets and other types of national walls).

[13] The initiative is a multistakeholder effort involving the World Bank, ITU, Mozilla, Liquid Intelligent Technologies, CSquared, and the Internet Society. https://documents1.worldbank.org/curated/en/099063023160023332/pdf/P1761460fac12e0b09cb90f26880158a4f.pdf.

[14] The other components are data sovereignty and trust and data value creation.

models and data formats for data sharing purposes via Application Programming Interfaces (APIs). Interoperability also requires data to be traceable and trackable from its origin to its end-use point.

A survey conducted by the EC in 2018 listed interoperability as the main technical barrier for data sharing (Botta, 2023). A lack of interoperability acts as an entry barrier, as it hinders the seamless exchange of data between different stakeholders and the formation of innovative data-driven solutions. Information asymmetry is another consequence of lack of interoperability. Certain stakeholders exclusively possess and use critical data, and this type of asymmetric information hinders competition (Hałaburda and Yehezkel, 2013). Therefore, also from an economic perspective, interoperability is important for promoting free entry and the ensuing dynamic efficiency (Scott Morton and Kades, 2021).

In the EU, policymakers have addressed the issue of interoperability in several cases. The EC (European Commission, 2019) mandates interoperability for accessing energy data to promote competition in the retail market and avoid excessive administrative costs for eligible parties. According to the EU Digital Market Act, if deemed necessary, the EC has the authority to request that European standardisation bodies develop the necessary standards aiming to promote interoperability (European Commission, 2023d).

In June 2023, the EC adopted legislation to ensure that metering and consumption data across countries follow a common reference model that can be customised at the national level (European Commission, 2023e). [15] However, this legislation only addresses administrative procedures. The EU legislator addressed the technical aspects of interoperability by establishing the Data Spaces Support Centre (DSSC) in October 2022, funded by the EC under the Digital Europe Programme, to identify common standards, technologies, and tools to support the establishment of sectoral data spaces in Europe.[16]

In the energy sector, grid operators handle a high variety of data: consumer metering data, network operation data or detailed technical data about their lines or transformers. In this context, standards set by grid operators may form barriers for new entry and third parties that would require access to consumer data for providing their innovative data-driven solutions (Fekri et al., 2021). It is also essential that this diverse range of data is made

[15] Implementing Act on metering and consumption data is part of the Digitalisation of Energy Action Plan launched by the European Commission in October 2022.

[16] See https://internationaldataspaces.org/the-data-spaces-support-centre-is-now-launched/.

accessible to third parties to enable further innovation. Therefore, it is important to involve smaller or newer stakeholders in the initial stages of establishing standards and interoperability rules to avoid favouring incumbent providers and manufacturers over the others.

Finally, digitalisation is a "relatively new" concept in the energy sector.[17] This scenario is in evident contrast with the "Big Tech" sector, whose key companies have vast resources and the required knowledge to quickly take up market shares in new sectors when they integrate digital solutions. "Big Tech" companies might achieve these objectives by leveraging their own technical standards across sectors. This situation presents new regulatory challenges related to leveraging market power across recently connected sectors through digitalisation (Manganelli and Nicita, 2022).

In summary,

- Interoperability benefits are that:
  - It allows for seamless communication and data exchange among different systems and devices, while,
  - On the other hand, setting interoperability requirements might favour some providers or manufacturers over others.

- At the same time, standardisation benefits, are that:
  - A relevant part of the interoperability processes, are known in advance and help lowering economic and technical barriers to implement new information exchange processes; however,
  - Listing standards might limit the adoption of future innovative standards and leave some manufacturers out. The processes for approving new standards may be complex, and the standards in the EU may differ from those in the US and other regions. Also, implementing new standards might be incompatible with other existing ones and, finally, the adoption of existing data standards into EDS might entrench market power from a few gatekeepers, leveraging their market power from the ICTs to EDS.

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[17] It can be argued that digitalisation in the energy sector is not a novelty. Rossetto and Reif (2021), points out that the process can be seen as series of consecutive digitalisation waves that have covered diverse parts of the system. The latest wave addresses issues related to distribution networks, consumer premises, and retail markets.

2.3.6 Economic considerations of personal energy data sharing

The replacement of traditional meters with smart meters is a key element of digitalisation and the customer-centric strategy. They track household consumption in real-time, which is essential to implement timely tariffs and economic incentives to value customers' flexibility.

Crowdflex, [18] the UK's largest domestic flexibility study, based on 25,000 households, estimated a 15-17% demand reduction during the evening peak in response to incentives incorporated into flexible Time-of-Use (ToU) tariffs.[19] Furthermore, households with an EV demonstrated even greater flexibility, reducing their daily demand consumption by up to 23% during the evening peak.

Smart meters were shown as possibly affecting most of the technical dimensions of energy systems, as described in Section 2.3.2. Crucially, these dimensions entail significant economic consequences. For instance, smart meters influence the crucial regulatory activity of "market definition" from both geographic and product perspectives, as they provide granular data used in dynamic tariffs that subsequently affect the price elasticity of demand,[20] as well as market power and market boundaries (Elzinga and Mills, 2011).

The availability of smart meter data also enables market participants to actively participate in the energy markets, as this data eases metering the hourly consumption and the overall process of switching providers. At the same time, the availability of hourly metering data also modifies the strategic incentives for incumbent providers. They might want to price more aggressively and offer profiled pricing and bundling strategies to keep entrants off the market. While these incumbent strategies are likely to generate economic surplus, as they are based on service quality improvements, they will simultaneously aim at maximising the extraction of consumer surplus by the incumbent. The incumbent's unregulated access to users' data and its algorithmic operability will likely reinforce these processes.

These economic consequences also cascade throughout the entire energy data ecosystem since implementing smart meters requires hiring highly skilled workers or adopting new

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[18] An Ofgem Strategic Infrastructure Fund project conducted in 2021 by NESO, Scottish and Southern Electricity Networks Distribution, Octopus Energy and Ohme. See https://www.nationalgrideso.com/future-energy/projects/crowdflex.

[19] This was shown by the differences in energy consumption between flexible (Agile) tariff customers vs. flat tariff customers, in correspondence to a price plunge on the 25th of October 2020.

[20] The traditional metric in economics for measuring market responsiveness to price increases.

digital solutions to communicate with them. Moreover, smart meters might be owned and operated by grid operators or third parties, which might have implications for the energy agents' market position.

A key factor in the success of smart meters rollout is their adoption strategy. In some countries such as Austria or Spain, their installation is mandatory by grid operators and recovered by network tariffs, while in others such as Germany, it is optional and directly funded by customers. In the latter case, installation costs and ease of use may represent a significant socioeconomic barrier to consider their deployment. Moreover, consumers do not necessarily have extensive knowledge of smart meters and their technology, which may increase their reluctance to install them. In the following, we focus on one specific use case, exemplifying how smart meters might play a key role in shaping economic incentives. Moreover, we use this case to explore some key related economic issues, including economies of scale due to network effects (Katz and Shapiro, 1994), cross-platform benefits (Rochet and Tirole, 2003), the incentives to enter the market (Giovannetti and Siciliani, 2020; 2023), and the economic value of personal data and data portability (Krämer, 2021; OECD, 2021).

Consider the contractual choices offered to a new UK customer by Octopus Energy a transnational supplier.[21] Under the heading on "Smart Meter Data Preferences" the supplier asks, "How would you like your readings stored?" and provides three alternative temporal profiles:1) Half-hourly, 2) Daily, and 3) Monthly. After the user's choice is made, a message appears stating that "choosing to store your readings half-hourly will help us better match the electricity you are using with renewable generation and reduce carbon emissions." This statement implicitly encourages (nudges) the consumer to use the smart meters' more frequent readings and information storage, by emphasising the collective benefit of reducing carbon emissions.[22] Then, a "deterring" statement follows: "Important: If you choose daily or monthly reporting, you will not be able to access your half-hourly data through us." Clearly, the benefits from the efficient half-hourly tariffs will differ among users, as they require that the customer can adapt their consumption to the different prices through demand that can be remotely activated (EV charging point, storage device) and simpler changes in the time of domestic energy usage.

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[21] Octopus Energy Group is a British renewable energy group specialised in sustainable energy. It was founded in 2015. It now supplies green energy in the UK, Germany, the USA, Japan, Spain, Italy, France, and New Zealand. "Smart Meter Data Preferences" were obtained from Octopus' webpage, https://octopus.energy/blog/track-my-energy-use/ (accessed in spring 2024).
[22] In behavioural economics, a nudge is a way to set a choice architecture that affects people's behaviour in a desired direction without restricting options (Thaler and Sunstein, 2021).

The usage by the retailer of the personal data collected highlights the economic incentives and trade-offs of personal data sharing.

- **First**, personal data sharing is useful for reducing asymmetric information.
  - A clear benefit is that by supplying granular information to the consumer, the retailer helps them to adapt their timing of energy consumption in view of reducing costs.
  - However, the associate's risk is that granular data-based advice from the retailer to the consumer clearly has the potential of reinforcing "brand loyalty" (Chen and Xie, 2007), decreasing consumers' willingness to look for alternative providers, hence reducing potential competition by implicitly increasing the consumer's switching costs.

- **Second**, personal data sharing is useful in reducing carbon emissions, as
  - Frequent metering readings allow for a better integration of RES, through better demand forecast, leading to reduced carbon emissions. Awareness of this benefit also increases customers' satisfaction, if carbon emissions negatively affect their preferences.
  - However, higher preferences lead to a higher willingness-to-pay, possibly leading to higher prices, absent other competitive effects. Under more competitive scenarios, higher perceived quality allows the incumbent retailer to maintain a price differential vs. its competitors or entrants when they are unable to match such quality.

- **Third**, personal data sharing is useful in constructing a set of retailer's recommendations based on actual customer consumption.
  - Hence, in exchange for real-time metering information, the provider will make recommendations, possibly advertising and bundling energy services with additional types of services or commodities: a home EV charger, an air-source or ground-source heat pump. The retailer may also provide free or discounted, or even zero, energy prices when wholesale prices decrease.
  - However, one can strategically use zero prices or cross-subsidisation within platform markets to attract customers on one side of the market. Thus, the other side, e.g., advertisers or sellers of complementary products, are willing to pay higher prices to the platform due to the cross-platform benefits they receive. Such cross-side platform externalities might be pivotal in inhibiting competition and entry into platform markets.

These considerations show that the time-frequency of smart meter readings leads to an increased perceived product/service quality with no marginal cost borne by the seller. Increased quality is only due to the feeding of the most frequent user data into the grid optimisation algorithms, whose cost is mainly a fixed one. Hence, paradoxically, due to the economic value of private users' data, at no extra cost, the retailer might charge a higher price based on the user's higher perceived quality of energy, for example, as it might have a reduced carbon footprint, which is only achieved because of the availability of the user's data.

In summary, the provider might extract extra 'rent' from the user's data by selling a higher-priced service with better quality, whereby the cost required to increase quality is only based on the interaction between the user's data and the retailer's algorithms. Or, in a more competitive market, the provider might use this customer personal data to outcompete possible entrants or existing competitors that have no direct access to these data or to their derived versions when fed to train the incumbent provider's pricing algorithms. In this second case, while regulation on data portability seems to be a clear indication of how to redress these potential rent extraction activities,[23] its success depends on the range/scope/definition of personal data and on whether these include derived products/services that are the outcome of (proprietary) algorithms to whom the portable data were fed. Hence, including data traceability as a standard might play a role in changing the dynamics of rent extraction.

Moreover, zero prices in traditional markets would signify the absence of scarcity or economic trade-offs. Instead, when based on personal data sharing, zero-price offers, typical of the digital economy (Kende, 2021) from Wi-Fi access in coffee shops to social media accounts and basic cloud services, are averaged with the value the retailer extracts from the personal information that users agree to provide when signing the agreements on the terms of use of the free service, after confirming to have read lengthy, complex contractual agreements. Such terms and conditions often refer to the use of personal information, either directly provided or, even more interestingly, indirectly provided, for example, by agreeing on the use of cookies and tracking, whose detailed information might be richer than what the user is aware of.

In this context, zero prices become a crucial business strategy, generating cross-side platform externalities, reducing competition and entry into platform markets. The interplay of

[23] The EC has addressed the issue of data portability in Art. 20 of the General Data Protection Regulation (GDPR), granting data subjects the right to request transferring their data to other service providers than the data holder.

these externalities with the lock-in costs introduces further policy dilemmas often linked to distributional implications, since alternative regulatory scenarios might help one side of a platform while weakening the other. In these settings, regulatory intervention might also exert differential and opposite effects not only between but even within single sides of the platform (Giovannetti and Siciliani, 2023). This might be the case if users on the same side of a platform are exposed to different levels of switching costs due to an asymmetric distribution of search costs or cognitive abilities.

Moving to more advanced use of personal data obtained via smart meters, below, we discuss the economic implications of the specific "tracker-based" cutting edge beta smart tariff offered to Octopus's customers.[24]

The tariff was advertised as being "Built with fairness in mind." It features energy prices that change daily based on the wholesale cost of energy and, crucially, requires the installation of a smart meter.

Once again, these types of "tracker-based" smart tariffs enable specific business strategies, which in turn present potential economic risks and benefits.

- The first strategy is *Advertising*, defined in the tracker cookies agreement as the ability to "Create more relevant campaigns, products, and services". This clearly has the benefit of increasing users' information, while risking reducing inter-retailer competition due to the new asymmetry of information linked to the retailer's advertising, of which one user is a customer.

- The second strategy is *Tailoring*, defined in the tracker cookie agreement as the ability to "make predictions about future behaviour based on current behaviour" to help develop and tailor our products and services.

- This has the benefit of leading to an:
    - Increased level of user's satisfaction, due to product tailoring and differentiation (Hotelling, 1929),
    - While, however, risking the softening of competition linked to stronger brand loyalty effects due to tailoring, leading to increased switching costs (Klemperer, 1987).

[24] Based also on details on this tariff. For a summary see: https://octopus.energy/blog/track-my-energy-use/.

- The third strategy is on *Market Segmentation*, defined in the tracker cookies agreement as the ability to "build a profile personally for you, so we can do things like show you products and services that we think will be of particular interest and relevance to you." This has the benefit of allowing a
  - Better identification of user preferences due to better profiling of the services available in a segmented market,
  - However, this approach risks softening competition because the increased market power results from reduced demand elasticity in a more segmented market.

- The fourth strategy involves *Ecosystem Alliances and Mergers*, allowing data firms to enter the market as energy retailers.
  - This strategy offers the advantage of combining various customer personal data sets to provide superior products.
  - However, markets become less competitive when a merged supplier has access to more complementarities and information than its competitors.

- Finally, smart tariffs create opportunities for *Supply-Side Demand Strategies*. These are possible when consumers are simultaneously energy producers/exporters or prosumers (Gautier et al., 2018).
  - This arrangement has the benefit of allowing prosumers to switch roles between demand and supply of energy, smoothing demand and reducing cost. through the "Smart Export Guarantee". As a result, intertemporal elasticity is increased.
  - However, a multiplication of the roles of users and the ensuing increasing tariff complexity, as determined by comparing supply and demand prices, might result in a decrease in price elasticity of demand when choosing among different retailers within a given time.

Finally, in assessing the benefits and risks of the strategies enabled by the digitalisation of the energy systems, it is important to focus on the nature and source of information on which such tariffs are based and whether such information is easily accessible to a wide range of service providers.[25] Are these only personal data or derived data? Are they collected from a sole source of information or merged from different sources, so that implementing

[25] Designing and introducing EDS where energy data is efficiently shared with all the energy sector stakeholders is at the core of the EDDIE project.

regulations on actual data portability might be feasible in theory but complex in practice? As an example, the above-discussed smart tariffs are based on a mix of data sources. These include, according to their terms and conditions, third parties such as price comparison websites and affiliates or partners, which may send customers' personal information. These tariffs also rely on the provider's access to national energy databases, which include information about a customer's property, meter details, previous suppliers, EV charging point services, and location data that corresponds with the location settings on customers' phones when using the mobile app. Additional regulatory efforts are necessary to address this complexity, with a focus on ensuring the transparency of the algorithms that receive data from personal users' smart meters.

2.3.7 Conclusions and regulatory implications

Regulatory frameworks include laws and regulations for all the involved agents in the energy and interrelated sectors. However, the increasing digitalisation of the energy sector requirements should be considered when adopting a new perspective on how to implement improvements in the energy regulatory framework. These include the standardisation and interoperability of all the involved devices and data formats and the regulatory framework for grid operators and the rest of the involved agents.

The first element of this perspective requires setting a pan-European framework to improve access to data and incentivise the data-driven innovation.[26] Current European regulation should be further developed to provide cheaper prices for aftermarket services, new opportunities and services related to the data, and better access to data collected by devices. It is critical to establish a framework for sharing data across sectors and Member States while also incentivising the development of common European data spaces in various sectors such as energy, agriculture, mobility, finance, environmental, and health.

The second element, for a new perspective, requires implementing digitalisation solutions in the energy sector and a regulatory framework for all the involved agents that is properly designed. On the one hand, grid operators need efficient incentives to implement digital solutions that improve their operational efficiencies, which improves social welfare. On the other hand, the regulatory framework for suppliers should enable implementing innovative tariffs to further develop flexibility from customers.

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26 https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-data-strategy_en.

A third step for a new perspective is the awareness that the implementation of innovative digital solutions needs a specific regulatory framework. For instance, the technical developments in smart meters have opened the possibility to install them beyond the point of connection with the grid and for specific purposes. They are known as submeters (or second meters) and are devices installed to record the flexibility provided by a specific unit within an industrial building or household, e.g., a cooling device, a water heating device, or an EV charging point. Aggregators and providers of flexibility consider them key in the deployment of flexibility services from small resources and consider them useful for billing or settlement (Chaves-Avila et al., 2024). Submeters are introduced by the EC (European Commission, 2024a) where Member States are mandated to establish national requirements to check and ensure the quality and consistency of their data, as well as their interoperability requirements.

A fourth requirement, for a new perspective, is the setting of interoperability requirements, as these become increasingly relevant with the connection of more digital devices in the power system. Such interoperability requirements are essential to ensure fair competition in the provision and adoption of digital solutions. Few interoperability frameworks might result in economic barriers to manufacturers, additional devices to enable communication with devices, or higher administrative costs, among others. The first Implementing Regulation on Interoperability was approved in 2023 (European Commission, 2023e). Future implementing acts would include interoperability requirements and non-discriminatory and transparent procedures for access to data required for demand response and customer switching (European Commission, 2022b).

Digitalisation is a key factor for efficient use of the physical energy assets within a given economic framework. The overarching aim of an EDS should be to enable the emergence of new business models supported by a new perspective on the appropriate regulatory frameworks. In doing so, such frameworks should aim to (i) maximise the network effects, (ii) minimise the transaction costs of using the data space, and (iii) prevent the emergence of dominant players, whose market power might be greatly enhanced by access to, and processing of, vast sets of integrated micro, meso, and macro data. In principle, the transaction costs of a centralised data space can be lower. However, political economy considerations of cooperation among the constituent systems and countries that make the enterprise feasible are more likely to be present in a decentralised structure.

Lastly, it is important to note that new areas for utilising decentralised energy data will evolve gradually over time. Just as early town gas networks evolved over time and with new fuel uses, a future EDS will also evolve with increased electrification of the economy and services, following a path-dependent process. Therefore, it is important to allow for time and co-evolution of the data space and the energy sector to generate new business models. However, innovative solutions such as edge computing enable another transformation from centralised solutions towards decentralisation. From an economic perspective, as future EDS facilitate the emergence of new services, a new perspective on this sector's regulation is instrumental in transferring whole sector efficiency gains to consumers. This is only possible if accompanied by a reduction of the information asymmetries necessary to prevent the use of smart meter granular data for private information rents based on proprietary and exclusive algorithms from gaining more market dominance.

2.4 Economics of Data Interoperability in a Data-Driven Energy Sector

2.4.1 Introduction

In the past decade, the massive connection of RES has changed the characteristics of the generation mix, which has become more random, variable and highly correlated with weather conditions, e.g., sun or wind, varying at fine geospatial levels (ESMAP, 2020, Davies et al., 2023, Zardo et al., 2022). Inevitably, traditional rigid consumption profiles must become flexible to adapt their consumption to the available RES production at each time. In this regard, hourly electricity markets play a key role when allocating RES generation and consumption schedules, and two opposite outcomes are seen in countries with high volumes of RES: electricity prices become negative when there is a surplus of RES, or electricity prices peak when there is a deficit of RES production and costly pollutant technologies must be called on.

Customers must adapt their consumption profiles and become flexible through implicit flexibility which is expressed by their reaction to price signals. This form of flexibility opens the door to implementing ToU tariffs, differentiated by hours, days of the week or seasons. However, this is not straightforward and requires the massive installation of smart meters that are able to record hourly consumption of energy in households. This transforms the role of the different stakeholders in the power system, enables frequent data exchanges and communications between them and adds to the complexity of interactions between the different agents. Figure 2.2 provides an overview of this transformation and contrasts the corresponding data flows in power systems with passive consumers vs. emerging systems with active consumers equipped with smart meters.

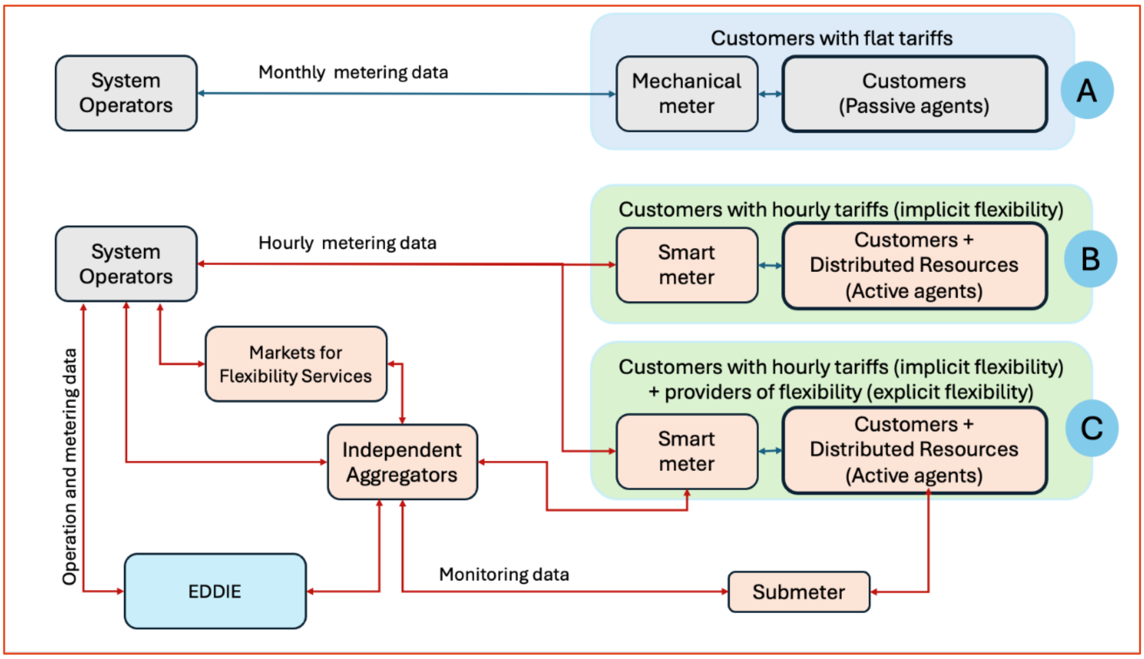

Figure 2.2: Data flows in the power system.

Note 1: Case A represents the system before implementation of smart meters, Case B represents the current system with smart meters, and Case C represents the future system with providers of flexibility and data exchanges with other sectors through EDDIE platform as described in Section Economic considerations.

Note 2: black arrows correspond to past data flows, red arrows represent data flows in the new paradigm.

As is shown in Case A of Figure 2.2, prior to the deployment of smart meters, customers had mechanical meters that recorded the accumulated monthly (or bimonthly) electricity consumption, and the possibility of differentiating the time of consumption was limited, at best, to peak and off-peak periods. In Case B, the possibility to record hourly consumption of energy opens the door to implement hourly electricity prices, which has the potential to transform passive customers into active customers, while enabling the suppliers to offer complex dynamic price schedules. These might play a clear role in incentivising consumption in some hours over others, which increases efficiency and RES integration. However, the possibility of introducing new dynamic pricing strategies will necessarily also impact on the competitive nature of the markets. The net effect of such an impact needs to be carefully considered by considering how static efficiency, i.e., better matching dynamically changing demand and supply, and dynamic market efficiency, that includes the impact on contestability, entry conditions, market power and the speed of innovations, are affected.

The transformation of the energy system made by smart meters goes beyond the implementation of hourly economic incentives to customers. Smart meters have the potential of transitioning the traditional energy sector into a data-driven energy sector. Energy data becomes the core of many system operator processes and new roles such as metered operator, metered data administrator or data access provider, among others, are created (European Commission, 2023a). In this new scenario, the interaction between customers and system operators grows. As defined in the European Commission (2019), smart meters should also provide real-time data to the customers to allow them to react to the real-time price signals.

2.4.2 Economic considerations

Poletti (2022) from Octopus, a key European supplier, has defined this transition as an historic shift, that moves from the traditional Demand Side Response (DSR), to one of Intelligent Demand. Indeed, historically, energy systems always focused on adjusting energy supply to meet the demand. For instance, DSR was incorporated into the 2005 Energy Policy Act in the United States. In the United Kingdom, the Economy 7 tariff, utilising base-load generation to offer cost-effective electricity during off-peak hours, commenced in October 1978 (Hamidi et al., 2009). Moreover, since the 1950s, New Zealand and South Africa have been managing peaks in electricity demand using 'ripple control', first introduced in France, back in 1927 (Poletti, 2022). This method widely used already by 1948 (Ross and Smith, 1948), worked by transmitting a high-frequency signal (ripple) at the substation with the standard 50 Hz power supply over the existing power lines while also having specific receivers installed at the consumer's premises detecting the ripple control signals to activate or deactivate connected devices accordingly (Kwon, 2009). Ripple control helped in grid load management by turning on or off water heaters or streetlights, during peak and off-peak hours balancing the load and preventing grid overloads. It was contextually beneficial for consumers with different electricity tariffs for different times of the day, as it could be used to switch devices to operate during cheaper tariff periods, optimising energy costs. As a result, Ripple control could be used to support demand response programs where consumers reduce their electricity usage during peak demand periods in response to signals sent by the utility company (Poletti, 2022).

However, DSR techniques arose from the need to optimise a system based on coal fuelled and nuclear power plants, matching electricity usage based on systems that could be anticipated with little uncertainty. As the energy system incorporates intermittent RES in the power grid, Poletti (2022) advocated replacing traditional DSR with the data-based energy management concept of 'Intelligent Demand.' This becomes essential, since, not only integrating RES supplies have an intermittent nature, but also the demand for electricity is changing drastically. For instance, the diffusion of EV home chargers and heat pumps, all necessary tools towards net zero, due to their intermittent timings, could add to the traditional 1kW household demand winter peak an additional 9-12kW load.

An example of "Intelligent demand strategy" is shown in Figure 2.3, superimposing wholesale electricity prices (grey bars) with "Intelligent Octopus Charging" (red line), between 30th of December 2021 and the 2nd of January 2022, whereby the key (intelligence) element is shown in the almost perfectly symmetric dynamics between the two curves, whereby any decrease in wholesale electricity prices (in p/kWh) is matched with an increase in Intelligent Octopus Charging (in MW). Even more interestingly, the spiking of charging in response to negative wholesale electricity prices when wholesale prices go down, can be matched to the instances when Intelligent Octopus tariffs send a command to the EVs to start charging.

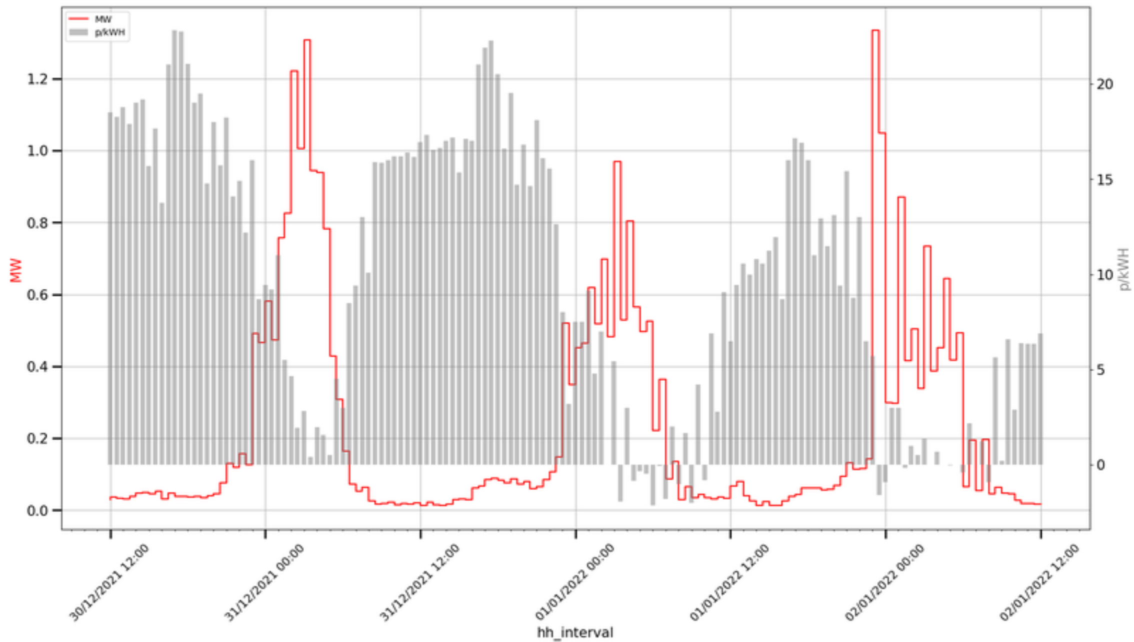

Figure 2.3: Intelligent Demand and wholesale energy prices with "Intelligent Octopus."
Source: Poletti (2022)
https://octoenergy-production-media.s3.amazonaws.com/images/fig2021-12-30.width-800.png.

The interaction between intermittent supply and intermittent demands is what allows data-driven systems and algorithms to achieve the necessary efficiency. However, as these key economic components of demand and supply are transformed, price signals also move to reflect these changes. In this case, it becomes unavoidable to address the potential economic consequences of these new intelligent tariffs that are transforming what economists call market fundamentals. Moreover, in non-monopolistic markets, the strategic implications of these dynamic pricing strategies will also shape the resulting competitive dynamics, market prices, demand and efficiencies in the short term and, in the longer term, innovation rates.

Finally, users might have different cognitive abilities and willingness to invest their time in understanding and comparing alternative complex intelligent tariffs. These differences might be related to socio-demographic factors, or to the level and composition of energy consumption of a household, depending, for example, on whether the household has a home charger, an EV or a heat pump. Each retailer might then find an incentive in using intelligent dynamic pricing tariffs, as strategic devices, possibly to soften competition, or discourage entry, due to the potential increase these tariffs might induce on the asymmetry in the switching costs among consumers (Giovannetti and Siciliani, 2023). Hence, it is important to consider the concerns that such tariffs, while necessary in incentivising intelligent demand, might not be used to segment an incumber retailer's customers, based on their differentiated willingness to switch between intelligent and more rigid tariffs, either within those on offer by the same retailer, or between those offered by competing ones.

2.4.3 Operational Considerations

The impacts of RES go beyond the hourly electricity prices and affects the operation of the power system. Grids have limited capacity and grid constraints (congestions or operational constraints) might occur more frequently in highly decarbonized power systems, especially at the distribution grids where many RES and most of the Distributed Resources are connected. These Distributed Resources include in-home devices (electric boilers or heating devices), small generators behind the meter, storage devices or EVs and their charging points. However, the same Distributed Resources can and should be part of the solution for grid constraints as they evolve into active Flexible Resources that respond to the needs of System Operators through the new data-driven services such as flexibility services.

In this model, independent aggregators pool a group of Flexible Resources and offer to the new markets for flexibility services the possibility to modify the consumption or generation patterns of Distributed Resources on request of System Operators to solve their grid constraints. The implementation of this new paradigm requires establishing new data exchange processes between all the involved parties as is shown in Figure 2.2 (case C). First, System Operators use energy operation data to forecast and anticipate in-advance grid constraints to be later solved by Flexible Resources. This also includes sharing energy operational data from other System Operators to coordinate. Second, Independent Aggregators use energy data from Flexible Resources collected through submeters to assess its potential flexibility to be offered to System Operators. Third, System Operators send operational setpoints to the Independent Aggregator to request the activation of its Flexible Resources. Independent Aggregators also implement cross-sectorial data exchanges (e.g., electricity, gas, transportation or heat, among others) as there are many links between energy sectors and electricity flows can be modified through changes in other sectors. In the data exchange processes, submeters play a key role. They are additional smart meters used to monitor energy flows of individual Flexible Resources, which are also needed to validate the activation of Flexible Resources by Independent Aggregators or System Operators (Chaves-Avila et al., 2024).

In all these processes, the need to set data interoperability requirements between system operators, metering administrators, customers and manufacturers of their home devices become relevant. As defined in European Commission (2019), interoperability means the "ability of two or more energy or communication networks, systems, devices, applications or components to interwork to exchange and use information to perform required functions". The same Directive sets the need to further develop "interoperability requirements and non-discriminatory and transparent procedures for access to metering data, consumption data, as well as data required for customer switching, demand response and other services."

The definition of the data interoperability provisions for the red data arrows in the Case C (Figure 2.2) have relevant economic implications on the performance of markets for the new data-driven services: a lack of interoperability in the data exchanges might require a manual data processing or implementing additional costly software and hardware solutions. Thus, data interoperability requirements set the entrance costs to participate in these markets and the economically feasible minimum bid unit to recover all the operating costs associated to the data communication flows. This data interoperability also includes the home devices that should react to the request of the aggregators, i.e., manufacturers must include data interoperability solutions to their devices.

In consequence, interoperability requirements constraint the number of potential participants in these markets, which in turn impacts the liquidity that sets the efficient performance of new data-driven flexibility markets. Thus, power system costs are reduced, and consumer surplus is maximised. However, such requirements might also open new channels for leveraging market power and information rent between data and energy platforms.

2.4.4 A European Distributed Data Infrastructure for Energy (EDDIE)

A complementary solution to improve data interoperability is setting national common-front doors, where Independent Aggregators can access all the energy data with a single communication link and regardless of who generates this hourly data. In this context, the EDDIE project introduces a decentralized, distributed, open-source data-sharing infrastructure as these challenges have broad implications on an industrial, economic, and social level in Europe and beyond.

Solutions tested in EDDIE also open the discussion about the adoption of centralized, decentralized or hybrid data architecture. Centralized corresponds to a single data platform that hosts all the information, while a decentralized corresponds to a group of platforms interconnected between them with a common front door as defined in EDDIE. In the middle, hybrid architecture corresponds to a combination of centralized and decentralized solutions. The adoption of an architecture model also has relevant economic implications. Decentralized solutions can make better use of existing data platforms and reduce their implementation time and cost, accelerating the implementation of flexibility services. However, this requires data interoperability requirements between them, as well as a common front door to access all the data. Centralized solutions can be more feasible solutions when any energy data platform is implemented from scratch. Additionally, their implementation costs might be higher than decentralized solutions.

Potential economic benefits of data interoperability go beyond the processes related to energy consumption and flexibility services. Recently approved European Data Act aims for a fair and innovative data economy based on the sharing of data of multiple connected objects or the Internet of Things (European Commission, 2023b). Data Act seeks to harmonise the access and use of data across Europe, which includes the development of interoperability standards for data-sharing and for data processing services. In economic terms, the European Commission estimates that 80% of the industrial data is not currently exploited and could create an additional GDP of EUR 270 billion by 2028 and increase competitivity. Data interoperability also overcomes potential vendor lock-in or switching between data processing services, which means removing barriers to entry and exit, main characteristics of markets in perfect competition. Information asymmetry is another shortcoming that will be significantly mitigated by making data interoperable between different sectors. It will facilitate the emergence of new cross-sectoral innovative data-driven solutions (European Commission, 2020). For instance, facilitating seamless data exchanges between the mobility and the energy sectors removes entry barriers, streamlines access to information and, leads to optimised usage of EVs while increasing competition and lowering costs for consumers/users in both sectors. For manufacturers of home devices, data interoperability requirements are essential to enable third parties (beyond the manufacturers) to activate these devices. Otherwise, independent aggregators must install additional costly communication solutions.

Finally, defining data interoperability standards is critical and might become inefficient when incumbents lobby to impose their interoperability standards on the rest. This would provide a competitive advantage for the incumbent over the rest and would create entry barriers for some providers, limiting the number of providers. Thus, ending with markets in non-perfect competition.

2.5 Cost Allocation for a Sustainable Energy Data Space

2.5.1 Introduction

In an increasingly data-driven world, the concept of data spaces has emerged as a foundational element for enabling secure, interoperable, and sovereign data sharing across sectors and organisations (Franklin et al., 2005). It fosters broader collaboration between different actors while often allowing to preserve data ownership. Within this context, energy data spaces are gaining prominence as key enablers of the digital energy transition (Berkhout et al., 2022). In the energy sector, data spaces have the potential to enhance efficiency, transparency and innovation. They facilitate the exchange and integration of data among stakeholders in the energy ecosystem, ranging from grid operations and consumption patterns to renewable generation and markets. However, while significant attention has been paid to the technical architecture of data spaces, considerations related to pricing and cost distribution for their long-term sustainability have not yet been systematically addressed in the literature. This section aims at filling this gap by exploring the principles and challenges of cost allocation in energy data spaces, with a particular focus on the incentives for different participants.

Significant changes in energy infrastructure are expected across many regions globally. On the supply side, there is a growing emphasis on green energy, driven by the increasing adoption of global net-zero CO_2 emissions goals (DeAngelo et al., 2021). However, while the expansion of renewable energy brings environmental and economic benefits, its variable and intermittent nature poses challenges for system dispatchability and reliability. Price fluctuations caused by variable renewable generation may lead to periods of price spikes, as well as periods where prices drop to near-zero or even turn negative. Overall, increased reliance on renewables makes the supply side less flexible than before. Meanwhile, the demand side of the energy system is also undergoing significant changes. For instance, the widespread adoption of EVs is raising electricity consumption among both private and industrial consumers. At the same time, demand is becoming more flexible over time. In some countries, private consumers can choose billing contracts with hourly electricity pricing, allowing them to monitor real-time conditions and charge EVs during off-peak hours. Similarly, industrial consumers are becoming more flexible as factories are increasingly automatized. This enables production to be scheduled based on electricity costs at different times. Thus, while traditionally the electricity supply was designed to follow the demand, the situation is progressively shifting; supply is becoming less flexible, while demand is gaining adaptability, as consumers seek lower costs and reduce emissions (see e.g. Sioshansi 2020).

This new paradigm highlights flexibility as a feature of future energy systems. Technologies, such as smart meters and AI, have the potential to optimise flexibility on both the demand

and supply sides. However, a baseline requirement is extensive data exchange, as (near) real-time data availability is essential for managing flexibility. This has led to the development of new data exchange systems in recent years at national and international levels. Some examples at the national level include the Austrian Distribution System Operators (DSOs) and Transmission System Operator APG,[27] who have operationalized the distributed data space for Austrian energy data exchange starting in 2012; the Danish Transmission System Operator (TSO) Energinet, who has introduced Datahub;[28] and the Spanish DSOs, who developed SIORD.[29] At the international level, the EU has supported several projects aimed at enabling collaboration across countries on data exchange, including energy data spaces. These projects aim to establish a trustworthy framework for leveraging EU energy data. Aligned with the EU's Clean Energy Package, they seek to reduce data integration costs and enhance the competitiveness of energy service companies in a unified European market.

While the design of data spaces addresses significant technical challenges, it is also essential to optimise their development and management from an economic and organisational perspective. Key questions include how the data space should be governed and by which entity. In the European context, a government body could play a role in guiding progress in a consistent and trusted direction for the continent. Additionally, proper cost allocation is crucial, as it ensures that users are treated fairly and that there is transparency around how resources are consumed, and who bears the associated costs. This serves to support the long-term sustainability of data spaces.

This section focuses on the economic design of energy data spaces, with emphasis on cost allocation and the creation of appropriate incentives for participants. From a cost perspective, an energy data space entails significant initial design and infrastructure costs, followed by ongoing operational expenditures related to data centres, continuous system operation and maintenance, and technical staffing, among others. Since the initial development costs of energy data spaces are often grant-funded,[30] we focus on the operational costs to ensure long-term economic viability. Moreover, while initial participants of a large energy data space might be energy system operators, the ecosystem is not confined to the energy sector. Over time, cross-domain actors may benefit from access to

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[27] https://www.eda.at/?lang=en
[28] https://energinet.dk/data-om-energi/datahub/
[29] https://www.edistribucion.com/en/innovacion-nuevas-tecnologias/GalvaniPlataformaSIORD.html
[30] Moreover, several foundational components of data spaces leverage existing digital infrastructure.

energy data. In that context, it might be legitimate and efficient that a share of operational costs is allocated to external users, reflecting the broader public-good value of the data sharing infrastructure.

Finally, it is important to note that while a data space may be open source, this does not mean it should be entirely free of charge. Open-source technology allows certain layers of the code to be publicly accessible, modifiable, and distributable under open-source licenses. However, implementation and customization can still incur costs.[31] For instance, EDDIE aims to introduce a decentralized, distributed, open-source energy data-sharing infrastructure, and one of its primary goals is to minimize implementation costs, although participants may still be required to pay fees to cover operational expenses.

2.5.2 Emerging models and value creation in energy data spaces

This section outlines the main features and design principles of energy data spaces, reviews ongoing European initiatives, identifies core value propositions and business models, and discusses how these developments give rise to specific challenges for cost allocation and incentive design.

2.5.2.1 Features of energy data spaces

An energy data space is a framework that supports trusted and secure sharing of energy-related data within a collaborative ecosystem, where participants agree to exchange data in compliance with shared values, regulations, and fair treatment principles.[32] It provides the technical, legal, and governance structures that enable interoperable and sovereign data exchange across the energy sector to foster innovation and system efficiency. In energy data spaces, the value of data is usually co-created, and participants benefit from each other's presence, introducing positive network externalities. Data is typically non-rival or partially rival, meaning that multiple users can benefit simultaneously without necessarily depleting the resource. Energy data spaces generate benefits across multiple levels, where different actors gain simultaneously or trigger beneficial chain reactions.

For example, consider a very large manufacturing company that, through energy data access, increases demand flexibility and optimises production, reducing electricity costs.

[31] For instance, Android is open source, yet manufacturers like Samsung and Xiaomi invest in developing their own OS adaptations. Similarly, while Linux itself is open-source, Linux-based systems like Red Hat Enterprise Linux and Ubuntu Pro offer paid enhancements, such as improved stability, ease of use, and security updates.

[32] Definition adapted from the Data Spaces Support Centre (https://dssc.eu/).

This, in turn, may lead to lower product prices (benefiting consumers), higher company profits (resulting in increased tax revenue), optimised green energy use (reducing emissions), and/or reduced need for grid expansion (lowering system costs). However, this type of scenario raises some fairness questions in cost allocation. While the company gains direct benefits, additional societal benefits also emerge, which leads us to an important question: how much should a company be required to pay for accessing data that ultimately benefits diverse parts of society?

In general, benefits may emerge at multiple levels. For example, the technical document "Blueprint of the Common European Energy Data Space" (Dognini et al., 2024) outlines five such cases:

- Collective self-consumption and optimised sharing for energy communities
- Residential home energy management integrating Distributed Energy Resources (DER) flexibility aggregation
- TSO-DSO coordination for flexibility
- Electromobility: roaming services, load forecasting, and schedule planning
- Renewables operations and maintenance optimization, and grid integration

These examples demonstrate a high degree of interdependence among actors, making it difficult to evaluate the marginal impact of adding or removing participant. This also complicates centralized cost-sharing approaches. Energy data spaces support two categories of data exchange, with implications for governance and cost allocation:

- *Regulated Exchanges*. These primarily involve data sharing between core energy system actors (mainly TSOs and DSOs), sharing operational and metering data to support the efficient and secure operation of the system and essential market processes, such as settlement and customer billing. Because these exchanges deliver broad system-wide benefits, they are usually governed by public or regulated frameworks. In such cases, maximising participation is crucial, as the value of the data space increases with more users, and cost recovery mechanisms should focus on reducing barriers. Onboarding all TSOs and DSOs at the outset may be difficult, and instead, a few early adopters, likely more risk-tolerant and innovative, may lead the way. To encourage participation, the focus should be on ease of entry and cost minimization for the early adopters, rather than monetization of data.
- *Non-regulated Exchanges*. These exchanges encompass commercial or cross-sectoral interactions, where firms or organisations use energy data to provide innovative services or create new business models. For instance, mobility operators offering smart-charging solutions or financial institutions developing energy-linked

products. These participants may come from outside the traditional energy domain. Additionally, these data exchanges may enable existing services to be offered in different countries.[33] Other examples include intermediaries providing flexibility assessments or prosumers sharing data with service providers. In these cases, users can decide whether to grant third-party access to their data (including companies outside the EU, provided they are EU-registered). It is therefore legitimate that part of the operational cost of the data space be allocated to such external users, reflecting the value they capture through access to and later use of energy-related data.

Due to these different features, if an energy data space facilitates both types of exchanges, they should be treated independently.

Finally, it is important to emphasise that while cost allocation often implies a centralized charging mechanism, this does not require centralizing the data itself.[34] A centralized model offers several advantages over fragmented or competitive approaches:

- **Economies of Scale**. Like natural monopolies, data spaces involve high development costs but relatively low marginal operational costs. As user numbers grow, average costs per participant decline, making a single coordinated infrastructure more efficient than multiple competing systems.
- **Standardization and Stability**. A unified system allows for technical standards to be established from the beginning. Competition could result in fragmented standards, which in turn complicates their adoption and raises the costs. Additionally, if a competing system is acquired, its standards may change, forcing users (e.g., TSOs or DSOs) to incur high transition costs. This uncertainty could delay participation. As the value of an energy data space is expected to grow with more users, such delays create the wrong incentives for its deployment.[35]

[33] EDDIE's website perfectly illustrates this with a cartoon showing an Austrian family sharing data with a hypothetical Spanish company, "Hola Energía," to access otherwise unavailable services.
[34] For example, EDDIE introduces a distributed and decentralized framework in which data is not stored on central servers; instead, individual actors retain ownership and data is stored as closed to the source as possible as recommended in the European Strategy for Data (European Commission, 2020). However, it functions as a centralized entity that could charge fees to different participants.
[35] A historical example is the smartphone OS market after the iPhone's 2007 launch. Various competitors emerged: Nokia with Symbian, Microsoft with Windows Mobile, Blackberry with BlackBerry OS, and Google with Android. During this period, consumer uncertainty about future standards led to hesitation in adoption. See, e.g., West and Wood, 2013.

- **Accountability and Dependability**. A single coordinating entity can ensure consistent implementation across Member States, enabling participants to understand where and how digital energy services can be deployed. Therefore, the establishment of a CEEDS with clear Union-wide rules should encompass the matter by putting in place a reliable monitoring and overview in that sense. It should be possible to hold national data space facilitators accountable within that framework.
- **Data Sovereignty and Security**. Energy data is highly valuable and must be protected. Trust in the data space depends on each participant's confidence that sensitive or commercially valuable information will not be exploited without consent or oversight. Early competition could lead to large foreign entities (e.g., Amazon, Google, Microsoft, Meta, or even non-EU governments) dominating Europe's energy data space. This would limit EU control over citizens' data and could raise concerns about misuse or unauthorised commercialisation. Key actors, such as TSOs and DSOs, understand this risk and may hesitate to share information with unregulated or foreign organisations. Moreover, private firms can more easily change data policies than EU-regulated entities, introducing further uncertainty and disincentivising early participation. Preserving data sovereignty is therefore both a technical and governance imperative.

In sum, even if a competitive approach were initially pursued, market dynamics would likely lead to consolidation. Establishing a single coordinating entity from the outset would help set standards, build trust, and ensure both efficiency and data sovereignty, while allowing for decentralised data storage and control. This entity would also be responsible for charging costs to participants.

2.5.2.2 Overview of European energy data space initiatives

Several European initiatives are currently experimenting with the design and implementation of energy data spaces. These initiatives illustrate the diversity of possible architectures, governance structures, and business models. At the same time, they highlight the value that can be unlocked when data sharing becomes mainstream and systematic, secure, and transparent. Among the most significant efforts are five Horizon Europe "Innovation Action" projects dedicated to developing energy data spaces:[36]

[36] These five Innovation Action projects were launched under the Horizon Europe Cluster 5 call HORIZON-CL5-2021-D3-01-12: Establish the grounds for a common European energy data space (https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2021-d3-01-01).

- **SYNERGIES**[37] is a marketplace-oriented data space where organisations (e.g., DSOs, TSOs, aggregators, retailers, local energy communities, and digital service providers) can exchange datasets and services through structured contracts. It supports hybrid storage (centralized cloud or distributed systems) and relies on blockchain-based smart contracts for transparency and automation. Compensation can be monetary, crypto-based, or barter through dataset exchanges, depending on the use case.
- **OMEGA-X**[38] is also a marketplace-based space, built on the GAIA-X[39] federated architecture. Participants can be consumers or providers, organised at the community or company level. Contracts are structured as Data Product Usage Contracts, which are human- and machine-readable, tamper-proof, and verifiable. Its use cases cover renewable integration, flexibility, electromobility, and energy communities, with strong emphasis on interoperability across national and sectoral boundaries.
- **ENERSHARE**[40] adopts a reference architecture based on the 4+1 model.[41] It applies blockchain-based smart contracts to manage transactions and receipts between data providers and consumers. Its pilots span multiple countries and applications: predictive maintenance of wind farms in Spain, cross-sector flexibility services in Italy, planning and digital twin applications in Greece, and senior household monitoring in Portugal. These pilots demonstrate data access can enhance operational efficiency, improve planning, and support consumer-oriented services.
- **Data Cellar**[42] focuses on enabling Local Energy Communities (LECs). It envisions a token-based compensation model for datasets, combined with distributed ledger technologies to handle flexibility and energy trading contracts. Its value propositions include improved energy efficiency, predictive maintenance, reduced transmission losses, and better customer engagement. Beyond community members and service providers, it explicitly targets municipalities, policy makers, and the research community, showing how data access can create spillovers beyond immediate market actors.

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[37] https://synergies-project.eu/.
[38] https://omega-x.eu/.
[39] https://gaia-x.eu/.
[40] https://enershare.eu/.
[41] The 4+1 View Model (Kruchten, 1995) describes system architecture from four technical perspectives (logical, process, development, and physical), supplemented by use-case scenarios that validate the design.
[42] https://datacellarproject.eu/.

- **EDDIE**[43] is designed as a decentralized system, expected to be compliant with GAIA-X principles, where DSOs and TSOs provide access to real-time and historical consumption and metering data through regional hubs and in-house devices. Rather than hosting data centrally, EDDIE facilitates interoperability and standardized access across countries, enabling companies to expand services cross-border. This highlights the role of energy data spaces in scaling up European digital markets.

In addition to the above projects, there are also other initiatives working towards the development of a CEEDS,[44] such as **Energy data-X**,[45] **Int:net** (Interoperability Network for the Energy Transition)[46] or **INSIEME** (Integrated Network for Data Space and Interoperable Energy Management in Europe).[47]

2.5.2.3 Benefits, business models, and network effects

Across the five above-mentioned initiatives, there are several value propositions expected to emerge.

- **Better transparency and knowledge sharing**. Data spaces reduce information asymmetry by giving smaller actors and consumers access to datasets previously held mainly by large utilities and system operators.
- **Lower transaction costs**. Standardized interfaces, smart contracts, and automated data integration reduce manual labour and harmonize processes across countries.
- **Increased competitiveness and reduced market entry barriers**. By decreasing integration costs, new service providers can enter more easily, fostering cross-border competition and innovation.
- **Broader innovation ecosystems**. Data availability enables new applications (e.g., AI-driven forecasting, digital twins, advanced flexibility services) and encourages experimentation in sandboxes or pilot projects.
- **Higher system efficiency and societal benefits**. Better forecasting, flexibility management, and predictive maintenance reduce grid expansion needs, support renewable integration, and ultimately lower emissions.

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[43] https://eddie.energy/.
[44] https://energy.ec.europa.eu/publications/common-european-energy-data-space_en.
[45] https://www.energydata-x.eu.
[46] https://intnet.eu/.
[47] https://insieme.energy/index.html.

There are different business models that can emerge from the development of energy data spaces, e.g., marketplaces for direct data trading, tokenized exchange within communities, subscription-based access for standardized datasets, or bundled services where data is provided alongside analytics and decision-support tools. Moreover, the non-rival nature of data allows multiple layers of value creation from the same dataset, creating both opportunities and challenges for cost allocation.

It is important to note that network externalities are particularly strong, i.e., the more participants join, the greater the value of the data space. Early adopters benefit from privileged access, but full potential is realized only when many actors (especially regulated ones like TSOs and DSOs) participate. Conversely, adoption may be slowed by technological or institutional barriers, such as uneven national data infrastructures or consumer reluctance to adopt smart meters (in cases where smart meters are not mandatory).

The energy data space initiatives presented in Section Overview of European energy data space initiatives underline that energy data spaces can generate benefits well beyond the direct users. Value is created at multiple levels: private (reduced costs, new services), system-wide (improved efficiency, lower investment needs), and societal (emission reductions, consumer empowerment). This reinforces the challenge of designing fair cost allocation mechanisms. While large firms may capture significant private benefits, part of the surplus accrues to society at large. The choice of cost-sharing rules must therefore balance fairness, efficiency, and incentives, ensuring sustainability without discouraging participation.

2.5.3 Cost allocation and pricing mechanisms

The long-term sustainability of energy data spaces depends on fair and transparent cost recovery. Beyond technical and governance design, it is essential to determine who pays, how much, and according to which principle. This section examines the main objectives and methods of cost allocation and pricing, focusing on how fairness, efficiency, and incentives can be balanced to ensure both participation and economic viability.

2.5.3.1 General aspects

Implementing an energy data space entails both establishment and operational cost. Users may be required to contribute through usage-based payments that support cost recovery. As such, it is useful to distinguish, but also connect, the concepts of cost allocation, pricing, and business models. Cost allocation defines how the underlying costs of a project, such as building and operating a system, are distributed among participants. Pricing refers to the rules (or tariffs) applied to users when they access goods or services (such as data). Pricing schemes can build directly on cost allocation (e.g., proportional pricing by usage), but they may also deliberately diverge, for example by subsidising certain users to encourage participation or fairer treatment. For instance, there may be subsidized broadband access for rural or low-income households, emphasising the idea of digital access as a public good (even if operating costs are not fully recovered). Similarly, in some projects early adopters may receive preferential rates to stimulate demand.[48] Thus, while pricing schemes may be linked to cost allocation, they can also reflect other choices defined by the business model of the organisation offering the goods or services under consideration, or by regulation. A business model normally represents the rationale of how an organisation creates, delivers and captures value. Pricing mechanisms must therefore be designed not only to recover costs, but also to support the long-run economic sustainability of the business model or regulatory framework.

Pricing mechanisms have long been studied in economics. Classical models such as Cournot (1838) and Bertrand (1883) examine how firms compete under market and strategic assumptions, while concepts like first-, second-, and third-degree price discrimination show how users can be charged differently based on their willingness or ability to pay. There are also price discovery mechanisms, such as auctions (see, e.g., Milgrom and Weber, 1982; Wilson, 1969; Krishna, 2009), which allow users to reveal preferences when costs or values are uncertain. For instance, Khezr and Menezes (2019) analyse how auctions can fund expansion of natural monopoly infrastructure (such as electricity networks) when multiple firms require access. These examples highlight that pricing is not only a tool for cost recovery, but also a mechanism for shaping incentives and behaviour within the system.

On the other hand, there is also extensive literature on cost allocation, which often focuses on identifying axioms and properties that make allocation rules acceptable (see, e.g., Young, 1985). Designing appropriate cost allocation rules is not merely a matter of technical calculation but also one of economic reasoning and ethical judgment. Even in everyday situations, fairness is not straightforward. For example, when splitting the cost of a Spotify subscription between friends living together, should the bill be divided equally, according to usage, or according to income? If these friends share a taxi together but the destination of one of them is far out of the way, should they all pay the same or not, because the detour adds time and cost? Questions of fairness arise even in these simple examples. It is therefore

[48] When Tesla first rolled out its Supercharger network, new buyers of the Model S received unlimited free Supercharging for life. Today, however, the network is well developed, and receiving free charging with a new EV would be considered an exceptional privilege.

unsurprising that energy data spaces, with their many more stakeholders and public good characteristics, pose an even greater challenge.

2.5.3.2 Cost allocation objectives

Whenever multiple actors benefit from a shared resource or infrastructure, the fundamental question arises: how should costs be distributed? Cost allocation is therefore not just an accounting exercise but a central problem of economic coordination and collective decision-making. Examples abound across sectors: governments share the expenses of cross-border infrastructure; firms divide R&D costs in joint ventures; municipalities apportion the costs of waste collection; and digital platforms allocate cloud or network expenses among users.

In all these cases, allocating costs is more than an accounting task. It is a matter of economic design and collective decision-making. Allocation rules largely depend on context, but in general they must balance several (often conflicting) objectives: efficiency (ensuring that total costs are covered and resources are used optimally), fairness (ensuring that users are treated in a justifiable way), incentive compatibility (ensuring that participants behave honestly and remain engaged), and stability (ensuring that no participant or group has an incentive to withdraw from the collective arrangement). Other context-specific properties may also play a role. Achieving all objectives simultaneously is rarely possible, which explains why cost allocation has been an important topic across different situations and sectors.

Everyday situations illustrate the challenge. When splitting a restaurant bill, a taxi fare, or a streaming subscription, different intuitive principles may apply equal division, proportional division by usage, or differentiation by income or ability to pay. Each rule seems reasonable but yields different results, showing that fairness depends on context and interpretation. The same ambiguity arises at larger scales, for example when sharing the costs of pollution abatement among industries, coordinating climate adaptation investments among countries, or funding shared research facilities across universities.

Within this broader landscape, there are specific cases that pose distinctive allocation challenges. Natural monopolies (e.g., electricity grids, water networks, rail systems) exhibit high fixed costs and strong economies of scale, making it inefficient to duplicate them. Here, allocation concerns how the joint cost of maintaining the network is divided among users (e.g., freight and passenger trains, or electricity consumers). Similarly, cross-border or multi-organisational projects (e.g., international pipelines, cross-border interconnectors, or federated data infrastructures) require agreement among multiple decision-makers who may have divergent interests and, in some cases, incentives to free ride. Cost allocation in energy data spaces represents another specific challenge, as it combines features of shared digital infrastructure with public good characteristics, requiring mechanisms that ensure fairness, participation, and long-term sustainability.

2.5.3.3 General principles and axioms

The literature on cost allocation distinguishes between normative principles (broad economic and ethical objectives such as efficiency, fairness, stability, and incentive compatibility) and their formal expressions, known as axioms. Different axioms translate these abstract principles into precise mathematical or logical conditions that allocation rules may satisfy in a given context. They serve as analytical tools to evaluate whether a cost-sharing method is economically sound, fair, and sustainable. Some axioms are foundational, while others are refinements or more context specific. Foundational contributions by, e.g., Young (1985), Tijs and Driessen (1986), Moulin (1988), and Hougaard (2009) have developed these axiomatic frameworks, showing that while principles provide normative guidance, axioms define the concrete properties that operationalise them. Principles and axioms rarely align perfectly, and trade-offs are often evidenced in different context, i.e., methods that satisfy one property may violate another, highlighting the trade-offs inherent in fair division problems.

In the following subsections we summarise key axioms that are related to efficiency, fairness, stability, and incentive compatibility in cost allocation. We illustrate their importance with some examples from various domains and discuss their relevance in the context of energy data exchange spaces.

i. Efficiency (budget balance)

While efficiency plays a key role in many market design contexts, in cost allocation it simply means that the amounts allocated to all users should exactly sum to the total cost. In other words, the total cost must be fully covered, with neither deficit nor surplus. Example: In electricity grids, tariffs are calibrated so that total revenue matches the justified costs of system upgrades: there should be no deficits (which would make the project unviable) and no surpluses (which would unfairly burden users).

Although this is an essential property, it says nothing about how the costs should be distributed. Very unfair or extreme allocation rules, such as one user paying everything, would still satisfy efficiency as long as total cost recovery holds. This highlights an important point: a “perfect” allocation rule does not exist. Benefiting some users (by asking them to pay less) necessarily implies harming others (by asking them to pay more). Hence, if some users prefer allocation method A to B, others will prefer the opposite. In what follows, we assume any acceptable allocation method must satisfy efficiency.

ii. Stability-related axioms

These axioms concern whether users have incentives to remain in the system (or to leave it).

Individual rationality (Stand-alone test)

No user should pay more than their stand-alone cost if acting independently. This ensures stability, since no user will want to exit if their allocated share is smaller than the cost of acting alone. Example: In district heating networks, a household should not pay more for connection than the cost of installing an individual boiler or heat pump.

Stability (Coalitional stability)

Groups of users (coalitions) should not have an incentive to leave the collective arrangement. This extends individual rationality to groups: no coalition should be able to cover its own costs more cheaply outside the arrangement. In cooperative game theory, this is captured by the core: the set of allocations where no coalition can profit by deviating. For example, in joint transmission projects, utilities must find it preferable to cooperate under a shared cost allocation scheme rather than build separate lines.

In the context of energy data spaces, each user compares the value of participation with the allocated cost (i.e., the participation fee). Operational costs are expected to be relatively small once the system is established, and the value of participation will normally exceed the fee. Therefore, these stability properties are unlikely to be binding in practice. A user that benefits from the data space is unlikely to leave because of a slightly higher fee, and a group of users that all gain from participation will not withdraw due to imperfections in cost allocation. We therefore expect these properties to hold for most reasonable allocation methods in this context.

iii. Fairness-related axioms

Fairness is notoriously difficult to define, and consensus on what constitutes a fair rule is rare. This is precisely why multiple cost allocation methods exist: if there were universal agreement on fairness, one rule would suffice for all contexts. Nevertheless, one fairness axiom is broadly accepted.

Symmetry (Equal treatment of equals)

Identical users (under the chosen metric) should pay the same. Although fairness can be debated, the absence of this property would be widely perceived as unjust, as it implies that cost shares depend on arbitrary identities rather than relevant characteristics. For example, in an energy community, two households drawing the same amount of electricity from a shared battery should be charged equally.

In energy data spaces, this axiom is clearly desirable: two identical users paying different fees would be viewed as highly unfair.

iv. Incentive-related axioms

These axioms ensure that allocation rules do not create perverse incentives or allow manipulation.

Incentive compatibility (Strategy-proofness)

Users should not benefit from misreporting information. In other words, a cost allocation rule is incentive compatible when participants have no strategic advantage in providing false or misleading data about their usage, costs, or contributions. This property ensures that truthful behaviour is the best strategy for every participant. For example, in community battery projects, households should not be able to exaggerate their flexibility potential (such as overstating their ability to shift consumption), to obtain more favourable cost allocations. If users can manipulate reported information, the mechanism becomes vulnerable to gaming.

No advantageous splitting or merging

Users should not be able to manipulate allocations by splitting into multiple (artificial) entities or merging strategically. This ensures robustness against artificial restructuring of participation. For example, in electricity markets, a large industrial consumer should not be able to divide itself into smaller artificial consumers to qualify for cheaper tariff brackets.

Monotonicity

If a user increases their consumption level, their cost share should also increase. This guarantees that greater consumption or demand leads to at least as high a cost responsibility, and that lower consumption never results in a higher charge. For example, in shared solar projects, a household consuming more electricity from the shared system should not end up paying less than a smaller consumer.

In the context of energy data spaces, these incentive-related axioms are particularly important, since different users will provide and consume data. Regarding Incentive compatibility, it is not clear whether a user would be able to misreport any information, since data transfers are typically recorded automatically, leaving little or no room for manipulation. However, the last two axioms are clearly crucial. We are not interested in an allocation rule that could motivate users to split or merge strategically. Moreover, some users may naturally appear either as large single entities or as several smaller ones. For example, a national TSO might be organised into regional business units (e.g., north, south, offshore), or an aggregator might manage data from households in different regions. If an allocation rule satisfies *No advantageous splitting or merging*, the allocated cost remains the same whether the system perceives a large user, or the same user divided into smaller units.

Monotonicity is also relevant. Small changes in user activity from one period to another should be reflected in the allocated cost. For example, higher data consumption should result in a higher fee, while lower data consumption should lead to a lower fee. This ensures that cost allocation remains consistent with actual behaviour and provides clear and predictable incentives for participants. However, the axiom only specifies the direction of the change, and it does not specify how much the cost should change. In other words, when activity increases, the corresponding fee should not decrease, but the exact relationship between the two may depend on the specific cost allocation method chosen.

v. Other axioms

There are also context-dependent properties that, while theoretically interesting, have limited practical relevance for energy data spaces. For instance, *Additivity* requires that if two independent cost-sharing problems are combined, the allocation for each agent equals the sum of their allocations in the separate problems. This condition is unlikely to hold for energy data spaces, as combining two such spaces may generate a total value greater than the sum of their individual values due to complementarities between datasets. Consistency requires that if one user leaves and their share is removed, the allocation rule applied to the remaining group yields the same relative results for those who stay. In energy data spaces, however, the departure or addition of a participant can alter both the overall value of the system and its cost structure. Hence, while these properties are important in some settings, they are unlikely to be critical for the operation of energy data spaces.

As such, in the following, we mainly focus on the axioms *Symmetry*, *No advantageous splitting or merging* and *Monotonicity*.

2.5.3.4 Examples of allocation methods

Several methods can be considered for distributing costs in energy data spaces. However, before presenting them, the initial question to address is what cost allocation should depend on, i.e., what information is available and measurable about users and their activities (in theoretical terms, this means defining how users are characterised). Different methods require different types of input data: some rely on clearly observable metrics (e.g., number of users, data volume, or transactions), while others depend on more complex or value-based assessments that may be difficult to quantify in practice. Understanding these informational requirements is therefore essential before selecting an appropriate allocation rule.

In energy data spaces, participants can play dual roles: they may consume data (by accessing or using information) and provide data (by contributing datasets to the system). The overall value of the data space arises from the interaction between these activities, i.e., each user's contribution enhances the usefulness of others' data, and the total value grows as more participants join. In principle, a fair cost allocation should reflect each participant's contribution to this overall value or the benefits they derive from participation.

However, this is rarely straightforward. Estimating the exact monetary value of specific datasets, whether provided or consumed, is typically infeasible. In theory, data value could be defined as the incremental economic benefit generated by access to or use of a dataset, such as improved efficiency, cost reduction, or new revenue streams. A DSO, for example, might estimate the financial benefit of reduced forecasting errors enabled by additional metering data, while a TSO could quantify avoided or deferred grid investments resulting from better congestion forecasting. Yet even in such cases, isolating the value of a particular dataset from other interacting factors remains highly uncertain.

The challenge becomes even greater when considering both data consumption and contribution. If allocation depends on consumption alone, should it be measured by data volume (e.g., gigabytes – GB)? Such an approach assumes each unit of data has identical value, which is rarely true. Conversely, if data contributions are considered, it is difficult to assess their quality or relevance objectively. For instance, if two DSOs use similar data but one provides richer and more accurate datasets, their respective contributions to system value differ, but quantifying that difference is complex. Moreover, if contributions were measured purely by volume, users might be motivated to upload low-value or redundant data, violating the principle of incentive compatibility. To avoid this, external governance or auditing mechanisms are needed to define what constitutes valid, high-quality data contributions.

Accordingly, the choice of a cost allocation method depends on the type and quality of information available about users. The following subsections present several allocation methods, ranging from simple, proxy-based approaches to value-oriented models, and discuss their relevance and applicability to energy data spaces.

i. Uniform (equal split) allocation

Under uniform allocation, every participant pays the same fixed fee, regardless of usage. This approach is simple, transparent, and easy to administer, making it attractive when the costs of measuring individual contributions are high. However, it may discourage heavy contributors, who may feel they are subsidising lighter users, and it can incentivise overconsumption among those who use more than average. Because payments are unrelated to activity, it is unnecessary to estimate the value of data consumed or provided. For example, in local energy cooperatives, members may each pay the same annual membership fee to cover administrative costs, regardless of how much electricity they consume or generate. On the other hand, this simplicity can create wrong incentives: participants may withhold potentially useful data, or consume extra data, knowing their fee remains constant regardless of contribution. For instance, a DSO might refrain from sharing detailed grid operation data.

ii. Proportional allocation

Although uniform allocation is simple and transparent, it ignores the heterogeneity in value creation and resource use associated with different data types and participants. When cost allocation depends on user characteristics, it becomes necessary to define how activity is measured and how data consumption and provision are jointly evaluated. Suppose that each user's overall activity can be represented by a single quantitative indicator, such as total GB of data consumed, the net balance between data imported and provided, or another standardised metric reflecting both data quality and frequency of use. Once such an indicator is established, a natural approach is to allocate costs in proportion to this measurable activity.

Under proportional allocation, users pay in proportion to their level of engagement or usage. Despite its simplicity, the rule possesses remarkably strong theoretical properties and has been extensively analysed across different contexts (see, e.g., Moulin, 1987; Chun, 1988;

Skaperdas, 1996; Hougaard, 2007; Hougaard et al., 2017; Szwagrzak and Østerdal, 2025). These references show that even though proportional allocation is very straightforward to apply (once the metric is defined), it has been rigorously tested and proven to satisfy different desirable axioms in diverse settings, from resource division to contest theory. In particular, it is the only allocation rule that satisfies the *No Advantageous Splitting or Merging* property, making it robust to strategic manipulation.

Its transparency and intuitive fairness make proportional allocation appealing, especially when user activity can be measured objectively. For example, in electricity distribution, tariffs often charge consumers proportionally to their kilowatt-hour (kWh) consumption, ensuring that heavier users bear a larger share of costs. Likewise, in data platforms, fees are commonly based on the number of queries or downloads executed by each participant.

iii. Weighted proportional allocation

In this variant, total costs are distributed proportionally to users' activity levels, but adjusted by weights that capture additional, context-specific factors beyond raw usage. These weights allow cost allocation to reflect heterogeneity among participants, such as differences in timing, contribution, or institutional role.

Relevant weighting dimensions may include:

- Time of participation where early adopters pay less to encourage initial network growth
- Quality or quantity of data contributed rewarding users who enhance the collective value of the data space
- Organisational size and (financial) capacity, e.g., recognising differences between large system operators and smaller service providers
- Different user types, distinguishing between regulated entities (e.g., TSOs, DSOs) and non-regulated or cross-sectoral actors

Unlike the proportional rule, the weighted proportional approach may be dynamic, i.e., weights can evolve over time to incentivise behaviours aligned with the data space's strategic objectives. For instance, a European energy data space is likely to involve initially a limited number of progressive DSOs and TSOs, i.e., a "coalition of the willing," before scaling to broader participation. This early phase offers an opportunity to experiment with cost allocation models where weights may favour participation and data contribution over strict cost recovery. As participation broadens and the data space matures, the weighting structure can gradually converge toward a more neutral proportional rule, emphasising focus on raw activity levels. The few DSOs and TSOs that were among the early adopters may also be promised to be awarded with lower weights in the future than other users with the same activity levels. Illustrative analogies exist in other domains. In community solar projects, early adopters often pay reduced fees to reflect their higher initial risk and role in enabling scale. Similarly, in data-sharing platforms, participants providing large or high-quality datasets may receive discounted access fees compared to those primarily consuming data. In both cases, a weighting mechanism can help align private incentives with collective benefits.

Moreover, the weighting scheme in this allocation rule can be further refined to link data contributions and data consumption of different users. For example, weights could depend on the ratio of data provided to data consumed, adjusted for quality and relevance. Such formulations help avoid free-riding behaviour and ensure that actors contributing with valuable data are rewarded, while heavy consumers of shared data bear a fairer share of the costs.

iv. Cooperative game-theoretic approaches

Both proportional approaches rely on measurable individual activity indicators, but neither captures externalities, i.e., cases where one user's participation increases value for others. This limitation is particularly important in data-intensive systems, where value often arises from combining heterogeneous datasets. For example, when a person drives a car, the navigation system relies on both digital map data and real-time GPS signals. Without either of them, the whole system would not function. In this simple example each dataset has limited value on its own, yet together they generate substantial utility. Hence, the total value emerges from interaction and interdependence rather than isolated contributions. Such interdependence can be formally analysed using cooperative game theory, particularly within the framework of Transferable Utility (TU) games (see, e.g., von Neumann and Morgenstern, 1944; Peleg and Sudhölter, 2007; Hougaard, 2009).

Cooperative game-theoretic methods examine how costs or benefits evolve as agents form coalitions, providing a structured way to account for interdependencies. Several allocation rules exist within this framework. The Shapley Value (Shapley, 1953), for instance, allocates costs based on each participant's average marginal contribution across all possible coalitions; the Nucleolus (Schmeidler, 1969) seeks allocations that minimise dissatisfaction and promote stability; egalitarian approaches aim to assign shares that are as equal as possible under some constraints, emphasising equality over contribution or marginal value (see, e.g., Dutta, 1989; Hougaard and Smilgins, 2016). These approaches can be relevant in energy data spaces, where value creation depends on joint participation. However, there is a major challenge: the number of possible coalitions among n users is $2^n - 1$, i.e., it grows exponentially. For example, with three users there are seven possible coalitions, but with twenty users there are more than one million. As a result, exact computation of allocation rules like the Shapley Value may become infeasible for large systems.

v. Auction- and bargaining-based approaches

It is noteworthy that, instead of a specific cost allocation rule, it may be possible to delegate the task to the market, while defining an appropriate framework and set of guiding rules. In auction-based mechanisms, participants bid for access, and prices are determined endogenously through an auction. These methods, grounded in market and mechanism design theory, encourage efficient resource allocation and often elicit truthful revelation of willingness to pay. Khezr and Menezes (2019) propose auctions as a fair mechanism for multiple firms to jointly fund new infrastructure facilities. Auctions are suitable where excluding some participants is acceptable, and this may only apply to some data spaces.

Beyond formal allocation rules, costs can also be distributed through negotiation and bargaining among participants. In such cases, allocations depend on bargaining power, regulatory frameworks, and mutual dependencies. For example, when the EU implemented its "Roam Like at Home" policy in 2017 under the Roaming Regulation (Regulation No. 531/2012, as amended),[49] telecom operators had to abolish retail roaming charges across member states. Since network usage varied widely (with southern tourist destinations hosting more inbound traffic), operators negotiated bilateral agreements within regulated wholesale price caps. This bargaining-based approach offered flexibility while ensuring that no operator was disproportionately disadvantaged.

Such approaches can place a burden on users, which may be undesirable in practice. Moreover, relying entirely on market or bargaining mechanisms can lead to situations where core axioms are violated. For example, two identical users might pay different fees depending on their bargaining power (violating *Symmetry*), or an auction could generate either more or less revenue than the total system cost (violating *Efficiency*).

[49] https://eur-lex.europa.eu/eli/reg/2012/531/oj.

vi. Hybrid approaches

In practice, hybrid approaches can combine features of the above methods. Examples include: two-part tariffs, combining a fixed fee (uniform component) with a variable fee (proportional to activity); using cooperative game theory to allocate total cost among broad user groups, followed by proportional allocation within each group; defining clear cost allocation methods for regulated data exchanges, while leaving non-regulated or commercial exchanges open to bargaining or market mechanisms.

Finally, it is important to recognise that cost allocation does not need to be static. In the early development phase, the primary goal may be to promote participation and establish trust, which justifies subsidised or weighted proportional rules favouring early adopters. Once the network matures and participation becomes widespread, cost allocation can gradually transition toward standard proportional schemes focused on efficiency and long-term sustainability.

2.5.3.5 Example of cost allocation methods

Consider a toy numerical example of an energy data-sharing infrastructure with four users, labelled A, B, C, and D, which costs in total €120 to operate during a given period.

Under uniform allocation, the total cost is divided equally, so each user pays €30. While this method is straightforward, it ignores all information about user behaviour or activity. The allocation therefore becomes (30, 30, 30, 30) across the four users. The *Monotonicity* axiom would be violated, as changes in user activity have no effect on the allocated share. Furthermore, *No Advantageous Merging* is not satisfied: for instance, if A and B decide to merge and act as a single organisation, the system now has three users (AB, C, and D). When the costs are divided equally, each user pays €40. As such, A and B together now pay only €40 instead of €60 (a one-third reduction without changing how much data they actually process).

Next, assume that we want to base the cost allocation on activity levels, under the principle that higher activity implies a larger allocated share of the cost. Suppose the four users have the following activity levels under a chosen metric (here measured in GB):

- User A: 10 GB
- User B: 20 GB
- User C: 30 GB
- User D: 40 GB

In a proportional scheme, costs are distributed according to each user's share of total usage. The total data consumption is 100 GB, and users A, B, C and D would pay respectively €12, €24, €36, and €48, summing to €120. This implies a unit cost of €1.20 per GB, which is very easy to explain to the participants. This scheme remains straightforward but now incorporates user activity, assuming there is a coherent way to measure it. *Monotonicity* is satisfied, since increasing activity leads to a higher allocated share for any user. Moreover, *No Advantageous Splitting* or *Merging* is satisfied only by the proportional rule: if A and B merge, they pay €36 (= 30/100 × 120), which equals their total cost without merging. Similarly, splitting would not affect the total cost allocation.

Next, one might wish to incentivise early participation in the data space, and the weighted proportional rule could be applied. Suppose user C joined significantly earlier than the others and played a crucial role in helping to establish the data space, e.g., by contributing initial datasets, testing the platform, or bearing early development risks. To acknowledge this foundational role, C receives a preferential weight that reduces their effective contribution for cost-sharing purposes. Assume the weights of the four users are (1, 1, 0.5, 1), such that user C is rewarded for early entry. The weighted proportional rule yields: $\left(\frac{1*10}{z} * 130, \frac{1*20}{z} * 130, \frac{0.5*30}{z} * 130, \frac{1*40}{z} * 130\right)$ with $z = 1 * 10 + 1 * 20 + 0.5 * 30 + 1 * 40.$

This results in allocations of approximately (€14.1, €28.2, €21.2, €56.5).

Compared to the standard proportional rule, user C's allocated cost decreases from €36 to €21.2. This reduction occurs because C's lower weight functions as a discount reflecting their early and strategically important participation, with the remaining cost redistributed among the other three users.

So far, cost allocations were based on observable activity levels (GB of data). However, in many data spaces the main source of value does not stem from individual usage, but from the interactions and synergies created when different users combine their data. To capture these interdependencies, we now move from activity levels to a value-based representation of the system using a cooperative value function. For four users, assume the values of all possible coalitions are given as presented in Table 2.2: Examples of coalition values among the four participants.

Coalition	Value
∅	0
{A}	200
{B}	300
{C}	400
{D}	100
{A,B}	800
{A,C}	850
{A,D}	300
{B,C}	950
{B,D}	400
{C,D}	500
{A,B,C}	1400
{A,B,D}	900
{A,C,D}	950
{B,C,D}	1050
{A,B,C,D}	1500

Table 2.2: Examples of coalition values among the four participants

For example, users A and B individually create values of 200 and 300, but together produce 800, indicating a synergy effect. When all four users participate, the total value of the data space is 1,500, exceeding the sum of their individual contributions. The table captures the interdependence among users, but as noted earlier, the problem grows rapidly with the number of participants. Even with only four users, there are 15 (=2^4 – 1) non-empty coalitions.

Using the Shapley value (Shapley, 1953), the total value can be allocated among users as (375, 475, 550, 100) summing to 1,500. These numbers represent each user's allocated share of the total system value (when everyone participates) derived from the Shapley value, the unique solution concept satisfying a specific set of axioms. One of these axioms, the dummy player axiom, is illustrated in this example. User D adds exactly 100 to any coalition, regardless of its composition. Under the definition, such a user is a dummy player, and the Shapley value correctly assigns D exactly 100.

However, the Shapley value is known not always to lie in the core. The core consists of allocations that no coalition would want to deviate from because they can guarantee themselves at least their coalition value by acting independently. An allocation outside the core therefore fails to satisfy some coalition's stability constraint: at least one group of users could obtain a higher total value by breaking away from the grand coalition. Although the Shapley value is fair in an axiomatic sense, it does not necessarily ensure such coalition stability.

To translate these values into a cost allocation, several approaches are possible. One simple illustrative method is to treat higher Shapley values as indicators of greater contribution and therefore assign lower costs to such users. For example, subtracting each user's Shapley value from the total system value (1,500) and allocating the total cost proportionally to these residuals yields an approximate cost allocation of (€30, €27.3, €25.3, €37.3) summing to €120.

Table 2.3 compares cost allocation methods that could be applied to our example and assesses the extent to which each method fulfils the main axioms presented in the previous section.

Cost Allocation Method	Symmetry (Equal treatment of equals)	No Advantageous Splitting / Merging	Monotonicity
Uniform (Equal-Split)	Yes	No	No
Proportional	Yes	Yes	Yes
Weighted Proportional	Depends (holds only if identical users have equal weights)	Depends (on how the weights are defined when users split or merge)	Yes
Shapley Value	Yes	No	Yes

Table 2.3: Comparison of allocation methods according to key axioms.

2.5.4 Data sharing costs and cost allocation in some European countries

As discussed in Section 2.5.2, several R&D projects are currently deploying energy data spaces across different European countries. The costs associated with such deployments are primarily covered by research grants, typically funded by the European Commission under the Horizon Programme or the Digital Europe Programme. Access to these data spaces and the related services is then normally free, without any explicit allocation of costs to the users of the data spaces. However, if we look at the national level, several data sharing infrastructures have emerged or are emerging in the energy sector, supporting trusted and secure sharing of energy-related data within a collaborative ecosystem, where participants agree to exchange data in compliance with shared values, regulations, and fair treatment principles. Among others, this is the case of the infrastructure for the sharing of electricity metering and consumption data. Directive (EU) 944/2019 prescribes that each Member State "shall organise the management of data in order to ensure secure and efficient data access and exchange, as well as data protection and security" (art. 23(2)). However, no specific, harmonised DMM is provided by the Directive. Different models have been implemented, and the data sharing infrastructures have been organised in alternative ways (Beckstedde and Rossetto, 2025).

In this section, we report some of the national experiences with the establishment of these data-sharing infrastructures, highlighting the main cost drivers and the way costs have been allocated to the various actors involved to ensure their recovery. By doing this, we aim to complement the theoretical analysis performed in Sections 2.5.2 and 2.5.3 with practical experience and suggest scope for further research.

2.5.4.1 Cost level and structure of energy consumer data sharing infrastructure

Assessing the level and structure of the costs associated with the establishment and operation of an infrastructure for the sharing of consumer data is not trivial for two reasons, somewhat interrelated. First, there is limited information publicly available on the costs associated with the management of those data. Second, as mentioned above, different countries have adopted different DMMs, which allocate the various roles to different entities. The same entities can then deliver different sets of tasks in the various countries, making any assessment more complicated. Any simplistic comparison of the balance sheet of similar entities across countries must be dealt with care. To the best of our knowledge, there is currently no comprehensive collection of data about data management costs in Europe. For some countries, such as Norway, more information is easily available, typically in the local language, but for most of them this is not the case.[50]

However, based on a series of interviews with experts directly involved in the establishment and operation of data sharing infrastructure in several European countries, it is possible to provide some general indications on the level and structure of the costs associated with data sharing.[51]

With regard to the level of costs, interviewed experts suggests that costs related to data management are in the order of a few tens of millions of euros per year for a typical European country. This amount is mostly due to the development of the infrastructure and does not include the deployment of smart meters. The cost of operating the infrastructure is a small fraction of the overall costs (a few million euros per year). This suggests that data

[50] Detailed information about the costs of the Norwegian data hub (Elhub) is provided every three years in a report presenting the results of the cost-effectiveness audit to which the data hub is subject. The report typically provides data also for Denmark and Finland, which have adopted similar data management models. The latest edition of the report is available here: https://publikasjoner.nve.no/rme_eksternrapport/2025/rme_eksternrapport2025_07.pdf.

[51] The information provided in Section 2.5.4.1 are mainly derived from a series of expert interviews conducted in January-February 2025. See Chapter 5 for more details on the research methodology.

management, although non negligible, represents only a tiny share of the total costs of the energy system in Europe.

Regarding the structure of costs, interviewed experts confirm that development costs are driven mostly by: i) the effort to find an agreement on the processes, the communication standards, and the system interfaces with all the relevant actors; and ii) the implementation of the IT solutions that technically support the DMM chosen. Every time there is a decision to implement a new process or functionality, experts representing the various stakeholders impacted by data management (e.g., system operators, energy suppliers, representatives of consumers, technology vendors) are typically mobilised in technical working groups, whose cost is clearly distributed among the stakeholders. IT solutions are normally purchased by external providers and tend to be custom-built. The use of standardised IT solutions can to some extent reduce this source of costs.

Operational costs are driven mostly by: i) personnel costs; and ii) software licences. The maintenance of the IT infrastructure and data storage are also relevant. The increase in the volume of consumer data associated with the move to hourly or 15-minute metering, or the obligation to retain the data for longer periods tend to increase the cost of data storage. Cloud-based solutions are expected to limit this increase, while some experts argue that relying on cloud-based solutions can pose problems in terms of data protection and sovereignty. Auditing the proper behaviour of third parties who have access to the data sharing infrastructure can also be a source of significant costs for some DMMs.

Although further and more systematic research would be beneficial to confirm these general indications, it is possible to conclude, based on them, that the costs associated with an energy consumer data sharing infrastructure are largely fixed (i.e., independent from the amount of data shared). Moreover, it seems that the complexity of the ecosystem within which data are shared has a clear impact on development costs. The more fragmented is the environment, the more effort must be implemented to reach an agreement on new processes and functionalities, and the more expensive technical implementation is likely to be. This is not to say that centralised solutions are necessarily superior, but only that it is important to strive for interoperable and possibly standardised solutions as much as possible.

2.5.4.2 Cost allocation in some European countries

Although ultimately the final customer pays, the costs of managing metering and consumption data can be allocated to different actors and recovered in different ways. The choice can be due to several factors, including the specific data management model of a country. To the best of our knowledge, there is currently no systematic collection of this information at the European level. However, interviews with experts and desk research suggest that data sharing cost allocation takes different forms in the various European countries. In what follows, we illustrate the cost allocation methods adopted in six European countries that implements different management models for metering and consumption data. Two of these countries, Italy and Norway, have implemented a centralised DMM. Spain and the Netherlands are typically considered countries characterised by a hybrid DMM, while Austria and Belgium have a more decentralised model in place.[52]

Let us start by looking at the two countries that implement a centralised DMM. In both Italy and Norway, there is a national data hub collecting the metering and consumption data from the DSOs, storing them, managing access to data, and performing a series of market processes. Consumers, suppliers and other eligible parties can access customer data on such data hubs.

In the case of Italy, the data hub, called 'Sistema informative integrato' (SII), is managed by Acquirente Unico (AU), a public company owned entirely by Gestore dei Servizi Energetici (GSE), which is owned by the Italian state through the Ministry of Economy and Finance.[53] The SII has an account separate from that of the other activities performed by the AU. Every year the SII budget is forwarded to the Italian national regulatory authority (ARERA), which determines the fee to be paid by every balance responsible party and by every actor delivering the service of "maggior tutela" to recover the cost of the SII.[54] The fee was set equal to EUR 0.045 per withdrawal point/month in October 2024.[55] More recently, ARERA launched a public consultation about the possibility of extending the application of the fee to the commercial counterparties, who are not balance responsible parties or actors delivering the service of "maggior tutela", that are registered on the SII and benefit from its services. As the number of commercial counterparties has grown over recent years, ARERA has signalled the

[52] The role played by EDA in Austria and Atrias in Belgium suggests that the Austrian and Belgian DMMs present some elements of centralization and are different from the so far fully decentralized models observed in France or Germany. See Beckstedde and Rossetto (2025) for a taxonomy of data management models.
[53] See https://www.acquirenteunico.it/organizzazione.
[54] The fee is also paid by every user of the natural gas distribution service.
[55] See ARERA decision 22 October 2024, 428/2024/R/COM. The structure of the fee has been decided on the consideration that costs are mostly related to the participation of each withdrawal point in the liberalised energy market, rather than the energy volume associated with each withdrawal point. Moreover, this fee structure does not penalise smaller actors.

intention to allocate to them half of the costs of the SII related to electricity, thereby achieving a fairer and more appropriate cost allocation.[56]

In the case of Norway, the data hub, called 'Elhub', is managed by Elhub AS, a subsidiary entirely owned by Statnett SF, the Norwegian transmission system operator, which is owned by the Norwegian state through the Ministry of Energy.[57] Every three year, Elhub is subject to an external audit of its historical and prospective costs. The Norwegian national regulatory authority (RME) approves the fee model that Elhub is allowed to charge to DSOs, power suppliers, energy service companies (third parties), and system vendors.[58] A proposal for the fee model that includes operational costs and investments is submitted by Elhub AS to RME after discussions with the industry. The last decision by RME, covering 2022-2025, specifies that any Elhub user, i.e. DSOs, power suppliers, energy service companies, and system vendors, pay a fixed fee based on the type of user. This fixed fee reflects the costs borne by Elhub to perform basic services and provide customer service for Elhub users. These costs are largely unaffected by the number of Elhub users, the number of metering points or the size of the companies. In addition to this fixed fee, DSOs and power suppliers pay and a fee per metering point under their control. The aim of this metering point-dependent fee is to distribute residual costs evenly across all metering points. For the period 2023-25, the metering point-dependent fee is equal to NOK 79.39 per year for the DSOs and NOK 19.85 per year power suppliers. Energy service companies and system vendors pay only the fixed fee.[59] This is justified by considerations related to the digitalisation of the end-user market. End

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[56] See ARERA consultation document 15 April 2025, 173/2025/R/COM. Following the conclusion of the public consultation, ARERA has confirmed the decision to split the fee fifty-fifty between the balance responsible party and the commercial counterparty. Actors delivering the service of "maggior tutela" pay the fee in full. In the natural gas sector, the split of the fee is a bit different: 10% for the "utenti del bilanciamento", 40% for the "utenti del dispacciamento" and 50% for the "controparti commerciali". This distribution of the fee will take place from April 2026. See ARERA decision 18 June 2025, 262/2025/A, available at: https://www.arera.it/fileadmin/allegati/docs/25/262-2025-A.pdf.

[57] See https://elhub.no/. Statnett SF has a license as settlement authority in Norway.

[58] System vendors are IT companies selling software and sometimes also hardware to market parties only.

[59] Energy service companies pay a fee of NOK 57,000 per year (the same of DSOs and power suppliers) A reduced fixed fee of NOK 25,000 per year is paid by system vendors. This reduced fee reflects the costs that Elhub bears to offer system suppliers access to test environments and associated services in Elhub. See RME decision 19 December 2022, available at: https://www.nve.no/media/15019/202218127-6-rme-godkjenner-statnett-sf-sitt-forslag-til-gebyrmodell-for-elhub.pdf.

users have the right to share their own data from Elhub with third parties, and end users who choose to share their data will not necessarily have a contractual relationship with each individual third party for a specific metering point. Public authorities such as NVE, Statistics Norway (SSB), Enova, approved research institutions, and service providers acting on behalf of other parties that already pays Elhub fees are exempted from paying Elhub fees. On top of these regulated fees, which represent most of Elhub revenues, the data hub may perform additional services beyond ordinary support, of a nature that benefit only the individual service recipient. The charges for these services are not regulated.

Let us now look at the two countries that implement some form of hybrid DMM. In Spain and the Netherlands there is no national data hub. Metering and consumption data are normally stored at the DSO level. However, the function of permission administrator and data access providers have been centralised in recent years. Datadis performs that role in Spain, while MFF/BAS does it in the Netherlands.

In the case of Spain, Datadis provides final customers and authorized third parties, such as energy service providers, with secure, centralized access to the metering and consumption data across all Spanish distribution companies.[60] Datadis is a 'comunidad de Bienes' created by the Spanish electricity DSOs. Final customers and authorised third parties can access Datadis free of charge. Datadis operates as a gateway, as the data remain within the relevant DSO. The cost of processing the data is covered by the regulated income of the DSOs. DSOs cover the entire cost of Datadis in proportion to their regulated income.[61]

In the Netherlands, interested parties can become part of Marktfaciliteringsforum (MFF), an association whose members jointly make agreements about the exchange of energy data. MFF is practically supported by Het Normo, previously known as Beheerder Afspraken Stelsel (BAS), a separate and independent legal entity with the Dutch TSOs and DSOs as its shareholders.[62] Het Normo is in charge of the implementation and monitoring of the agreements made within the MFF, and administers the Energy Data Exchange Framework (EDEF).[63] Participation in the MFF is free of charge and open to all stakeholders. Dutch system operators are mandated by law to enable energy data exchange and cover the costs of Het Normo. Electricity and gas TSOs and DSOs share these costs as follows: Tennet and Gasunie,

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[60] See https://datadis.es/home.
[61] Small DSOs, initially not involved in the setup of Datadis, contribute, pro quota, only to maintenance costs.
[62] See https://hetnormo.nl/.
[63] See https://www.mffbas.nl/en/. A summary overview of MFF/BAS can be found in Hermans (2024).

the electric and gas TSOs respectively, cover 50% of the costs of Het Normo (25% each), while the Dutch DSOs cover the remaining 50% (each DSO contributes in proportion to the number of users connected to its network). The expenses incurred by the system operators are then recovered via network charges.

Finally, let us turn to the two countries that have a more decentralised DMM in place. In Austria and Belgium, there is no data hub nor a specific platform for the centralised management of access and consent to data access. However, different actors of the system have developed a standardised data exchange framework, which includes communication protocols, data formats and processes to support the access and exchange of data.

In the case of Austria, DSOs and TSOs established Energiewirschaftlicher Datenaustausch (EDA) via their association 'Österreichs Energie' to support all market participants with secure and efficient communication and standardised information exchange.[64] EDA enables data exchange via three different connection types, which aim to satisfy different needs. Data, which remain stored at the level of DSO, can be shared either via the EDA portal (web-based solution), via email, or via a communication endpoint. Electricity and gas system operators cover most of the costs of EDA.[65] However, some of the costs are recovered via fees which are applied to energy service providers and energy communities. Depending on the market role selected, different fees apply: the use of the EDA portal is free for everybody up to 50 metering points, while the use of email connectivity or communication end-point, which support the exchange of a higher volume of data, is charged, depending on the underlying role which is using the related connection type.[66] This fee structure purposely facilitates market communication for small market participants, who are subsidised by the fees paid by larger participants. However, as the data space is becoming increasingly mission-critical, and more diverse in terms of functionalities supported and participants, pricing structure is most probably going to be adapted to cope with this evolution. The need for such step-by-step adaption of cost allocation schemes may also be addressed within the CEEDS.

In the case of Belgium, electricity and gas DSOs play the role of data manager and, in 2011, have jointly established Atrias to support them.[67] Data exchange occurs on the MIG 6 communication protocol. Atrias acts as an IT partner of the DSOs, executing some functions

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[64] See https://www.eda.at/.

[65] A pricing model is used that fairly distributes costs between the electricity and gas sectors; however, this pricing model is not publicly accessible.

[66] A list of prices is provided here: https://www.eda.at/pdf/anlage5preisblatten.pdf.

[67] See https://www.atrias.be/.

on their behalf. In particular, Atrias is involved in the communication of data between all market parties, in the management of the access register, and in settlement calculation. Atrias is not involved in data storage (this role is performed directly by the DSOs). Since 2021, the Flemish regulator (VREG) has introduced a data management tariff that is expected to cover all the costs borne by the DSOs.[68] This data management tariff is part of the periodic network charges that final customers pay. It is fixed per metering point. In 2025, the tariff was, for final customers connected to the low-voltage network, equal to €18.56/year (including VAT), irrespective of the type of meter.[69] Flexibility service providers pay a fixed fee per year to contribute to the data management function, but the amount is minor (roughly 200 euros per year) and covers only the administrative costs.

2.5.5 Regulation and Governance

As we have seen in Section 2.5.4, different cost allocation practices are implemented throughout Europe to recover the costs associated with energy data sharing infrastructures. This can be the consequence of the different data management models adopted, and the specific cost structures of the various entities involved. It is also likely to be the consequence of specific arrangements taken in the past at the national level. European legislation currently does not aim at reducing this variability, as it only defines a few general principles that cost allocation should follow, leaving ample leeway to the Member States in designing how the costs of supporting data sharing are covered.

In this section, we explore the regulation and governance of energy data cost allocation, by highlighting the minimum legal requirements introduced by EU legislation, and then reflect on the implications that data sharing governance has on the matter.

The section is organised as follows. Section 2.5.5.1 lists the requirements that each Member State should follow when designing a cost allocation method for data sharing. Section 2.5.2.2 provides an overview of the implications that data sharing governance has on the optimal design of cost allocation methods.

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[68] See https://www.vlaamsenutsregulator.be/nl/veelgestelde-vragen/wat-het-tarief-databeheer-en-waarom-het-hoger-dan-het-vroegere-meet-en-teltarief.

[69] In 2024, the data management tariff was more differentiated: the basic tariff was €13.95/year (including VAT), but customers with a digital meter who had opted for the reading of quarterly values as part of their energy contract (e.g., because they had concluded a dynamic price contract with their supplier) used to pay an additional €1.19 per year.

2.5.5.1 Minimum legal requirements for cost allocation in EU legislation

European sectoral legislation provides some details about how the costs associated with energy consumer data management should be allocated. Article 23 of Directive (EU) 2019/944 devotes a paragraph to the matter, where three requirements are stated. The paragraph is as follows:

1. "No additional costs shall be charged to final customers for access to their data or for a request to make their data available.
2. Member States shall be responsible for setting the relevant charges for access to data by eligible parties.
3. Member States or, where a Member State has so provided, the designated competent authorities shall ensure that any charges imposed by regulated entities that provide data services are reasonable and duly justified" (art. 23 (5)).

Hence, the Directive maintains that, at least for the management of the data relevant to Article 23,[70] costs should not be directly allocated to final customers or at least not allocated based on their request to access their data or for a request to make their data available. Apparently, this leaves the possibility to either charge final customers on the basis of a fixed charge independent from the direct use of the data sharing infrastructure or to charge other actors of the system that access those data, the so-called eligible parties.[71] However, the Directive then does not provide many details on the way eligible parties can or must be charged. It simply specifies that Member States are responsible for setting the charges and that, in case the charges are imposed by regulated entities, such as, for example, a national mandatory data hub, those charges must be reasonable and duly justified.

Although a proper investigation of the appropriate interpretation of these provisions is beyond the scope of this section, it seems that such provisions rule out the use of cost allocation methods based on cooperative game-theoretic or auction-base approaches. A purely uniform allocation of costs is likely to be equally incompatible with the letter of the Directive, as it does not appear to be neither reasonable nor duly justified to charge the same cost to everybody, independently of the use of the data sharing infrastructure and any cost-

[70] Article 23 (1) specifies that "For the purpose of this Directive, data shall be understood to include metering and consumption data as well as data required for customer switching, demand response and other services."

[71] Energy suppliers and other energy service providers can be eligible parties. See Nicolai and Münchmeyer (2025) for a discussion of the definition of eligible parties in the context of energy service interoperability.

responsibility. The use of a proportional cost allocation method seems to be the only approach compatible with the Directive. However, in the absence of any additional detail provided by the same Directive, a question remains: proportional to what?

2.5.5.2 Governance

The analysis of the costs associated with the establishment of energy data sharing infrastructure in Section 2.5.4.1 shows that an important cost driver is represented by the need to align the interfaces and the processes among the various actors involved in data management. Having all the actors on board is important to ensure an effective and efficient implementation of the chosen data exchange framework. However, this can be far from simple, given the diversity in capabilities and interests that can characterize them. Trust in the other actors is essential to promote cooperation and possibly accept to embrace changes in the status quo that generate costs or reduce the role of gate keepers in data management. A cost allocation which is perceived fair and transparent can play an important role in generating trust, thereby facilitating the establishment of an efficient and effective data sharing infrastructure. Again, some form of proportionality in the cost allocation method seems to be way forward.

The trust and willingness to cooperate for the establishment of a data sharing infrastructure may initially emerge only within a small group of good-willing and forward-looking actors. Other actors, either regulated ones or commercial, can be initially less inclined to be involved, for instance due to a conservative management or a not so clear business case. Given the network effects that a data sharing infrastructure can generate, as mentioned in Section 2.5.2, it is important that the chosen cost allocation method facilitates the participation of new actors. An expansion of participation can in fact increase the value generated and redistribute the burden on the actors that already contribute to cost recovery.

Eventually, it is possible to imagine that a different cost allocation method is adopted in the early stages of the energy data sharing infrastructure and when the infrastructure is fully in place and network effects have become significant due to the large number of actors already using it. Such an evolution in cost allocation can potentially facilitate the rapid uptake of the infrastructure and ensure dynamic efficiency. Therefore, the governance framework adopted should allow for adaptive cost allocation, with periodic reviews to realign charges with participation levels, data value, and system maturity.

2.5.6 Conclusions and policy recommendations

Section 2.5 explores the economic foundations of cost allocation in energy data spaces, emphasising the need for fair, transparent, and sustainable mechanisms to support their operation. As data exchanges becomes increasingly central to the digital energy transition, defining who pays for what, and according to which principle, will determine both participation incentives and system's long-term viability.

Based on the discussions of Section 2.5, four key conclusions and policy recommendations emerge:

1. *The establishment of a single coordinating entity for the European energy data space*.

Early competition between data space developers could fragment standards, reduce interoperability, and lead to dominance by large non-European digital platforms, undermining trust and data sovereignty. Data spaces exhibit economies of scale and natural-monopoly characteristics, making a coordinated framework more efficient. A unified entity can ensure stability, standardisation, and efficient governance. A centralised governance structure would ensure coherence across national initiatives, promote data interoperability, and maintain trust among stakeholders. Such an entity should guarantee neutrality, stability, and alignment with existing regulations.

2. *The adoption of proportional cost allocation as the default method*.

The proportional allocation as a cost sharing mechanism satisfies both Monotonicity and No advantageous splitting or merging, which are crucial for fairness and incentive-compatibility of data spaces. The method is simple, transparent, and robust against strategic behaviour, unlike uniform or game-theoretic rules. It aligns best with the efficiency and fairness conditions. It is easy to implement and ensures that costs are shared fairly in proportion to measurable participation or activity levels. This method has the advantage of potentially promote trust among the participants, a condition essential to ensure an effective and efficient governance of the same.

3. *Differentiate between regulated and non-regulated data exchanges*.

Regulated exchanges, such as TSO-DSO operational data flows, create broad system-wide benefits, which calls for governance and cost-recovery mechanisms consistent with their public good nature. In contrast, non-regulated exchanges enable commercial or cross-sectoral services and can rely on market-based pricing or weighted proportional mechanisms, reflecting user activity and data contribution. As these two categories differ fundamentally in purpose, incentives, and beneficiaries, they can be treated separately in a cost allocation exercise.

4. *Incentivise early participation and data contribution*.

Strong network effects in energy data spaces, where the value of the system increases with the number and diversity of participants, make early adoption critical for achieving scale. A weighted proportional allocation can incorporate rewards to early adopters or actors who contribute valuable data by assigning them lower weights or preferential terms, while satisfying the fairness and efficiency principles. Such incentives should help overcome initial reluctance to join the data space, support trust-building, and accelerate the growth of the data space ecosystem.

In summary, energy data spaces require more than technical interoperability. Their success calls for sound economic design. These recommendations help build a governance and cost allocation framework that support both the scalability and the long-term sustainability of the European energy data ecosystem.

2.6 AI-Fication of Consumers and Data-driven Market Dynamics

2.6.1 Introduction

The rapid digitalisation of the energy sector has transformed how data are collected, exchanged, and operationalised to manage electricity demand and supply (IEA, 2017). While the first waves of digitalisation focused on transmission networks and generation, the most recent one has reached the distribution and retail segments, integrating smart meters, connected home appliances, and AI-based decision systems (Rosetto and Reif, 2021). This transition opens the door to a new paradigm (the AI-fication of the energy consumers) where households and prosumers (Gautier et al., 2018) interact dynamically with energy systems through digital twins, edge computing, and real-time data flows within Energy Data Spaces (EDS). They represent structured, interoperable environments for sharing and processing energy data across stakeholders (Dognini et al., 2022), that provide secure access to distributed datasets while preserving privacy, standardisation, and interoperability. The CEEDS initiative[72] exemplifies this evolution, enabling retailers, aggregators, and consumers to access common datasets and algorithmic tools to take advantage of the potentials from combining multiple databases and enhance system efficiency, integrate RES, develop flexibility services and balance grid loads. This section proposes an economic and algorithmic framework to investigate how AI-enabled data spaces can reshape energy retail markets, focusing on dynamic pricing and demand flexibility.

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[72] See https://digital-strategy.ec.europa.eu/en/library/european-commission-advances-development-common-european-energy-data-space-ceeds

We explore the impact and potential outcomes of algorithmic dynamic pricing on different typologies of users, ranked according to their flexibility and demand elasticity. These dynamic pricing are meant to represent the outcome of AI flexible models, simulating a Reinforcement Learning (RL) model of dynamic pricing. The algorithms learn from and react to, the demand responses of how three heterogeneous consumer types: Smart, Moderate, and Inertia ones, whereby each class responds differently these to AI-driven price adjustments. Finally, we focus on exploring the potential implications, of the addition of these dynamic pricing algorithms, for efficiency, fairness, and market outcomes.

2.6.2 From Digitalisation to AI-Enabled Energy Data Spaces

CEEDS build upon the convergence of digital enablers such as Artificial Intelligence (AI), Internet of Things (IoT) devices, Digital Twins, and Edge Computing. In combination, these technologies enable decentralised but interoperable data management, where information flows seamlessly among producers, system operators, and consumers. AI models can learn from these datasets to optimise energy distribution and design dynamic tariffs that respond to real-time market conditions. Interoperability is central to the success of these Data Spaces, since without common data standards, semantic alignment, and secure sharing protocols, the potential of AI remains constrained. Interoperable data environments allow for cross-domain applications, for instance, integrating weather forecasts, mobility data, and smart home sensors into demand prediction models useful for system operators, retailers or independent aggregators. Such integration becomes essential as energy systems face increased volatility due to RES integration and demand peaks, that might even, occasionally, be leading either to negative prices when supply exceeds consumption, or blackouts when consumption exceeds volatile supply.[73]

2.6.3 Behavioural and Heterogenous Demand

Our focus in this chapter is on the consumers' implications of AI-fication of energy retailing strategies implemented through algorithmic dynamic pricing. We focus on consumers' outcomes based on their heterogeneity in cognitive, technological, and behavioural, traits. Such traits will also determine the outcomes of AI-based dynamic pricing.

While simplistic economic reasoning might assume average representative consumers, sometimes behaving as fully rational agents, plenty of real-world evidence, indicates that consumers differ, not only in their demo- socio-economic characteristics, but also in their

[73] This data integration should respect the unbundling processes for all the involved agents.

digital skills, attention capacity, and access to smart technologies such as smart, and sub-smart, meters, connected thermostats or remotely controlled appliances.

Inspired by a categorization introduced by the Climate Change Committee's (CCC, 2025)[74] that developed a taxonomy of UK household archetypes, we classify consumers into three stylised behavioural types:

1. *Smart Users*: Digitally literate, well-informed consumers with high price responsiveness and the ability to shift consumption across time.
2. *Inertia Users*: Less adaptive consumers who respond sluggishly to price signals and exhibit strong consumption persistence.
3. *Moderate Users*: Intermediate consumers displaying partial responsiveness and limited adaptation.

Each consumer type is represented by a specific demand function reflecting elasticity to price, time-of-day variations, and adaptive or inertia effects.

Smart Users

Their demand decreases sharply with price increases, because of the assumed high elasticity. Their demand also follows a sinusoidal daily pattern reflecting predictable hourly cycles, such as morning and evening peaks. Random shocks capture unpredicted external variability.

Inertia Users

These consumers adjust slowly. Their elasticity is smaller than the one of the Smart users, and their consumption exhibits adaptive persistence, depending partly on past consumption. This models habitual or automatic behaviour, where past usage influences current demand.

Moderate Users

Moderate consumers lie between the two extremes, in terms of elasticity and moderate time-of-day effects but no adaptive persistence. Their behaviour balances reactivity and stability.

[74] See: https://www.theccc.org.uk/wp-content/uploads/2025/02/The-Seventh-Carbon-Budget.pdf

This behavioural differentiation is essential for our aim, to assess heterogenous impact of energy retail AI-fication, because AI-driven pricing models that do not incorporate such heterogeneity risk over-penalising fewer flexible consumers, potentially raising fairness and social inclusion concerns.

2.6.4 AI-Driven Dynamic Pricing in Energy Data Spaces

In this Section 2.6, we operationalise these heterogenous behavioural consumer patterns within a simulated AI-driven pricing environment. This is to replicate dynamic pricing algorithms often built with Reinforcement Learning (RL) to represent continuously adjust tariffs in response to observed consumption, weather, or grid conditions.

In detail, we model the energy retailer as a learning agent whose goal is to maximise a reward function combining two key elements: revenue and system stability. Consumers, forming the environment where the algorithms learn, react to the observed process, through their three different demand functions. The algorithm interacts iteratively with the consumers' environment, adjusting prices based on the observed outcomes, following a typical exploration–exploitation strategy, whereby a first set of observations of the reactions to the offered prices, is explored to fine tune the algorithm through learning, while the second set of observations, is exploited, based on the reward function, after the exploration phase.

Dynamic Pricing

The Dynamic Pricing algorithm is built using a Deep Q-Network (DQN) (Messaoud et al., 2020), a deep reinforcement learning algorithm that approximates the value of each possible action given the current state.

For simplicity, we limit our state variable, at each time t, and for each consumer type, to include three dimensions only:

- the current price (p_t),
- the current demand (d_t), and
- the hour of day ($h_t \in [0,23]$).

At each step, the learning agent chooses an action a_t (increase, decrease, or keep price constant). The resulting new demand depends on both the market price, p_t, and consumer behavioural type. The environment, provides a reward, to the dynamic pricing algorithm, defined as:

$$R_t = Revenue - Penalty,$$

where $Revenue = p_t \times d_t$ and the $Penalty$ increases to capture situations whereby demand exceeds grid capacity or when too abrupt price jumps occur.

Three Learning Phases

The training process evolves through three conceptual phases:

1. Price Adjustment Phase: The AI agent explores random price actions to learn how demand reacts under uncertainty. This phase captures early exploration and randomness in decision-making.
2. Learning Cycles: The agent begins recognising temporal regularities (e.g. morning peaks) and adjusts prices cyclically. Randomness decays as the system transitions from exploration to exploitation.
3. Balancing Grid Efficiency: The AI agent learns to avoid overloading the grid or leaving capacity idle by optimising prices within an efficient range. The reward function guides this process.

Through repeated interaction, the DQN converges to a dynamic pricing a policy, π^*, that maps each state (price, demand, hour) to the pricing decision.

2.6.5 Simulation Design and Parameters

The initial simulation represents 24-hour electricity consumption cycles over 150 episodes, where each episode corresponds to a day. The environment consists of three parallel populations (*Smart*, *Moderate*, and *Inertia*) each governed by their respective demand functions.

We aim to compare two alternative pricing strategies, often offered as alternatives to consumers by energy retailers:

- Dynamic Pricing (AI) versus Fixed Pricing (benchmark).

For both pricing strategies, we allow for

- Hourly demand fluctuations reflecting daily routines.
- Random noise to mimic exogenous shocks; and
- Exploration-exploitation decay, ensuring convergence toward stable strategies.

For robustness, independent two-sample t-tests compare mean prices and demand levels between dynamic and fixed pricing after the learning phase (i.e. based on all remaining episodes after the learning phase occurring in the first 100 periods).

2.6.6 Results

2.6.6.1 Learning Convergence and Price Patterns

Across all consumer types, the DQN converges to a stable dynamic pricing policy after roughly 100 episodes. Fixed pricing remains constant (mean ≈ 0.50 £/kWh), while AI-based dynamic pricing yields differentiated prices across time and user types.

The resulting Average dynamic prices are significantly higher than fixed ones for all consumers:

User Type	Mean for Dynamic Prices (£/kWh)	Fixed Price	p-value
Smart	2.24	0.50	0.000
Moderate	2.60	0.50	0.000
Inertia	2.41	0.50	0.000

Table 2.4: Mean values and p-values across user types.

Smart users, despite facing higher nominal prices, experience the least variability and manage consumption more efficiently through time-of-day shifting. Figure-based indicates clear cyclical patterns: morning and evening peaks trigger higher prices, while mid-day and night rates decrease.

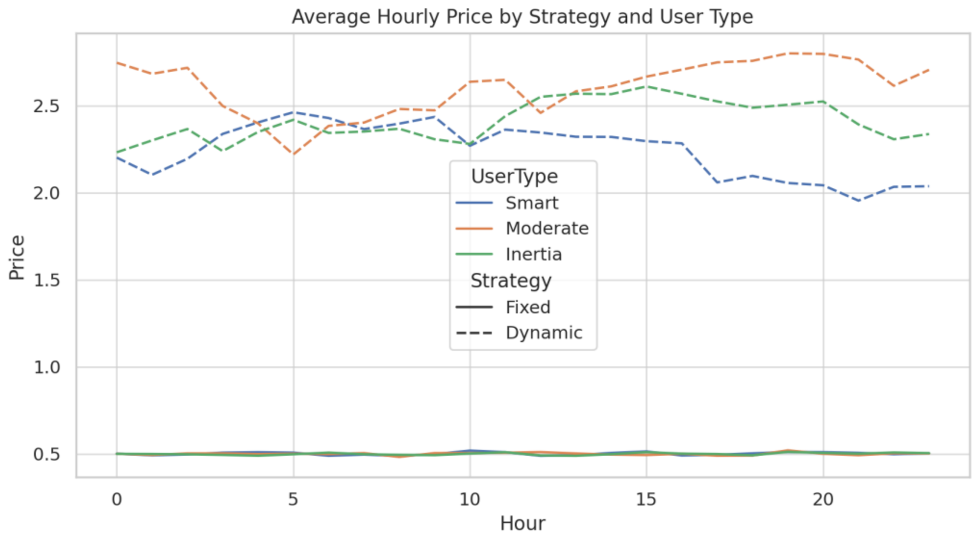

Figure 2.4: Average Hourly Prices by Strategy and User Type.

2.6.6.2 Demand Responses

Dynamic pricing significantly reduces demand compared to fixed pricing across all consumer types:

User Type	Mean for Dynamic Demand (kWh)	Fixed Demand	p-value
Smart	25.8	80.0	0.000
Moderate	30.8	86.0	0.000
Inertia	29.2	84.0	0.000

Table 2.5: Mean values and p-values across user types.

However, this Demand impact of dynamic pricing differs sharply across groups, according to their flexibility. Smart users exhibit pronounced responsiveness to hourly price fluctuations, effectively flattening their load curve. Inertia users remain largely unresponsive, maintaining near-constant demand. Moderate users show intermediate adaptation, partially shifting demand but with larger variance.

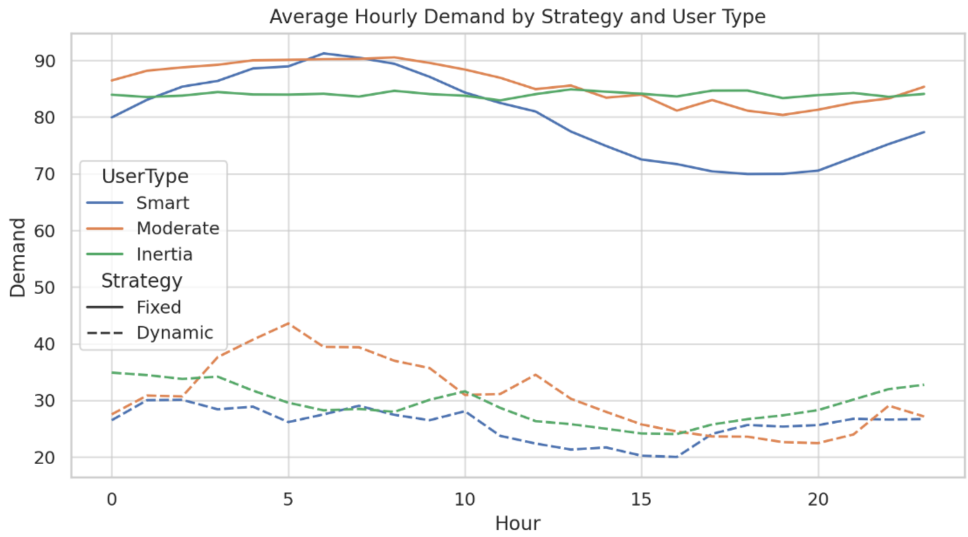

Figure 2.5: Average Hourly Demand by Strategy and User Type.

2.6.6.3 Temporal and Behavioural Variability

When comparing prices at three representative hours (10 am, 2 pm, 11 pm), Smart users consistently pay the lowest prices with the smallest standard errors, suggesting greater stability. Moderate and Inertia users face higher and more volatile prices, likely due to their limited responsiveness and slower learning.

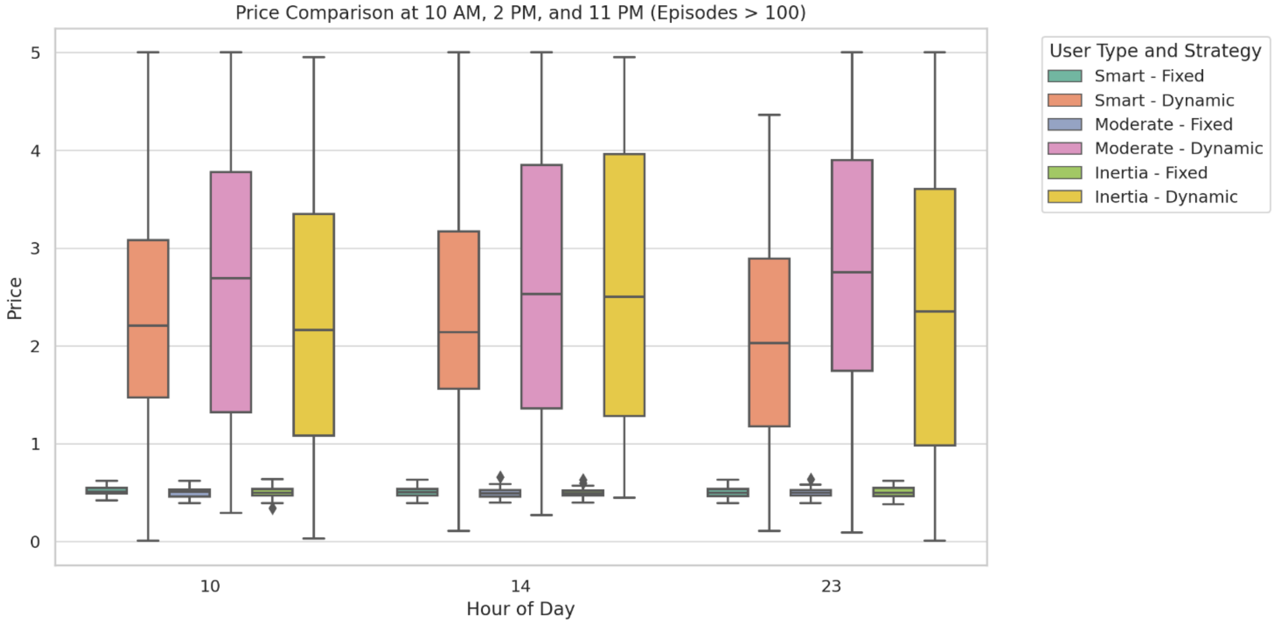

Figure 2.6: Means and Standard errors for dynamic pricing across three different hours (10 am, 2 pm, and 11 pm) by Strategy and User Type.

Daily price averages (after convergence) confirm this pattern: Smart users' prices stabilise, while Moderate and Inertia users show lingering oscillations. This indicates that AI-driven systems tend to reward flexibility, as adaptable users help balance the grid and indirectly smooth prices for themselves.

2.6.6.4 Joint Price-Demand Dynamics

Plotting hourly demand and price for Smart consumers after convergence (episode 100) reveals an inverse and well-synchronised relationship: high prices coincide with reduced demand, while low-price hours encourage increased consumption. The AI system learns to exploit this elasticity to maintain load balance, demonstrating the stabilising role of intelligent demand response.

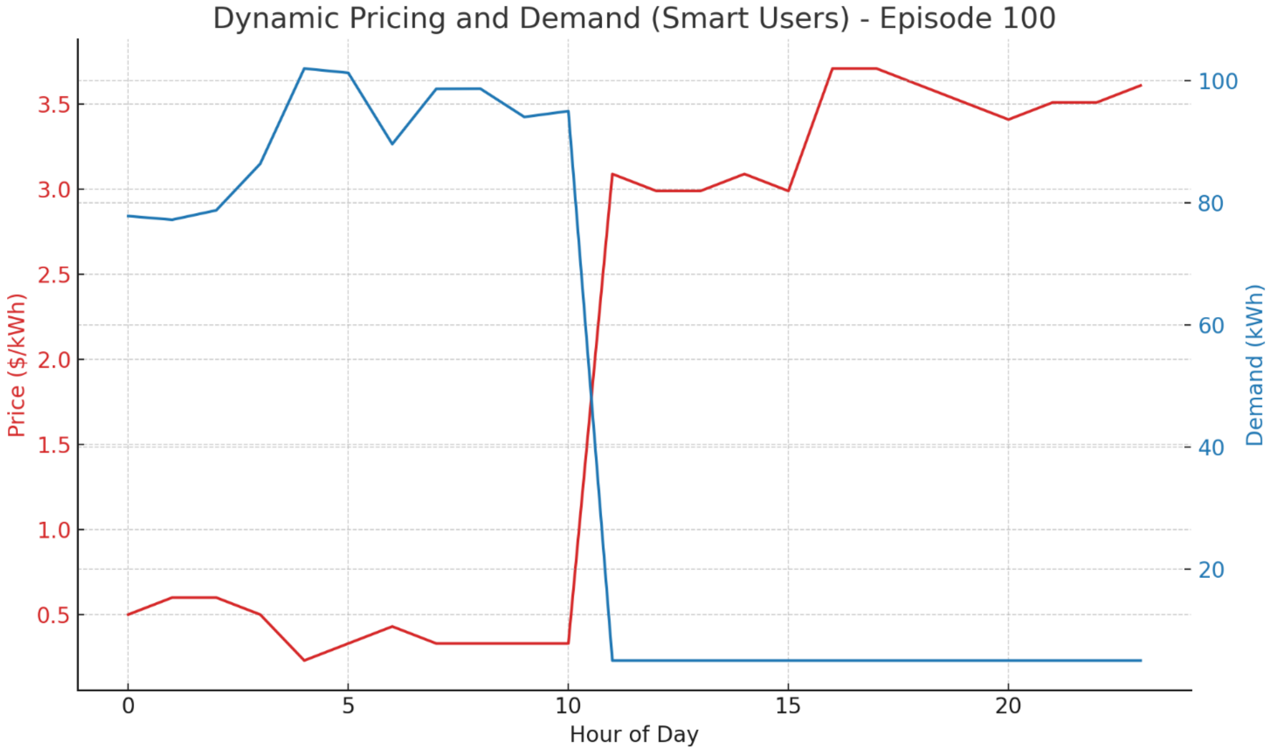

Figure 2.7: Simulated hourly demand and prices, at Episode (day) 100.

2.6.7 Discussion

2.6.7.1 Elasticity, Efficiency, and Equity

The results suggest that AI-induced dynamic pricing enhances system efficiency by aligning demand with supply in real time, reducing potential grid stress and increasing utilisation of renewable generation. However, these efficiency gains are unevenly distributed.

Smart consumers benefit the most, facing smoother and lower average prices due to their flexibility. Inertia consumers, unable to adjust, face higher effective costs and potential welfare losses. Thus, AI-fication, without any policy adaptation, incorporating forms of inclusivity risks deepening existing inequalities rooted in digital access and cognitive asymmetries.

2.6.7.2 AI as an Economic Agent

The DQN pricing model effectively acts as an economic agent that learns market-clearing prices through repeated interaction rather than explicit equilibrium equations. This provides insights into the potential of using machine learning to model behaviour within a microeconomics framework. The reward function substitutes for a profit-maximising objective, while the environment approximates a behavioural demand curve. Over time, the algorithm pricing policy converges to a stable state, a simulated equilibrium.

2.6.7.3 Initial Policy and Regulatory Implications

AI-driven dynamic pricing must be contextualised within existing energy regulations and consumer protection frameworks. Regulators face new challenges in ensuring algorithmic transparency, fairness, and explainability. For instance:

- Should consumers be allowed to opt out of algorithmic tariffs?
- How can interoperability standards in data spaces guarantee non-discriminatory access to data?
- How can algorithmic collusion among AI-pricing agents be prevented if multiple retailers adopt similar systems?

These questions point to the need for governance frameworks combining technical interoperability with economic accountability.

2.6.7.4 The Role of Energy Data Spaces

EDS enable these AI-driven interactions by pooling high-quality, standardised data across stakeholders. They also lower the cost of data acquisition, allowing smaller retailers or local energy communities to deploy advanced pricing algorithms. Yet, data sovereignty remains a key concern, as consumers should retain control over how their consumption data are shared and monetised. Critically, their data are merged with external data, and it is challenging to disentangle the individual contributions to the monetisation of composite data. Moreover, who owns the derived data, that had been obtained though the operations of the algorithm to which the original personal data are fed, during the training phase?

2.6.8 Commercial and Economic Considerations

From a business-economics perspective, AI-fication changes both cost structures and revenue models in energy retailing.

- Efficiency Gains: AI reduces forecasting errors, enabling better grid planning and more efficient renewable integration.
- New Value Streams: Data from connected devices become a monetizable asset, allowing the creation of tailored energy services, such as predictive maintenance or carbon-footprint dashboards.

- Cost of Intelligence: These gains come at the price of computational energy use, data management costs, and potential rebound effects from increased digital infrastructure.

Therefore, the economics of AI in energy markets must balance the efficiency benefits against digital overheads and ensure that value creation does not translate into consumer exclusion.

2.6.9 Lessons Learnt and Limitations

The simulations confirm that even simple reinforcement learning schemes can generate credible pricing dynamics that reproduce realistic energy-market phenomena such as daily cycles, price elasticity, and behavioural heterogeneity. They also demonstrate the usefulness of stylised AI-economic models in policy exploration, especially where empirical data are scarce or fragmented.

Nevertheless, several limitations remain. First, we adopted a Single Retailer Environment, as in the current model simulates only one retailer. Competition among multiple AI agents could introduce new dynamics, such as algorithmic collusion or price wars. Second, we assumed Static Consumer Typologies. However, real households may transition between behavioural types as they acquire new digital tools or face changing incentives. Third, we assumed simplified Grid Constraints. Future extensions could integrate physical network limits and renewable intermittency, allowing the AI to manage both pricing and dispatch. Finally, a more detailed welfare analysis is needed to evaluate redistributive outcomes and potential need for regulation or compensation mechanisms.

Future research could therefore model multi-agent AI competition within a shared data space, studying whether cooperative or adversarial algorithmic learning emerges and what it implies for system stability and fairness.

2.6.10 Conclusions

Section 2.6 aims to advance the understanding of how digitalisation and AI are transforming the microeconomics of energy consumption. By embedding reinforcement learning within behavioural demand models, it demonstrates that:

- AI-based dynamic pricing can effectively balance supply and demand.
- Consumer heterogeneity significantly shapes pricing outcomes and equity effects; and

- Energy Data Spaces are essential infrastructure for real-time data exchange and AI deployment.

The AI-fication of the energy retailing, represents both an opportunity and a challenge. It offers tools for efficiency, decarbonisation, and consumer empowerment, but only if accompanied by inclusive data governance and transparency in algorithmic decision-making.

As energy systems evolve toward decentralised, data-driven architectures, ensuring that all consumers, regardless of digital proficiency, benefit from AI-enabled flexibility will be the key to achieving a just and sustainable energy transition.

2.7 Conclusion

The analyses presented in this chapter evidence that digitalisation and data sharing are reshaping the economic foundations of the European energy system. Energy data has evolved from a technical by-product into a valuable economic and social asset. When managed through interoperable, transparent, and secure frameworks, it can reduce transaction costs, enhance market efficiency, and foster innovation across the electricity value chain. However, these opportunities are accompanied by new regulatory, organisational, and distributional challenges that require careful design of incentives and governance structures.

The conceptual and economic perspectives introduced in this chapter demonstrate that data can simultaneously exhibit characteristics of private and public goods. This dual nature justifies public intervention to ensure that the benefits of digitalisation (such as lower integration costs, greater flexibility, and increased consumer participation) are broadly shared. Interoperability emerges as a key piece for efficient and competitive energy data markets. Harmonised technical and organisational standards reduce entry barriers, limit information asymmetry, and enable new service providers to operate across Member States. However, setting interoperability requirements also entails balancing innovation with standardisation, and avoiding lock-in effects where incumbent actors can shape standards to their advantage.

Our cost-allocation analysis implies that sustainable business models for energy data spaces depend on transparent and fair cost-sharing mechanisms that reflect both individual usage and collective benefits. Given the strong network effects inherent to data infrastructures, the economic efficiency of a single interoperable framework is higher than that of multiple fragmented systems. The AI-fication of consumers and the increasing role of algorithms in demand management introduce further complexities. AI-based systems can greatly improve flexibility, forecasting, and efficiency, but they also risk concentrating market power and creating behavioural inequalities between digitally literate and less prepared consumers. This reinforces the importance of governance frameworks that ensure accountability, explainability, and inclusiveness in data-driven energy services.

In summary, the findings from this chapter highlight that the development of a CEEDS must go beyond technical interoperability. It requires an integrated economic design that aligns incentives among stakeholders, safeguards fair access to data and promotes innovation under clear and stable regulatory conditions.

3 USER EXPERIENCE AND BEHAVIOUR, INCENTIVES, AND USE CASES

3.1 Introduction

The description of EDDIE's task T7.2 was deliberately kept open and exploratory, offering a variety of interesting opportunities for conducting research. In the Grant Agreement, it was outlined as follows:

"This task evaluates the usable application prototypes implemented for the EDDIE Framework (e.g., smartphone apps for end-user consumers, web-based administrative console). In particular, this task assesses the User Experience (UX) of these prototypes and analyses the behavioural economics of the demonstrator prototypes as implemented in WP6 with a special focus on their potential end-user customers. The goal of this task is to identify and collect best practices and develop models for future use cases with respect to technological and economical dimensions of providing energy consumption data for different stakeholders."

This open-ended nature of the task first required translating it into clear research objectives and research questions, which are set out in the following section. Subsequently, we also outline the evaluation context and framework conditions of T7.2 that shaped our research efforts, along with the research approach and methods employed.

To address the defined objectives, the investigation was structured into two strands: *Research Strand A* and *Research Strand B*. Each strand is presented in a dedicated section of this report, detailing the activities conducted and the respective findings.

3.1.1 Research Objectives and Guiding Research Questions of Task T7.2

The objective of T7.2 was twofold. On the one hand, the prototypes implemented for the EDDIE Framework were to be evaluated. Particularly, T72.2 assessed the user experience (UX) of these prototypes and analysed the behavioural economics (BE) of the demonstrator prototypes as implemented in WP6 with a special focus on their potential end-user customers. On the other hand, we aimed to develop guidance for future use cases with respect to technological and economical dimensions of providing energy consumption data to different stakeholders.

From an analytical perspective, this work package addressed research questions that operate on both a 'micro' and 'macro level'. The former examined questions that arise from user interactions with the respective applications (UX) and often focus on user decision-making regarding energy consumption (BE). The latter level (macro) did not deal with individual interactions of end-users but took a more global perspective, investigating which components need to be integrated to generate promising innovative business models and use cases around shared energy data.

This led us to overarching research questions, which guided the achievement of the objectives:

- UX and BE insights (Research Strand A: 'micro level'):
    - How do people experience the now constantly available energy consumption data?
    - What mechanisms influence people's energy-consumption decisions when they make them based on energy data? Can we identify and utilize such mechanisms from a BE perspective?
- Business models and use cases (Research Strand B: 'macro level'):
    - What different types of business models or use cases can be identified around energy data?
    - How are (energy) data processed, and what requirements are imposed on them?
    - What additional data sources need to be integrated to enable the applications?
    - How can we support the design and engineering of such applications and data-driven services?

Please note, the research questions have been deliberately kept open and exploratory at the beginning. As the research progressed, these questions were further specified through individual studies and experimentations. "Experience", for instance, is a broad concept that encompasses numerous facets, each of which can be examined individually. This includes usability aspects, such as whether users can cognitively process the data presentation accurately. It also encompasses broader concepts, such as whether users feel empowered, because they now have a better understanding of their energy consumption. The same applies to the research questions from the second thematic group. For example, the first question about the different types of business models was refined during the work, focusing on typical aspects of business models, such as customer benefits, potential risks, and key stakeholders.

We now turn to key framework conditions of T7.2, before outlining the strategy developed to address the research questions.

3.1.2 Evaluation Context and Framework Conditions of T7.2

WP7 formally started at the very beginning of the project, ahead of the technical implementation of the demonstrators developed in WP6. Consequently, the initial phase of T7.2 took place at a time when most demonstrators were still under development and not yet available for direct evaluation. This lead time was deliberately used and needed for preparatory and exploratory work, ensuring that the subsequent evaluation activities could be grounded in a robust conceptual and analytical basis.

As the project progressed, demonstrators were continuously integrated into the evaluation process as soon as they reached a level of maturity that allowed for meaningful assessment. Rather than following a single fixed evaluation point, the evaluation activities within T7.2 were conducted in a rolling and iterative manner, aligned with the actual availability of the demonstrators over time. This approach ensured that each demonstrator could be assessed under appropriate conditions while remaining consistent with the overall objectives of T7.2.

Across the project, the demonstrators addressed a wide and heterogeneous range of use cases and system configurations. While several demonstrators provided direct interaction for end users through dedicated user interfaces, others primarily focused on technical, organisational, or infrastructural processes, such as backend data exchanges, or inter-organisational workflows, without a direct user-facing interface. Consequently, not all demonstrators were equally suitable for the evaluation of *user experience* aspects. Within T7.2, demonstrators offering a concrete end-user interface and direct user interaction were therefore prioritised for user experience–related assessments.

3.2 Methodology

As a response to the evaluation context as described above, T7.2 was addressed in two separate research strands.

Research Strand A scrutinised individual user interactions and dealt with the UX of energy data with special consideration of strategies from BE. It therefore addressed questions from the first thematic complex, specifically focusing on the 'micro level'.

Research Strand B took a step back and looked from a global and business-oriented perspective at how complex systems and services around energy data can be engineered and enhanced, for example, by integrating additional data (e.g., energy tariffs or sources of electricity). Accordingly, it addressed the questions we referred to above as the 'macro level'.

Research Strand A started earlier than Strand B, which, as described above, depended on the implementation of the demonstrators by the consortium partners (WP6). Strand A used this head start to carry out preliminary work in preparation for the evaluation of the demonstrators in Strand B. This included developing an understanding of fundamental user experience and behavioural economics mechanisms against which the partners' prototypes can later be evaluated (the micro level).

These specific characteristics and constraints described require a corresponding research strategy or philosophy, along with suitable research methods. In this project, we adopted Research through Design (RtD) as our overarching research philosophy. RtD is an established and respected approach within the design research community and increasingly recognized in fields like User Experience Design and Human-Computer Interaction.[75] At its core, RtD involves generating knowledge through the process of designing: by making and reflecting on artifacts, demonstrators or interactions. In this design process, prospective users are often closely involved as co-designers or participants, because they are the ones who will ultimately use and interact with the applications. Moreover, they are the experts on the problems they aim to solve with these apps[76]. This philosophy is particularly well suited to open-ended, exploratory inquiries such as T7.2, where the research object is not fixed in advance but instead takes shape through iterative development.

In our case, the very subject of investigation evolved as we engaged with it; we did not merely study a given system but co-developed it through design (in particular, Research Strand A, but also Strand B). Insights emerged not only from analysis but from the creative act of building, prototyping, and reflecting on what was produced.

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[75] E.g. Zimmerman, J., Forlizzi, J., & Evenson, S. (2007). Research through design as a method for interaction design research in HCI. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 493–502). Association for Computing Machinery. This foundational paper introduces Research through Design (RtD) as a rigorous approach for generating knowledge in Human-Computer Interaction (HCI). The authors provide a conceptual framework for understanding and evaluating RtD contributions, arguing that design is uniquely suited to address ill-defined, "wicked" problems. Widely cited, the paper has helped establish RtD as a legitimate mode of inquiry in design-oriented technology research.

[76] The inclusion of users in the design process is a core principle of Participatory Design (PD), which emphasizes collaboration between designers and users to ensure that the resulting technologies genuinely address users' needs and contexts. PD is not just about improving usability. It is a more holistic approach that empowers users as co-creators, making their knowledge and lived experiences integral to the design outcome (Schuler et al, 1993).

Given the exploratory nature of RtD, qualitative methods are especially well suited to support our inquiry. In our project, a significant portion of the research was grounded in the collection and analysis of qualitative data, particularly through in-depth interviews. To systematically interpret this data, we applied thematic analysis as outlined by Braun and Clarke.[77] This method enables a rigorous yet flexible approach to identifying, analysing, and reporting patterns (themes) within qualitative datasets. This approach allowed us to trace meaning across interviews and uncover insights that are embedded in participants' experiences and perspectives.

While qualitative methods form the core of our analytical approach, we also employed quantitative methods for selected aspects of the research. These were primarily used to analyse survey data, offering descriptive insights and enabling the calculation of correlations that complement our qualitative findings with additional patterns or tendencies.

3.3 Research Strand A – User Experience & Behavioural Economics

Research Strand A investigated fundamental interaction and decision-making mechanisms in the context of applications dealing with energy consumption. The initial goal was to explore the problem space and then establish some more generalizable results. For this reason, the variables or components of the applications and experiments were reduced to the essentials. That means we focused on 'pure' energy data and avoided data integration in Research Strand A.

Figure 3.1 illustrates the research activities related to Strand A. These consisted of creating the necessary tools to conduct user studies (A.I Supporting Infrastructure for running User Studies), creating research prototypes (A.II Research Prototypes addressing and embodying Research Questions), as well as different user studies (A.III and A.IV).

Strand B and its associated research activities will be introduced and discussed later, together with Figure 3.2. Both strands share the characteristic that the research within them built upon itself step by step. Fundamental, exploratory work is represented at the bottom of each respective figure. The insights gained here were used to refine questions at a higher level. In Strand A, confirmatory studies were then conducted to validate selected earlier observations. Strand B, in contrast, remained exploratory, as deriving generalizable results was neither intended nor possible due to the described diversity of the demonstrators. Both

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[77] Braun, V., & Clarke, V. (2019). Reflecting on reflexive thematic analysis. Qualitative Research in Sport, Exercise and Health, 11(4), 589–597. https://doi.org/10.1080/2159676X.2019.1628806

strands culminate in integrative frameworks (A.V BEUX.energy Framework and B.IV FutureUC.energy Framework). Table 3.1 provides an overview of the applications developed as part of Research Strand A (cf. also Figure 3.1). These applications were either essential for facilitating our user studies (supporting infrastructure) or were analysed as technical artifacts embodying hypotheses to the research questions outlined above (research prototypes). Each product is explained briefly in the subsequent sections. For further details or the source code of this software component, please refer to the linked documentation and/or code repositories in the following sections (in the footnotes).

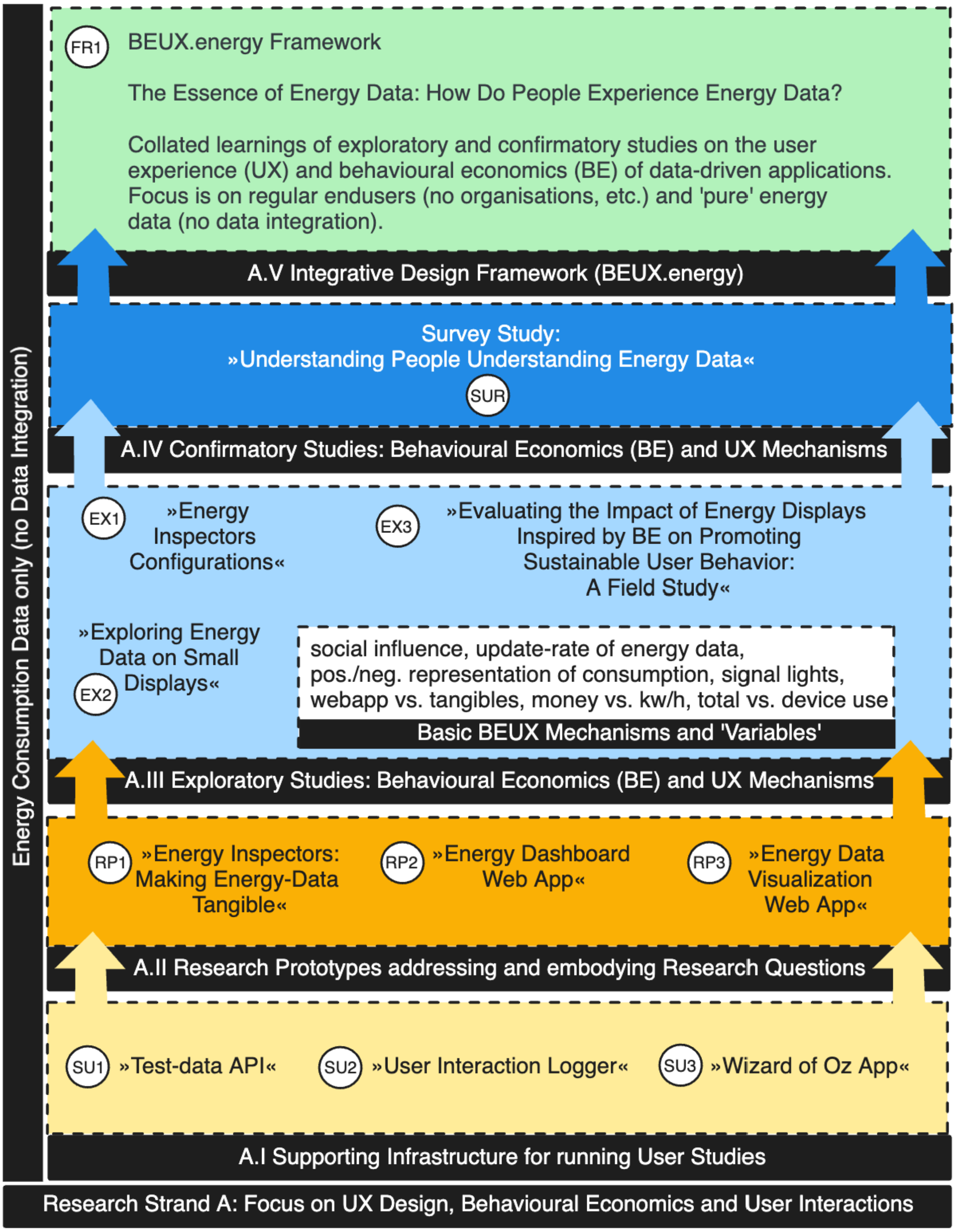

Figure 3.1: Research Strand A. For further explanations, also refer to Table 3.1 and the encircled labels

ID	Name of component	Description
SU1	»Test-Data API«	API service for integrating synthetic test data into early user studies
SU2	»User Interaction Logger«	Web app for logging user interactions with applications / digital products
SU3	»Wizard of Oz App«	Web app for remote controlling the Energy Inspectors (see next item)
RP1	»Energy Inspectors«	Tangible devices for displaying energy data. These represent the primary research prototypes developed in Strand A
RP2	»Energy Dashboard Web App«	Web app for displaying energy data, modelled after the Energy Inspectors, but provided as a software-based solution
RP3	»Energy Data Visualization App«	Web app employed as a support tool to rapidly collect feedback on various methods of presenting energy data

Table 3.1: This table presents the artifacts developed as part of the supporting infrastructure (SU) and research prototypes (RP) throughout Research Strand A. SU1–3 were designed to support user studies (see A.I in Figure 3.1), while RP1–3 represent research prototypes created to address research questions and collect user feedback (see A.II in Figure 3.1)

We regard these artifacts and software applications as (scientific) contributions or project outcomes, as they embody knowledge and ideas that are not merely conveyed through text but realized in tangible products. Within the framework of RtD, designed artifacts are not merely outcomes of a process but are themselves central to the generation and communication of knowledge. This perspective is well established in HCI and design research, where it is recognized that research contributions can be embodied in the form of artifacts, what Zimmerman et al. refer to as design exemplars. These artifacts capture complex design reasoning, reflect situated problem-solving, and manifest hypotheses about how the world could be. As such, they can offer unique insights that may not be fully expressible through textual description alone.

This view is further supported by Bardzell et al. (2015)[78], who argue that knowledge in RtD is often "immodest", emerging through entangled, materially grounded design practices that exceed conventional propositional forms. Similarly, annotated portfolios (Gaver et al. 2012)[79] have been proposed as a means of articulating and reflecting on the knowledge embedded in designed artifacts.

3.3.1 A.I Supporting Infrastructure for Running User Studies

As stated above, at the very beginning of the project (M1), no energy data from the EDDIE framework and no demonstrators were available. Hence, to quickly commence research on UX and BE, a supporting infrastructure was developed that included everything necessary to initiate early user studies and design explorations.

Test-Data API (SU1): As T7.2 started from M1, no energy data were available at the beginning of the project, particularly since access to such data was planned to be implemented only in later project phases. Consequently, for testing and preparatory purposes, a lightweight supporting software component was developed that imitated a very limited set of functionalities of an energy data space, primarily focusing on the provision of energy data.[80] Using an API, energy data could be retrieved through one of our development servers. The trick was that this data had, of course, been generated beforehand and uploaded to the server. This approach allowed us to prepare synthetic data, including timestamps, for controlled user studies. By calling a corresponding URL, the 'current' data (according to the timestamp) could then be retrieved. In other words, the API delivered data up to the current point in time, but not data that, according to its timestamp, lay in the future. Such data was withheld by the Test-Data API for later use, when its time has come.

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[78] Bardzell, J., Bardzell, S., Forlizzi, J., Zimmerman, J., & Antanitis, J. (2015). Immodest proposals: Research through design and knowledge. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (pp. 2093–2102). Association for Computing Machinery.
[79] Gaver, W., & Bowers, J. (2012). Annotated portfolios. Interactions, 19(4), 40–49.
[80] We developed two versions of the Test-Data API, led by M. Nacewicz and F. Lanznaster. Running version of Test-Data API: https://flo.cosylab.at/authentication/signup/
Documentation: https://flo.cosylab.at/docs/Test_Data_API_Nacewicz.pdf
Source code: https://git01lab.cs.univie.ac.at/maximilian96/test_data_web_app
Documentation 2nd version: https://flo.cosylab.at/docs/Test_Data_API_Lanznaster.pdf
Source code 2nd version: https://git01lab.cs.univie.ac.at/florianl64/bachelorarbeit

User Interaction Logger (SU2): A second tool we needed for our studies was software to log user interactions[81]. While comparable commercial solutions already exist, we wanted a tool that, firstly, was tailored precisely to our requirements and, secondly, ensured that the logged user data would not end up on a company server outside the EU. The principle of the User Interaction Logger we developed is straight forward: first, a new study is created within the corresponding web app. Then, various parameters are specified, such as which user interface elements are included in the software under study. Finally, URLs are generated, which can be integrated into the software being examined at the appropriate points. Whenever a user triggers a function, this is registered via the URL and logged in a database. The logged interactions can then be exported from the web app, for example, as a CSV file for later analysis.

Wizard of Oz App (SU3): The Wizard of Oz App[82] can be considered the manual counterpart to the Test Data API. While the latter provided synthetic data via an API for test applications where the data could then be displayed, the Wizard of Oz app allowed for direct manipulation of the test application's displays and LED lights. Of course, this does not work for all test applications; the Wizard tool was specifically implemented for the Energy Inspectors, a series of applications for energy visualization, which we will examine in the next subsection (see Figure 3.3). Wizard of Oz is a widely used concept, particularly in user studies. The idea is that the system being tested does not need to be fully implemented; instead, a human (the 'wizard') operates invisibly in the background, making changes to the system without the test user noticing. This creates the illusion that the system being tested is fully functional, without the need for the investment required to fully program it. We built such a tool for the applications or prototypes presented in the following sections.

3.3.2 A.II Research Prototypes Addressing Research Questions

To investigate the UX and BE of energy-driven services, we developed custom applications. This approach offered full control over the design and functionality, enabling us to translate specific hypotheses into targeted prototypes. In turn, these prototypes allowed us to directly explore defined research questions. The following paragraphs briefly outline their core features, while the later studies' section (A.III) provides further details on their evaluation.

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[81] Documentation Logger: https://flo.cosylab.at/docs/Interaction_Logger2_Noessing.pdf & https://flo.cosylab.at/docs/Interaction_Logger_Noessing.pdf
Source code: https://git01lab.cs.univie.ac.at/noessingm31/interaction-log
[82] Source code: https://flo.cosylab.at/docs/Wizard_App_Code_Rana.tar.gz

Energy Inspectors (RP1): The Energy Inspectors[83] were a group of three tangible devices designed to display energy data (see Figure 3.2). All of them were compact, making it easy to bring energy data into living spaces without being intrusive. The Energy Stick was a rectangular, magnetic device that visualized energy consumption using multicolour lighting. It was battery-powered and could be attached to a refrigerator or a magnetic board thanks to its magnetic underside. The Energy Peephole was also magnetic, and battery powered. However, it did not feature lighting but instead had a small round display that could be viewed through a peephole, showing electricity consumption. The Energy Notifier was like the Energy Peephole, but it had an illuminated casing to colour-code information.

Figure 3.2: The Energy Inspector devices (RP1): Energy Peephole, Energy Stick, and Energy Notifier

The motivation and design idea behind all three devices was to provide simple ways to display energy data, which was expected to become more easily accessible through projects like EDDIE. Figure 3.3 shows an illustrative use case for the Energy Inspectors.

Additionally, within the framework of WP7, these devices served as research tools, allowing us to experiment with different visualizations of energy data. Within Research Strand A, these

[83] Documentation including source code and 3D models: https://flo.cosylab.at/docs/Energy_Inspectors.pdf

devices could display energy data via the Test Data API (SU1) or the Wizard of Oz App (see description for SU3 above and Figure 3.4).

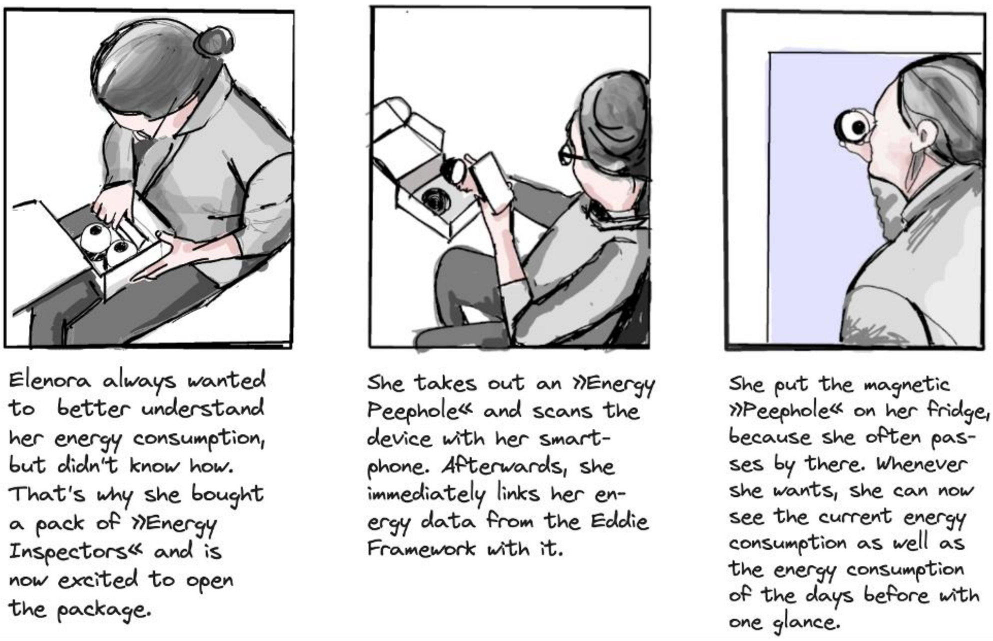

Figure 3.3: Storyboard illustrating the Energy Inspectors in use (Energy Peephole)

Energy Dashboard Web App (RP2): The Energy Dashboard Web App [84] was a virtual replication of the Energy Inspectors, offering the same functionality as its tangible counterparts. We implemented this conventional screen-based application to enable comparisons between software-only solutions and tangible devices (see study section A.III).

Energy Data Visualization Web App (RP3): The Energy Data Visualization Web App[85] was a lightweight application that enabled users to upload energy data in CSV format and explore it through a range of graphical representations. It served as a demonstration tool to showcase the potential of energy data visualizations and to gather participant feedback on different visual styles. It was used to test run trials and refine visualizations that were later presented to participants in our confirmatory survey study (A.IV; see further below).

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[84] For details, refer to:
https://flo.cosylab.at/docs/Impact_of_Energy_Displays_Geisselmann.pdf
[85] Documentation Vis.-App:
https://flo.cosylab.at/docs/Visualization_Webapp_Konduri.pdf

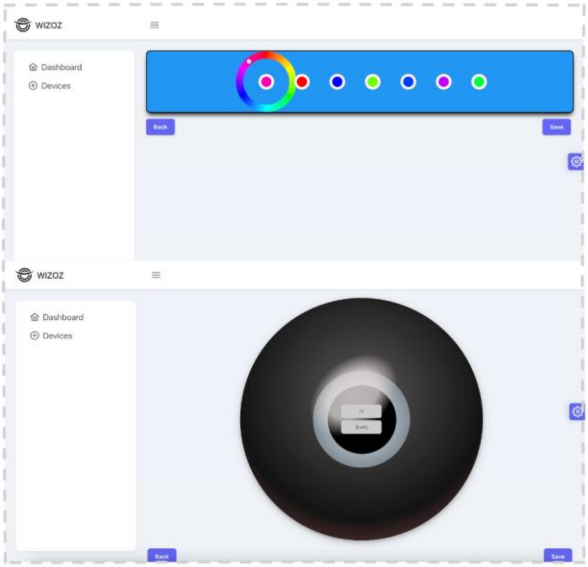

Figure 3.4: Wizard of Oz App (SU3) for manually adjusting Energy Inspector (RP1) devices. The two screenshots illustrate setting the right LED of an Energy Stick to red (top) and manually updating the display of an Energy Peephole (bottom)

3.3.3 A.III and A.IV: User Studies

As shown in Figure 3.1, there were two types of user studies conducted in the later stages of Research Strand A, utilising the previously described infrastructure and prototypes. Initially, we carried out a series of more open-ended explorations (Figure 3.1: A.II - EX1-EX4). Based on these experiences, we then conducted a more targeted confirmatory survey (Figure 3.1: A.IV - SUR).

Table 3.2 provides an overview of all user studies conducted as part of Research Strand A. On the following pages, we will briefly outline these studies. For detailed results, we refer to the attached online sources (footnotes). Subsequently, we will present the BEUX.energy Framework, which consolidates the insights gathered from all studies conducted as part of Research Strand A. This framework provides empirically grounded design recommendations for energy-based services regarding UX as well as BE mechanisms.

Energy Inspector Configurations (EX1 - Participatory Design Exploration): Once the Energy Inspectors were introduced as 'blank canvases', the key question became what should be 'drawn' on them, that is, how these devices could be meaningfully used to represent energy data. With their built-in technical capabilities, they could be customized through tailored firmware. In this initial study[86], conducted in close collaboration with four participants

[86] Details: https://flo.cosylab.at/docs/Energy_Inspectors_Configurator_Tuschek.pdf

following a Participatory Design approach, we explored potential uses for the Energy Stick, Energy Peephole, and Energy Notifier. The outcome was a web application that allowed for configuring the devices' behaviour, for instance, by adjusting the colour mapping, such as which colours the Energy Sticks should display in response to different levels/amounts of energy consumption. Unlike the Test Data API, this tool did not provide synthetic data; instead, it defined how the Energy Inspectors should react to real-time input.

Exploring Energy Data on Small Displays (EX2 - Participatory Design exploration): In our digitally connected era, small, computer-driven screens have become a natural part of everyday environments. The Energy Peephole and Energy Notifier leveraged this familiarity by using compact 240 × 240-pixel displays to communicate energy consumption data. In a dedicated Participatory Design study[87], we engaged five participants in iterative co-design sessions to explore how energy data could be meaningfully visualized within the constraints of such small displays. The goal was to develop representations that were not only informative, but also accessible and aesthetically appropriate for domestic settings.

ID	Study	Description	Study Type	N
EX1	»Energy Inspector Configurations«	Participatory design process for the implementation of a web app for configuring the Energy Inspectors	Participatory Design Study / User-centred Design workshops	4
EX2	»Exploring Energy Data on Small Displays«	Exploration of different visualizations for energy data on small displays	Participatory Design Study / User-centred Design workshops	5
EX3	»Evaluating the Impact of Energy Displays Inspired by Behavioural	This was a field study that systematically investigated a range of variables and mechanisms inspired by BE.	3 weeks field study	6

[87] Details: https://flo.cosylab.at/docs/Small_Displays_Viazihin.pdf (German)

	Economics on Promoting Sustainable User Behaviour: A Field Study«	It represents one of the key scientific contributions of Research Strand A, offering empirical insights into how behavioural factors shape energy-related practices in everyday life.		
SUR	»Understanding People Understanding Energy Data«	A survey study that investigated some of the key observations from the preceding exploratory studies (EX1–EX4) using a larger sample (quantitative research).	Survey	98

Table 3.2: User studies conducted as part of Research Strand A (N=Number of participants). Studies 1-4 were exploratory (EX1-4), while study 5 was confirmatory (SUR). See also Figure 3.1.

Field study of applied principles from Behavioural Economics (EX3 – Field Study): This represents the main study[88] conducted using the Energy Inspectors. Many of the prior reports on the supporting infrastructure and prototypes were ultimately aimed at enabling this field study, which involved six participants over a duration of three weeks (see Figure 3.5 to get an impression of a deployment in natural settings). As can be inferred from these numbers, this was a qualitative research design aimed at exploring in-depth principles of Behavioural Economics[89] using Energy Inspectors.

[88] Details: https://flo.cosylab.at/docs/Impact_of_Energy_Displays_Geisselmann.pdf
[89] See e.g. Frederiks et al. (2015)

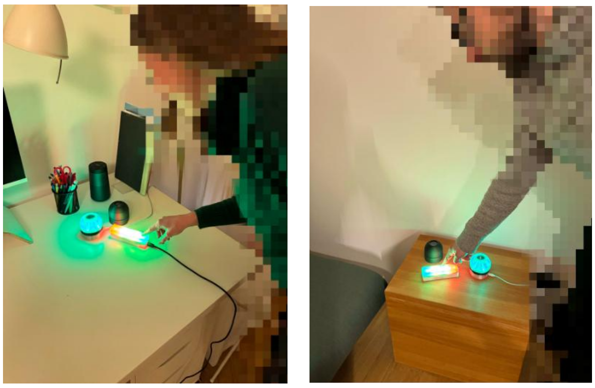

Figure 3.5: Participant interacting with Energy Stick after the devices haven been set up at their home

The Energy Inspectors were set up to explore five design features grounded in Behavioural Economics theories. These features were systematically adjustable, allowing for the testing of five variables:

- **units of measurement for energy costs**: CO2 emissions vs. Cents/Euros
- **update rate**: 1 hr vs. 4 hrs vs. 24 hrs updates of information
- **social comparison**: comparison of consumption with peers vs. with national average
- **framing**: gain vs. loss (information can be framed positive and negative ways)
- **modality of feedback**: tangible devices (Energy Stick, Peephole, Notifier) vs. screen-based apps

In other words, over the course of the three-week field study, the way information was displayed systematically changed. For example, in one week, consumption costs were represented in Euros, while in another week, they were expressed as CO2 emissions. We logged the interactions with our software described above and (synthetic) energy data was provided using our API (SU1). In this way, we were able to obtain valuable information regarding the participants' experience with the devices and reactions to the different design features inspired by BE.

A thematic analysis of this information including three interviews per participant (18 interviews total) led to the diagram displayed in Figure 3.6.

Broadly speaking, the illustration captures how the Energy Inspectors were initially able to draw the participants' attention (theme: »Building Awareness of Energy Use«). Many of them were not aware of their energy consumption at all. Over the course of the study, new behaviours began to emerge (theme: »Building New Energy Habits«), and by the end of the three weeks, we were able to observe signs of a more lasting behavioural change (theme: »Maintaining Energy Consumption Habits«).

The field study, in addition to the presented diagram, provided valuable insights, which were incorporated into the BEUX.energy Framework (A.V) that will be presented later. At this point, it is worth noting that our participants revealed differing attitudes toward money and environmental protection (indicated by subthemes »Moral Obligations vs. Financial Priorities« and »Savings Should Pay Off« in Figure 3.6). This observation inspired the development of a survey study, which we will introduce next section.

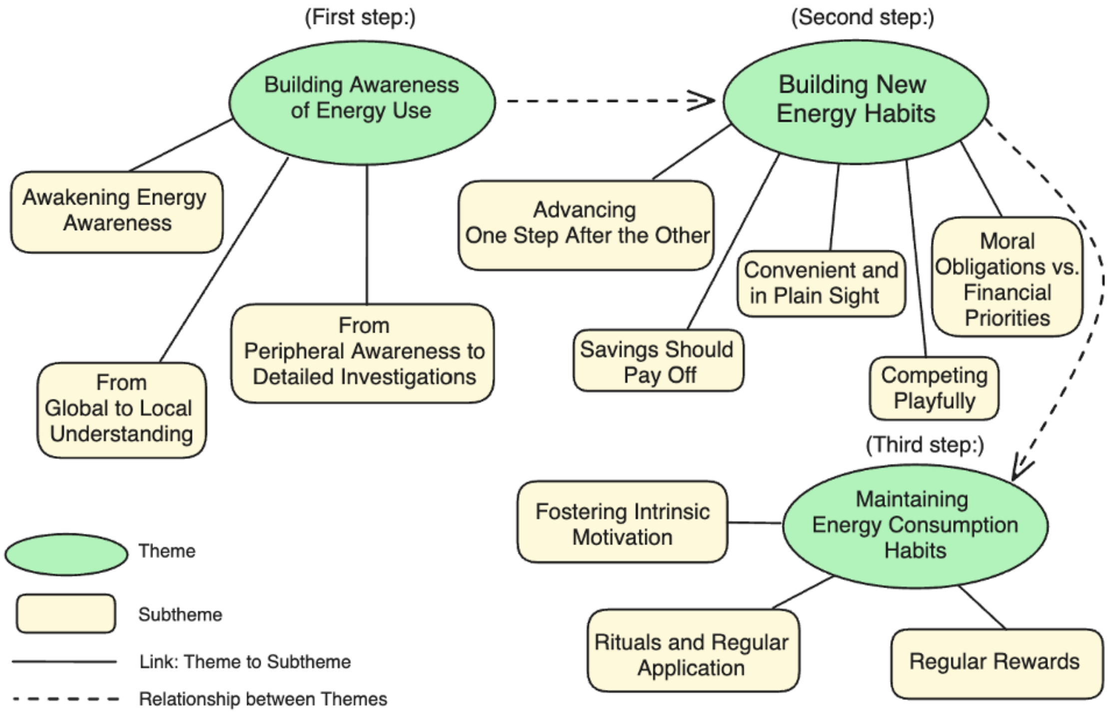

Figure 3.6: Findings from the field study displayed as a diagram from a thematic analysis

Understanding People Understanding Energy Data (SUR - Survey): Following the insights gained during the exploratory stages (EX1-EX4), we developed a survey[90] to also conduct confirmatory research. It aimed to quantitatively examine specific aspects and variables that had stood out in the exploratory phase. To this end, the survey consisted of several thematic sections, each of which had been informed by patterns and themes identified in the preliminary studies. This included, among other things, the variables or design elements that

[90] https://flo.cosylab.at/docs/Survey_Study.pdf

were identified as important in EX3 (units of measurement for energy costs, update rates, social comparison, framings, modality of feedback; see above):

- *General Information and Demographics*: We collected basic contextual information about participants, including their interest in reducing electricity consumption, primary motivations for saving energy (e.g., cost, environmental concern, curiosity), current methods used to track energy use (such as provider apps, smart meters, or none), household composition, age, and gender.
- *Understanding and Interpreting Energy Data Visualisations*: Participants were asked to interpret different types of data visualisations, including bar charts (e.g., identifying days with high consumption), line graphs (e.g., spotting usage patterns), and more detailed visualisations breaking down consumption into categories such as appliances or lighting (see, e.g., Figure 3.7). We also gathered feedback on the clarity and perceived usefulness of these visual formats. Moreover, we asked them about their perceived cognitive load. It should be noted, however, that the present survey (SUR) was not intended as fundamental research on data visualization per se. There already exists a rich body of scientific literature on this topic. Rather, our intention behind these tasks (that is, the examination of different types of visualizations) was to encourage participants to engage with the subject matter during the survey, become increasingly familiar with it, and mentally immerse themselves in it.

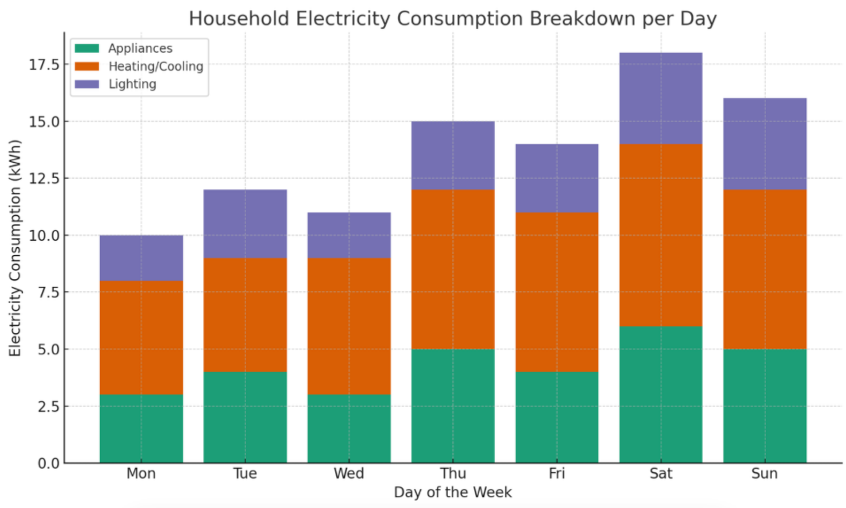

Figure 3.7: One of the graphs presented in the survey

- *Preferences for Visualisation Styles*: This section explored participants' reactions to playful, artistic, or metaphorical visualisations of energy use (see Figure 3.8). Questions focused on the emotional and motivational impact of such styles, their aesthetic appeal, and whether participants would consider such representations suitable for daily use. Additionally, we asked about preferred levels of initial detail (overview vs. fine-grained data) and general design preferences (e.g., minimalist vs. artistic).

- *Preferences for Interacting with Energy Data and App Features*: We explored participants' desires regarding potential features of an energy feedback application. Topics included interest in setting energy-saving goals, comparing usage with others, real-time updates, tracking long-term trends, receiving actionable advice, and exploring energy data through interactive elements such as zoom or scroll functions.

"Low Energy Comsumption"⟶"High Energy Comsumption"

Figure 3.8: A metaphoric visualization of energy use.

The more energy is wasted, the worse the climate in the picture (taken from the survey SUR)

- *Personality and Personal Preferences*: To explore potential connections between personality traits and preferences in data interaction or design, we included items assessing characteristics such as openness, conscientiousness, trust, emotional stability, and artistic inclination (as operationalized by the "Big Five": BFI-10 (Rammstedt at al., 2014)[91]). Additional questions addressed environmental attitudes (Nature Relatedness: NR-6 ,Nisbet at al., 2013)[92] and materialistic values (Material Values Scale: MVS-9 (Richins at al., 2004)[93]).

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[91] Rammstedt, B., Kemper, C. J., Klein, M. C., Beierlein, C. & Kovaleva, A., (2014). Big Five Inventory (BFI-10). Zusammenstellung sozialwissenschaftlicher Items und Skalen (ZIS).

[92] Nisbet, E. K., & Zelenski, J. M. (2013). The NR-6: A new brief measure of nature relatedness. Frontiers in Psychology, 4, Article 813. https://doi.org/10.3389/fpsyg.2013.00813

[93] Richins, M. L. (2004). The Material Values scale: Measurement properties and development of a short form. Journal of Consumer Research, 31(1), 209–219. https://www.jstor.org/stable/10.1086/383436

- *Survey Experience Feedback*: Finally, we asked participants to reflect on their experience of completing the survey, particularly regarding the ease of understanding the English-language questions and their attentiveness and seriousness during participation. We also included a few extremely simple items in the survey to detect inattentive or careless responding.

Results[94]: We invited 136 computer science students to participate in the survey. A total of 99 students accepted the invitation. After excluding one response that was clearly not completed seriously (self-reported lack of seriousness, etc.), we included 98 valid questionnaires in the final analysis.

Overall, participants showed a strong preference for clear, functional, and pragmatic approaches. Most respondents did not actively track their energy use, and those who did typically relied on smart home systems or apps provided by their energy suppliers. Saving money was the most frequently mentioned motivation, followed by environmental reasons and general curiosity.

Traditional bar charts were rated as the clearest and most effective visualization format, while metaphorical representations (such as landscapes that wither or flourish depending on energy efficiency) elicited mixed reactions. Although some participants found such designs emotionally engaging, many perceived them as aesthetically unappealing or potentially uncomfortable.

When it comes to app features, respondents favoured practical tools like device-level breakdowns, time-zooming options, access to past data, and minimalist visual design. In contrast, playful or socially comparative elements were met with low enthusiasm. Participants expressed stronger interest in features that provide actionable saving tips or educational content about the energy system, whereas artistic or highly visual displays were seen as less useful.

Regarding feedback and motivational framing, users responded most positively to monetary feedback and personalized goal-setting options. Cost transparency was highly valued, while stress-inducing or punitive feedback was viewed sceptically. Everyday analogies (such as comparing energy savings to a "load of laundry") were considered more intuitive than abstract units like kilowatt-hours or CO_2 equivalents. Gain-framed messages ("save up to

[94] https://flo.cosylab.at/docs/Survey_Study_Results.pdf

€0.55 per day") were substantially more motivating than loss- or environment-focused framings.

Psychometric analyses revealed that Nature Relatedness was the most consistent predictor of pro-environmental motivation and openness toward expressive visualizations. Participants with higher ecological orientation were more likely to appreciate metaphorical feedback and to express stronger energy-saving intentions. Material values, particularly the "Success" dimension, showed weak positive links to aesthetic appreciation of metaphorical visuals, whereas Conscientiousness was negatively associated with both materialism and interest in symbolic displays. Other personality traits from the Big Five showed no systematic effects.

In summary, users prefer energy feedback systems that are transparent, data-driven, and easy to interpret. While a smaller subgroup with stronger environmental identity is receptive to more metaphorical or emotionally rich formats, the majority favours a grounded, straightforward, and cognitively efficient presentation style.

3.3.4 A.V Integrative Design Framework (BEUX.energy Framework)

Design frameworks serve as valuable tools within disciplines like UX and HCI, synthesising research insights into actionable guidance for practitioners. They translate knowledge gained from a series of specific studies into more transferable concepts that can inform future design processes. In this report, we introduce the BEUX.energy Framework, specifically developed to support the design of user interactions with energy consumption data. This framework emerges from a thematic synthesis of findings gathered across the studies, including (field) studies and iterative design explorations with prototypes, conducted within Research Strand A.

Thematic Synthesis (Thomas at al., 2008)[95] is a method used to integrate findings from multiple qualitative studies. It involves identifying recurring concepts and themes across the dataset (in this case, our study notes, participant feedback, observations, and design reflections) and drawing them together to create higher-order interpretations. Recognising that our insights stem from these in-depth, context-rich explorations rather than large-scale quantitative surveys (except for SUR), the BEUX.energy Framework does not offer universal rules or prescriptive solutions. Instead, it presents a series of design lenses (i.e., the analytical

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[95] Thomas, J., & Harden, A. (2008). Methods for the thematic synthesis of qualitative research in systematic reviews. BMC Medical Research Methodology, 8(45). https://doi.org/10.1186/1471-2288-8-45

themes emerged from the thematic synthesis): distinct perspectives or areas of consideration that designers should consciously address when creating experiences around energy data.

These lenses highlight crucial aspects integrating both user experience (UX) and behavioural economics (BE) principles, which influence how individuals perceive, interpret, engage with, and make decisions based on their energy data (Figure 3.9). This data, while increasingly available due to smart metering and connected home technologies, remains inherently abstract and often invisible in everyday life. Our framework specifically focuses on designing interactions for regular end-users (not organisations or experts) engaging with 'pure' energy consumption data largely setting aside the complexities arising from integrating auxiliary data such as energy prices, grid carbon intensity, or source mix. The goal is to provide designers with theoretically grounded, yet practical considerations derived directly from our empirical work, ultimately aiming to foster more effective, engaging, and potentially behaviour-influencing energy data applications.

We go on to describe the framework and its individual design lenses. Each lens begins with a brief definition, followed by key design questions and actionable recommendations. We draw on examples from our Strand A studies to illustrate these, and reference highly influential scientific literature (in subsection theoretical foundations) that deepens or supports the concepts introduced. The design lenses may partially overlap, as certain design aspects inherently intersect or influence multiple lenses.

Lense 1: Sense-Making – Understanding & Mental Models

Definition:
Focuses on how users interpret and understand energy data. Clarity, cognitive load, and the alignment with users' prior knowledge are key. This lens supports insight and orientation.

Design Questions:
- Is the information clear and intuitive?
- Does it fit how users already think about energy (mental models)?
- Can users adjust the level of detail or explore as needed?

Recommendations:
- Use familiar visual forms (e.g., bar charts for appliance usage).
- Add contextual cues (e.g., "Your fridge uses as much energy as 3 TVs").
- Offer drill-down options for curious users.

Examples from Strand A studies:

- Participants rated bar charts as “very clear” (57 × “very clear”, 25 × “clear”) and reported low mental effort (M = 2.03, SD = 1.11) when interpreting standard visualizations.
- Participants strongly valued features like: “[Show] which devices contributed to total consumption” (M = 4.28), “Scroll through past data” (M = 4.16), “Zoom into data (e.g., 8:00–9:00)” (M = 4.10)

Theoretical foundations:

- Mental Models (Norman, 1983)[96]: Users develop internal representations ("mental models") of how systems function. Designs that align with or help users build accurate mental models facilitate better understanding and interaction, reducing errors and improving ease of use.
- Cognitive Load Theory (Sweller, 1988)[97]: This theory posits that human working memory has a limited capacity. Instructional or informational designs should minimize extraneous cognitive load (complexity not essential to the task) to free up resources for understanding the information and integrating it with prior knowledge.

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[96] Norman, D. A. (1983). Some observations on mental models. In D. Gentner & A. L. Stevens (Eds.), Mental models (pp. 7-14). Lawrence Erlbaum Associates.

[97] Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. Cognitive Science, 12(2), 257-285.

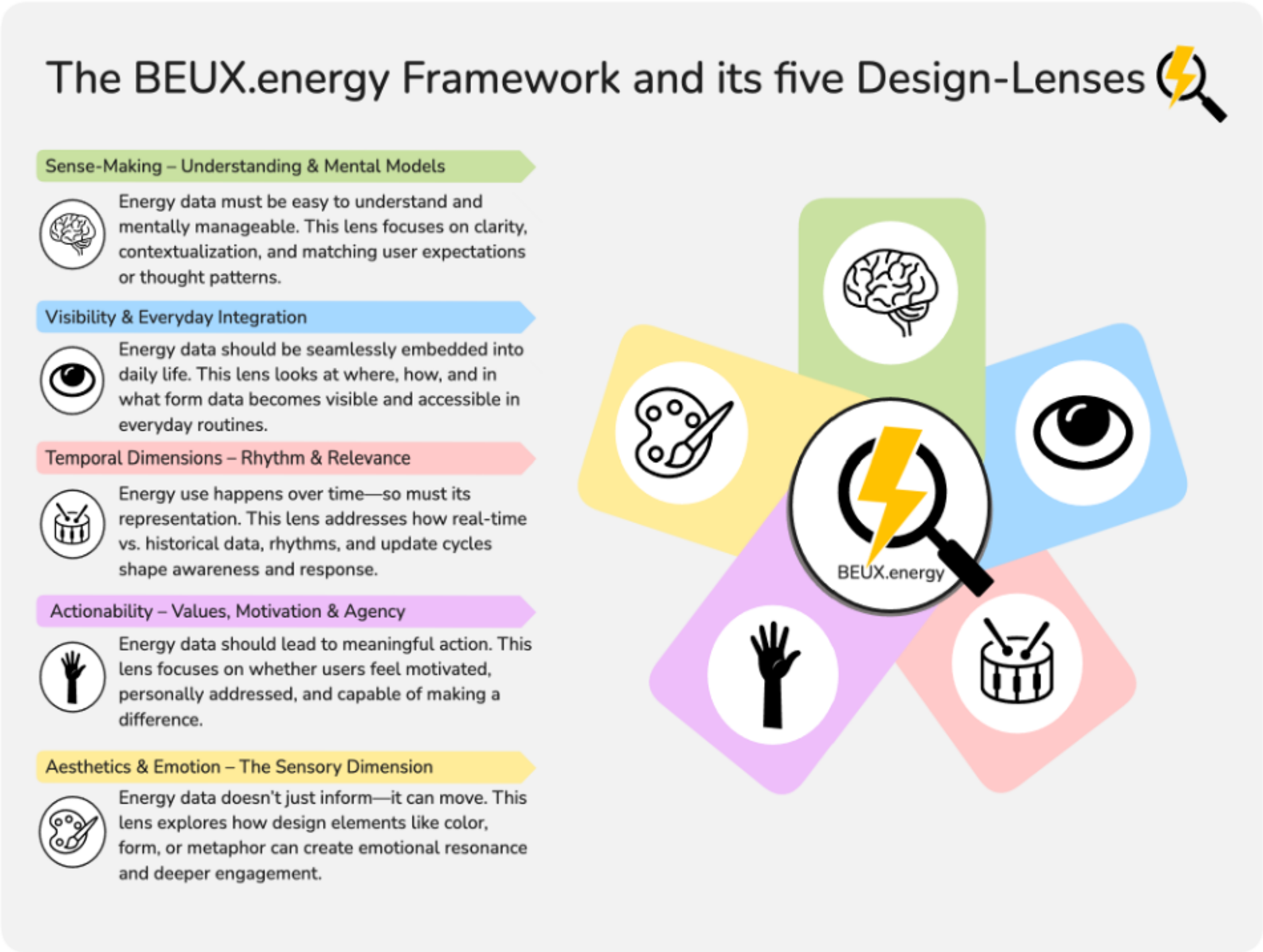

Figure 3.9: Overview of the BEUX.energy Framework

Lense 2: Visibility & Everyday Integration

Definition:

Covers how energy data become present in daily routines through physical or digital integration. Focuses on visibility, ambient presence, and access across contexts.

Design Questions:

- Where and when do users encounter the data?
- Is the representation ambient or attention-seeking and is that appropriate?
- Is it accessible in different contexts?

Recommendations:

- Use subtle ambient indicators (e.g., colour-changing lights).
- Ensure “glanceable” displays for hallway or kitchen use.

- Integrate into existing devices (e.g., on the fridge, smart mirrors, thermostats).

Examples from Strand A studies:

- The Energy Inspectors were designed and experienced as visible, tangible presences that brought energy data into everyday awareness. The constant presence of the devices and the daily seeing of them contributed to building awareness. Previously, the participants neither had easy access to energy data nor were they visible.
- "[The Energy Inspectors] were in the hallway, so they were the first thing I saw when entering or leaving the apartment. This really made it part of my daily routine to automatically check the devices."

Theoretical foundations:

- Ubiquitous Computing (Ubicomp) (Weiser, 1991)[98]: This vision describes the integration of computing into the environment and everyday objects, making technology pervasive yet unobtrusive. Energy data displays embedded in the home exemplify this concept, aiming for seamless interaction.
- Ambient Information Systems (Mankoff at al., 2003)[99]: These systems are designed to present information in the user's periphery, allowing for awareness without demanding focused attention. Subtle changes in light, sound, or movement can convey information like energy consumption levels.
- Tangible User Interfaces (TUIs) (Ishii at al., 1997)[100]: TUIs give physical form to digital information, enabling users to interact with data by manipulating physical objects or representations. This can make abstract concepts like energy flow more concrete and intuitive.

Lense 3: Temporal Dimensions – Rhythm & Relevance

Definition:

Addresses the role of time: real-time vs. historic, update frequencies, and patterns. It considers how temporal framing influences perception and behavioural response.

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[98] Weiser, M. (1991). The Computer for the 21st Century. Scientific American, 265(3), 94-104.
[99] Mankoff, J., Dey, A. K., Hsieh, G., Kientz, J., Lederer, S., & Ames, M. (2003). Heuristic evaluation of ambient displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 169–176). Association for Computing Machinery.
[100] Ishii, H., & Ullmer, B. (1997). Tangible Bits: Towards seamless interfaces between people, bits and atoms. In Proceedings of the ACM SIGCHI Conference on Human factors in computing systems (CHI '97) (pp. 234-241). ACM.

Design Questions:

- Which timeframes are relevant for the user?
- Are data updates well-timed and meaningful?
- Are temporal patterns clearly visualized?

Recommendations:

- Highlight change over time (e.g., trends, peaks).
- Allow zooming between time scales (e.g., day/week/month).
- Use rhythm-based visual metaphors (e.g., pulse, waves).

Examples from Strand A studies:

- Real-time visual spikes in an app led some users to turn off lights immediately, but others felt overwhelmed by the constant updates.
- Several participants remarked that immediate updates could make the app "feel more alive" or "more motivating," while historical views were valued for reflection and progress tracking. The balance between instant and retrospective information thus proved critical to perceived usefulness.

Theoretical foundations:

- Feedback Loops in Learning and Behaviour Change (Darby, 2006)[101]: Providing timely and relevant information about the consequences of one's actions (feedback) is fundamental for learning and adjusting behaviour. For energy, this can range from immediate feedback on appliance use to longer-term summaries.
- Goal Setting Theory (Locke at al., 1990)[102]: This theory posits that specific and challenging goals, when accompanied by regular feedback on progress, lead to higher performance and motivation. Historical energy data is crucial for setting savings goals and tracking achievements.
- Temporal Discounting (Thaler, 1981)[103]: A Behavioural Economics principle where people tend to value immediate rewards or outcomes more highly than equivalent future ones. This makes real-time energy feedback potentially very impactful but also highlights challenges in motivating actions for long-term (discounted) benefits.

[101] Darby, S. (2006). The effectiveness of feedback on energy consumption. A review for DEFRA of the literature on metering, billing and direct displays. Environmental Change Institute, University of Oxford.
[102] Locke, E.A., & Latham, G.P. (1990). A theory of goal setting & task performance. Prentice-Hall.
[103] Thaler, R.H. (1981). Some empirical evidence on dynamic inconsistency. Economics Letters, 8(3), 201-207.

Lense 4: Actionability – Values, Motivation & Agency

Definition:
Explores how visualizations lead to meaningful action. Focuses on motivation, personal relevance, and whether users feel capable of acting on the data.

Design Questions:
- Is it clear what the user can do?
- Are the actions relevant and achievable?
- Is the framing empowering?

Recommendations:
- Link data to concrete, small-scale actions.
- Use goal setting or challenges (e.g., “Save 5% this week”).
- Frame positive outcomes (e.g., money saved, CO_2 avoided).

Examples from Strand A studies:
- During usability testing, several participants expressed a desire for translating data into specific behavioural suggestions. One participant noted: “If I see that the water kettle uses a lot, I would use it more consciously.”
- A recurring comment concerned the need for progress tracking rather than static data: “I would like to know whether I am doing better than last week.”

Theoretical foundations:
- Self-Determination Theory (Ryan at al., 2000)[104]: This theory of motivation emphasizes the importance of fulfilling three innate psychological needs: autonomy (control over one's actions), competence (feeling effective and capable), and relatedness (feeling connected to others or values). Designs that support these needs can enhance intrinsic motivation for energy-saving behaviours.
- Theory of Planned Behaviour (Ajzen, 1991)[105]: Posits that behavioural intention is the key determinant of behaviour, and this intention is shaped by attitudes towards the

[104] Ryan, R.M., & Deci, E.L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. American Psychologist, 55(1), 68–78.
[105] Ajzen, I. (1991). The Theory of Planned Behavior. Organizational Behavior and Human Decision Processes, 50(2), 179-211.

behaviour, subjective norms (perceived social pressure), and perceived behavioural control.

- Prospect Theory (Kahneman at al., 1979)[106]: This theory from behavioural economics describes how people make decisions involving risk and uncertainty. A key insight is "loss aversion": losses tend to have a greater psychological impact than equivalent gains. Framing energy use as a loss (e.g., "money wasted") may be more motivating for action than framing savings as a gain.

Lense 5: Aesthetics & Emotion – The Sensory Dimension of Energy Data

Definition:
Highlights the emotional and sensory impact of data presentation. Goes beyond function to engage users through beauty, metaphor, and mood.

Design Questions:
- Does the design evoke an emotional reaction?
- Are aesthetic elements meaningful and intentional?
- Could metaphor or artistic form enhance engagement?

Recommendations:
- Avoid overloading with sterile technical charts.
- Visualize data as emotional landscapes, not just numbers, when appropriate
- Still: a clean, simple design might be most appropriate for most users

Examples from Strand A studies:
- Respondents favoured "clean, minimalist aesthetics" (M = 4.01), showing sensitivity to visual tone even in functional contexts.
- Qualitatively, they appreciated visual calmness and clarity over sterile technical overload.
  But minimalist design is not for everyone. Interestingly, those higher in Nature Relatedness and in MVS Success again showed significantly more interest for playful and emotional visualizations.

[106] Kahneman, D., & Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. Econometrica, 47(2), 263–291.

Theoretical foundations:

- Emotional Design (Norman, 2004)[107]: Argues that design influences user experience and behaviour on three levels: visceral (appearance and sensory appeal), behavioural (pleasure and effectiveness of use), and reflective (interpretation and personal meaning). Effective energy interfaces should consider all three.
- Aesthetic-Usability Effect (Tractinsky at al., 2000)[108]: This effect describes the phenomenon where users perceive aesthetically pleasing designs as more usable, regardless of their actual underlying usability. Attractive energy displays may thus foster greater engagement and perceived ease of use.
- Persuasive Technology (Fogg, 2003)[109]: This field studies how computers and technology can be designed to influence users' attitudes or behaviours in a planned way, without coercion or deception. Aesthetics and emotional design are important components in making technology persuasive and motivating.

The BEUX.energy Framework provides a structured approach for designers navigating the complex space of personal energy data interaction. By considering these five lenses derived from our explorations in Research Strand A, we believe designers can create energy applications that are not only informative but also more engaging, empowering, and effective in supporting users' goals, whether they be financial, environmental, or knowledge driven. This framework is a starting point, intended to evolve as our understanding of the human experience with energy data deepens. We encourage its use as a tool for reflection, ideation, and evaluation in the design process. It should not be understood as a prescription or a rigid set of rules.

3.4 Research Strand B – Innovation & Data Integration

Digitalized and shared energy data are powerful drivers of innovative business models. The range of possible applications becomes almost limitless when combined with other data sources. The demonstrators developed as part of WP6 illustrate the rich possibilities through their diversity. In Research Strand B (see Figure 3.10), we examine three of these demonstrators in search of patterns and models to inspire future use cases and business ideas. We start with an external perspective (outside view - OV, looking at how companies

[107] Norman, D. A. (2004). Emotional design: Why we love (or hate) everyday things. Basic Books.
[108] Tractinsky, N., Katz, A. S., & Ikar, D. (2000). What is beautiful is usable. Interacting with Computers, 13(2), 127-145.
[109] Fogg, B. J. (2003). Persuasive technology: Using computers to change what we think and do. Morgan Kaufmann Publishers

present their offerings and ideas to the outside world. From there, we will turn our focus inward and accompany the development of the demonstrators by the consortium partners (WP6), observing the developers closely (inside view – IV as well as EV2 and EV3).

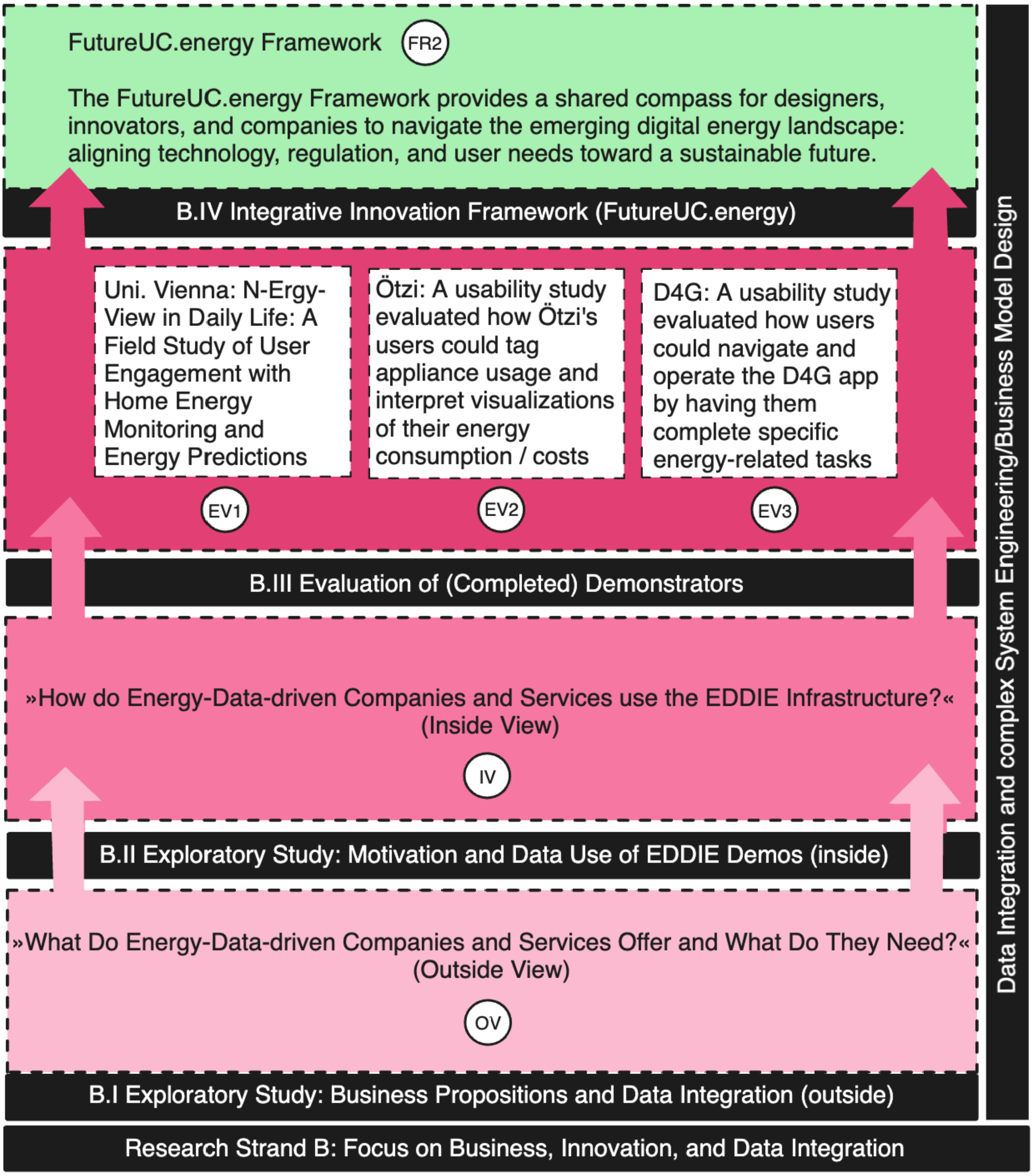

Figure 3.10: Overview of Research Strand B. For further explanations, also refer to Table 3.3 and the encircled labels.

ID	Study	Description	Study Type	N
OV	Outside view (OV) on how energy-data-driven companies present their products and services	Examination of how companies communicate their goals, challenges, and business propositions related to energy data	Analysis of company presentations and stakeholder interviews	10
IV	Inside view (IV) on the internal development of energy-data-driven services	Investigation into how services based on energy data are implemented within companies	In-depth interviews with developers and key employees	5
EV1	Evaluation of the demonstrator of the University of Vienna: »N-Ergy View« (WP6)	A field study and survey of N-Ergy View, an energy monitoring and analysis application, designed to help households understand and manage their energy consumption through, among other things, interactive visualizations	Field study and survey (total 27 participants)	27
EV2	Evaluation of the demonstrator of Ötzistrom (WP6)	We conducted a usability study to evaluate the app of Ötzistrom. Prior to that, we were actively involved as co-designers in the development process, which	Usability tests, co-design	11

		allowed us to gain a deep understanding of the app's inner workings and functionality. The app, enables users to tag their energy usage and visualizes this data through interactive charts that display consumption, costs, and usage trends over time		
EV3	Evaluation of the demonstrator of D4G (WP6)	We carried out a usability study to assess the D4G user interface. Having previously participated as co-designers in its development, we had already gained a thorough understanding of the app's structure and functionality. Its purpose is to empower homeowners with distributed energy resources to actively participate in the energy flexibility market by providing a transparent, user-friendly platform.	Usability tests, co-design	7

Table 3.3: User studies conducted as part of Research Strand B (N=Number of participants).

3.4.1 B.I Outside View on How Energy-Data-Driven Companies Present Their Products

The objective of this task was to gain a well-grounded overview of the general problem space to start off Research Strand B. This included understanding the business models of data-driven enterprises, identifying their target customers and the value propositions offered, exploring their data utilization strategies, and considering relevant data types beyond energy data.

To gather this information, selected companies were invited to present their business ideas in a 20-minute presentation followed by a Q&A session. A total of five presentations were held: two by consortium members and three by external firms. The session took place in a hybrid format (on-site and online), with invitations distributed in advance.

The entire presentation session was video recorded to enable later review by a broader audience and to ensure accessibility beyond the live event. These recordings were subsequently transcribed for further analysis.

In addition, a major energy provider (independent of the project consortium) was later brought in to provide further insights. Following the event, we conducted interviews with five employees in key positions at this company. These interviews were audio-recorded (after obtaining written informed consent), transcribed, and added to the overall dataset.

In total, ten transcripts (five presentations plus Q&A and five interviews) were analysed using a qualitative, thematic analysis approach, following the method described by Braun and Clarke (as outlined above).

The analysis surfaced several compelling themes and insights, many of which would merit a dedicated presentation. However, due to space constraints and the structural design of Research Strand B, these findings will be presented at a later stage, once all collected data have been consolidated within the FutureUC.energy framework. That consolidated presentation will also provide further details on participating organisations and individuals.

3.4.2 B.II Inside View on the Internal Development of Energy-Data-Driven Services (IV)

As the project progressed and developers from the consortium partners intensified their work with the EDDIE framework, we conducted additional rounds of interviews, this time with technical staff and developers from the participating companies (WP6). The aim of these interviews was to gain a clearer understanding, particularly from a technical perspective, of the types of data required to implement their business ideas and demonstrators.

The focus extended beyond energy data to include all other types of information that would need to be integrated to bring the envisioned services into practical use. We were particularly interested in understanding what the EDDIE framework would need to deliver from the perspective of these developers: what functionalities they required, what expectations they had, and whether they identified any current limitations or areas for improvement.

Interviews were conducted iteratively: new sessions were arranged if they continued to yield new insights with respect to our research questions. The process continued until a point of thematic saturation was reached, where additional interviews no longer brought substantial new findings.

As with the earlier round of interviews, all conversations were recorded (with consent), transcribed, and analysed following the thematic analysis approach by Braun and Clarke (as described above). While the findings from these interviews are insightful and touch on important technical and strategic questions, they will be presented and contextualized at a later stage, once the various data sources have been consolidated within the overarching FutureUC.energy framework.

3.4.3 B.III Evaluation of (Completed) Demonstrators

We focused on the evaluation of three demonstrators that became available sequentially over the course of the project: one from the University of Vienna (WP6), one from Digital4Grids, and one from ÖtziStrom. What was particularly interesting about the latter two demonstrators was that they initially were not conceptualized to include a user interface for end users in the conventional sense. Digital4Grids was primarily engaged in optimising processes around the flexibility market and had not planned a direct end-user interface. The same applied to ÖtziStrom; here, too, the focus was on processes rather than interfaces or the end-user experience.

Nevertheless, both companies expressed strong interest in exploring user interface concepts. Thanks to the good relationship between the University of Vienna (WP7) and the two companies, a decision was made to jointly develop applications with these partners and to evaluate them in the process. A key advantage for the evaluation was that this approach allowed for deep integration into the entire design process, including its conceptual background, rather than evaluating finished applications in isolation. In fact, the entire design process at these two partners was scrutinized. In the literature, such an approach is often referred to as Research through Design, a method that had already been applied in Research Strand A.

In summary, after reviewing the project's progress and in close coordination with the partners, we planned and conducted three evaluations of (completed) demonstrators: one from the University of Vienna (EV1), one from Digital4Grids (EV2), and one from ÖtziStrom (EV3).

Evaluation of Uni Wien's Demonstrator "N-Ergy View" (EV1)

To evaluate the "N-Ergy View" demonstrator (version September 2025), the study was built on two complementary pillars. One pillar consisted of three exploratory interviews that provided in-depth qualitative insights into users' perceptions, expectations, and potential usability issues[110]. The other pillar was a structured online survey[111] (n=24 respondents) addressing a broader sample to quantitatively assess perceptions of usefulness, environmental awareness, privacy attitudes, and willingness to pay. Insights from both components together offered a comprehensive understanding of user experience and acceptance. All participants were recruited among informatics students from the University of Vienna.

Key Features of N-Ergy View: The demonstrator "N-Ergy View" is an energy monitoring and analysis application designed for households (see Figure 3.11). Its main goal is to help users better understand, manage, and potentially reduce their energy consumption. N-Ergy-View offers a range of features aimed at increasing transparency, motivation, and environmental awareness around energy use. Users can explore their historical energy consumption through interactive visualizations, including charts that show data at quarter-hourly or hourly intervals. These graphs support zooming and exploration for a more detailed view of usage patterns.

In addition to monitoring, the app provides predictive analytics powered by a machine learning model. This includes daily energy consumption forecasts at various resolutions (quarter-hourly, hourly, and daily), designed to gently nudge users toward more energy-conscious behaviour by encouraging them to stay below forecasted values. Alongside this, cost predictions are generated based on dynamic electricity prices, helping users anticipate next-day expenses.

To support cost management, N-Ergy-View integrates real-time dynamic electricity prices (EUR/MWh) from the European EPEX Spot Exchange via the Awattar API. Users can compare these dynamic rates with their own fixed energy tariffs. The app then calculates and presents potential savings, making it easier for households to assess the benefits of switching to a dynamic pricing model. Visualizations focus not only on kilowatt-hours but also on monetary

[110] https://flo.cosylab.at/docs/N-Ergy-View_Interview_Guideline.pdf
[111] https://flo.cosylab.at/docs/N-Ergy-View_Survey.pdf

values (e.g., EUR/day), which users often find more relatable and impactful when reflecting on their energy habits.

Finally, the app raises environmental awareness by estimating each household's carbon footprint, based on the national energy mix and emission factors. Users can view how their energy consumption translates into environmental impact (kg CO_2-equivalent per kWh) and track the composition of the national energy mix, including the share of wind, solar, and fossil fuel sources. This enables environmentally conscious users to adjust their energy use during times when cleaner sources are more prominent.

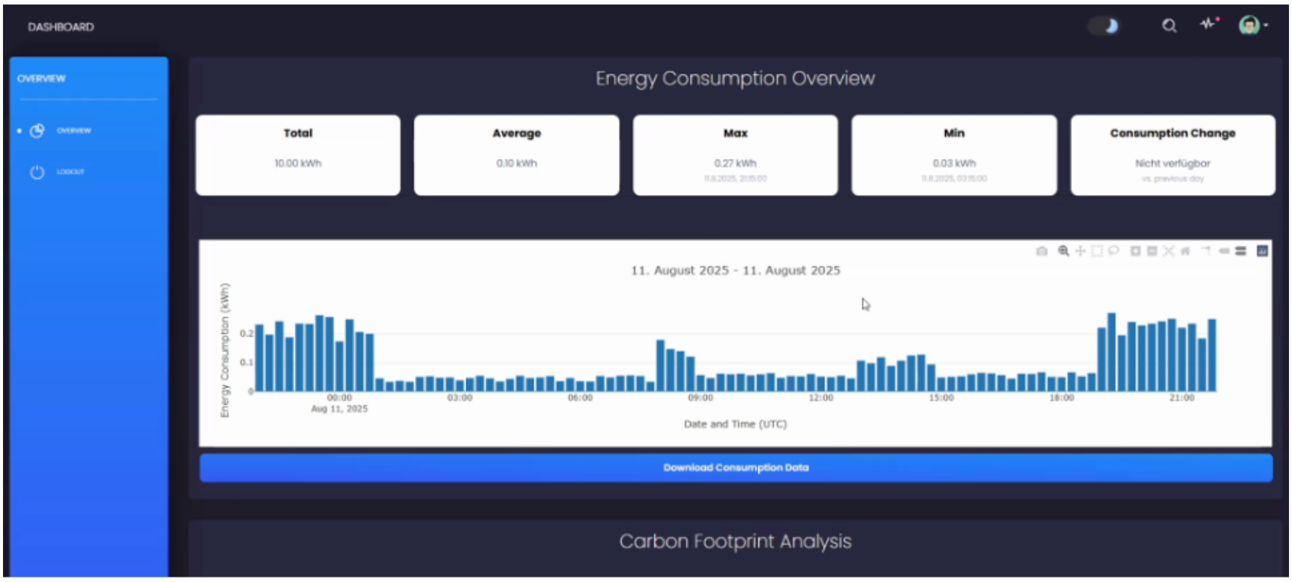

Figure 3.11: N-Ergy View's home screen

Summary of the Interview Study about N-Ergy View: The following thematic analysis draws upon participant feedback (n=3)[112] regarding the N-Ergy View app, the data sharing process facilitated by the EDDIE framework, and general attitudes toward energy consumption and data control. Three overarching themes emerged: User Experience and Application Utility, Trust and Data Governance, and Data Value and Motivation. We go on to report each theme.

Theme 1: User Experience and Application Utility

The first theme centres on participants' experiences with the N-Ergy View application and its perceived utility. Regarding onboarding simplicity and technical friction, participants described the initial process of granting data access as straightforward and quick, typically

[112] 12 people agreed to participate in a field trial, however due to technical limitations, N-Ergy View worked fully only at three households at the time of the evaluation.

taking only a few minutes. As P1 explained, "I believe it took only about two to five minutes until everything was confirmed." However, occasional technical frictions created uncertainty, particularly delays in data loading and difficulty locating the official Smart Meter opt-in controls at the Distribution System Operator (DSO) level.

In terms of the value of consumption visualisation, participants highlighted the motivating and informative role of core functionalities such as key performance indicators (total, average, minimum, and maximum consumption). These indicators helped them link consumption peaks to specific household activities (e.g., running the air conditioner or washing machine). As P2 noted, "I found it very interesting to see the total consumption as well as the maximum and minimum values, since such values are rarely found in normal bills."

With respect to feature enhancement and clarity, participants proposed several improvements to increase the app's practical value. They suggested including comparison graphs that overlay predicted (forecasted) and actual consumption and adding explanatory elements (such as tooltips) for complex data points like market prices and CO_2 calculation methods.

Theme 2: Trust and Data Governance

The second theme relates to perceptions of trust, data control, and potential risks around sharing one's energy data. Concerning perceived trustworthiness of actors, participants tended to trust large, well-established, or system-relevant institutions such as DSOs, TSOs, and energy providers. By contrast, newer commercial services or community-based initiatives inspired less immediate trust. The academic and European research nature of the EDDIE project contributed positively to perceived trustworthiness. As P1 explained, "I would trust those [DSO, TSO, Provider] blindly because they are large, long-established, or state-secured."

Regarding data control and ownership, participants expressed a clear desire for ongoing and dynamic control over their data. They wanted the ability to stop data sharing or revoke access at any time and preferred to manage such permissions directly within the Energy View app, as it represented the most accessible and user-friendly interface. As P2 stated, "I would already want to do it in the app."

When addressing risks of data misuse, participants voiced concerns about two primary issues: commercial exploitation and personal security. They feared that consumption data might be used for targeted advertising or reveal behavioural patterns such as when a household is unoccupied. As P3 warned, “Companies could recognize high consumption (e.g., for an air conditioning system or an e-car) and place advertisements accordingly.”

Theme 3: Data Value and Motivation
The third theme explores participants’ perceptions of data as an asset and their motivations for engaging with the application. Under data as currency and trade-off, participants described their data as a form of “currency” or “good.” They understood data sharing as a conscious exchange, providing access to their data in return for valuable services such as visualisation and analysis. As P1 summarized, “I definitely see data as currency, which is sometimes worth a lot.”

Finally, in terms of drivers for engagement, financial incentives were the strongest motivator for behavioural engagement. Participants appreciated the opportunity to compare fixed tariff costs with potential savings through dynamic, market-based pricing. While environmental awareness and CO_2-related information were seen as meaningful, they were perceived as less immediate motivators. As P2 put it, “The function itself is very helpful and tangible, especially to see the savings potential […]. This is a huge motivator.”

Survey about N-Ergy View
This following report summarizes responses from 24 participants regarding perceptions of the N-Ergy View app. Before completing the questionnaire[113], participants were given a comprehensive demonstration of the app using pre-prepared data from a small household (rather than their own). The survey included demographic questions (age, gender) and 14 Likert-scale items (Q1-Q14) covering usefulness, environmental awareness, privacy concerns, and willingness to pay (see table below).

The age: ranged from 23 to 35 years (Median ≈ 26): 17 Male, 6 Female, 1 No answer

Descriptive Results: Table 3.4 presents the mean and standard deviation (SD) for each survey item (Q1–Q14). Scores were measured on a 1–5 scale (1 = strongly disagree, 5 = strongly agree).

Key findings: Highest agreement was observed for Q10 (“I can withdraw consent at any time”) and Q11 (“I would use the app if free of charge”) with means of 4.33.
Strong support also emerged for Q9 (explicit consent) and Q5 (combination of data beneficial).

[113] https://flo.cosylab.at/docs/N-Ergy-View_Survey.pdf

Lowest agreement appeared for Q8 (not worried about data sharing, M = 2.58) and Q12 (willingness to pay a monthly fee, M = 2.83).

Responses on Q14 (one-time payment) showed the largest variation (SD = 1.52), suggesting divergent views.

Item	Question (shortened)	Mean	SD
Q1	Visualization of historical energy consumption is useful	4.21	0.83
Q2	CO_2 emissions view helps me understand environmental impact	3.75	0.94
Q3	Comparing fixed vs. dynamic tariffs is helpful	4.00	0.93
Q4	Forecast motivates me to adjust usage	4.08	1.02
Q5	Combination of data (consumption, emissions, pricing) is beneficial	4.21	0.88
Q6	No concerns about app processing my smart meter data	3.38	1.06
Q7	Important that data is not shared with third parties	4.04	1.20
Q8	Not worried about app sharing data with third parties	2.58	1.25
Q9	Important to explicitly give consent before data is processed	4.29	0.81
Q10	Important to withdraw consent at any time	4.33	0.87
Q11	I would use the app if it were free	4.33	0.82

Q12	Willing to pay a small monthly fee	2.83	1.31
Q13	The value provided justifies a reasonable fee	3.00	1.25
Q14	I would consider a one-time upfront payment	3.17	1.52

Table 3.4: Descriptive statistics of survey items (Q1–Q14).

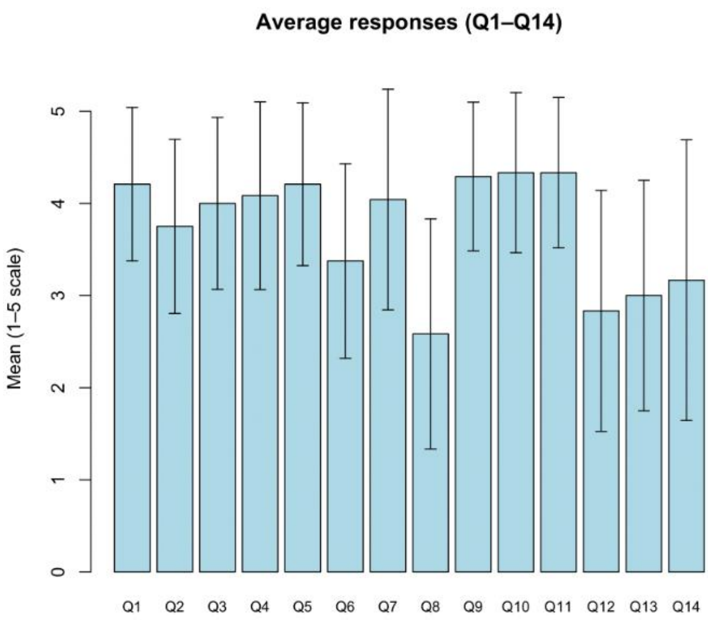

Figure 3.12: Average responses with standard deviations for Q1–Q14.

Overall, participants found the application features highly useful, especially regarding data visualization and privacy safeguards. However, monetization remains a barrier: while most participants would use the app for free, there is clear reluctance toward subscription fees. These insights suggest strong potential uptake if the app is positioned as a free or low-cost tool, with privacy protections emphasized.

Evaluation of ÖtziStroms's Demonstrator (EV2)

The development of the ÖtziStrom demonstrator was carried out as a co-design process between WP6 and WP7. Rather than evaluating a finished prototype, both teams collaborated closely throughout the design and implementation phases. This joint approach allowed WP7 researchers to contribute user-experience and behavioural-design expertise, while WP6 provided the technical foundation and domain knowledge.

The resulting demonstrator is a web application (version May 2025) designed to help end-users gain a detailed understanding of their household energy consumption. Its core concept involves users "tagging" the operational periods of their appliances, either in real-time or by manually entering usage times, which then enriches interactive energy consumption graphs with specific device-level data. This process aims to empower users to better understand their consumption habits and identify ways to use energy more efficiently, for example, by revealing cost implications of energy-intensive activities. Simultaneously, the app generates precise usage profiles for energy providers, enabling them to optimise energy procurement and enhance operational efficiency.

As of May 2025, the demonstrator was largely implemented; however, data integration had not yet been completed. Due to time constraints, we decided to evaluate the demonstrator using dummy data, that is, synthetic consumption data that was loaded into the web application to enable usability testing. This allowed end users to explore the data and provide qualified feedback.

We structure the report on this evaluation as follows: First, we describe the core features of the ÖtziStrom demonstrator. Next, we present feedback received from a representative of ÖtziStrom. We then outline the setting of the lab testing. Following this, we summarize key usability issues that were identified. Finally, we present the results of a qualitative analysis based on interviews conducted with participants during and after their interaction with the demonstrator[114].

Key Features of ÖtziStrom's (SEV) Demonstrator:
User Account and Profile Management: The system allows users to register and log in with a unique email and password and manage their user profile.

Personalized Dashboard: Users are greeted by a dashboard providing an at-a-glance overview. It features widgets for current total energy consumption, associated running costs, and percentage changes in consumption and cost compared to previous periods. The dashboard is designed to load with the most important data and graphs.

Energy Usage Logging ("Tagging"): Users can log the operational periods of their appliances, a process referred to as tagging.

[114] For more details, refer to https://flo.cosylab.at/docs/Oetzistrom_Details_Tircob.pdf

This can be done by activating or deactivating a device within the app in real-time or by manually inputting start and end times for past usage sessions (see Figure 3.13). The goal of tagging is to enrich energy consumption graphs with detailed information about the composition of that consumption, making the resulting picture clearer. The system calculates energy usage in kilowatt-hours (kWh) based on these logs and the predefined power consumption of each device.

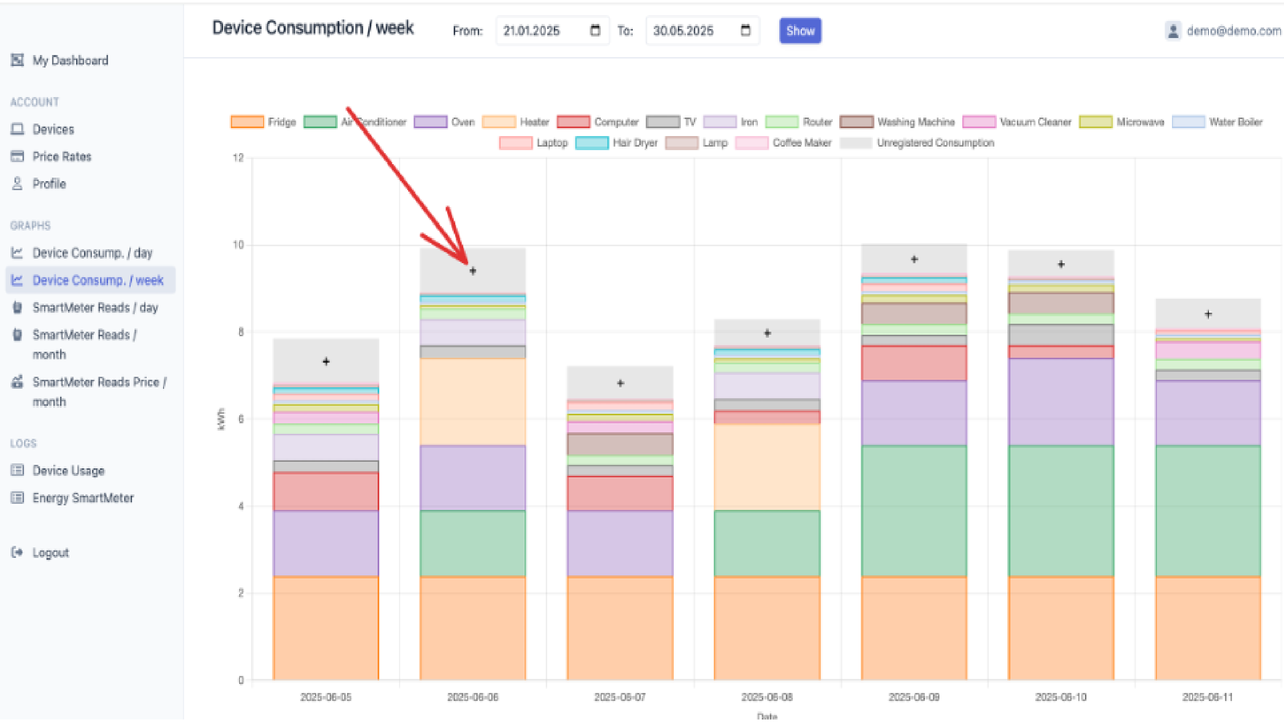

Figure 3.13: Bar diagrams representing energy consumption as implemented in ÖztiStrom's demonstrator (version May 2025). Each bar corresponds to the consumption of a single day. Clicking the "+" symbol (see arrow) allows the user to further specify (or "tag") the details of this area, i.e., which devices contributed to the energy usage.

Interactive Data Visualization: Energy consumption data is presented through a suite of interactive charts and graphs. Users can visualize their consumption patterns across different timeframes. This includes the ability to identify peak consumption times, examine energy usage by selecting or deselecting individual devices within the graph views, and see an overview of total energy consumption from a smart meter feed.

Device Management: Users can manually add, view, edit, and delete household devices including specifying their name and power consumption in watts. There is also functionality to add a predefined list of standard devices.

Energy Price Rate Management: The application includes a module for inputting and viewing varying energy price rates such as day, night, and evening tariffs. This allows users to understand the cost implications of energy-intensive activities at different times.

Data Integration Capability: Although the prototype used simulated data during development (in May 2025), the system is designed to support data import via APIs from platforms like EDDIE or smart home devices such as Synapsi. This is intended to enable a continuous measurement of total household consumption.

Ötzistrom's Own Judgement of Their Demonstrator:
The COO of Ötzistrom described their demonstrator as a gamechanger with the potential to solve key challenges for both customers and the energy provider. According to him, the app would significantly enhance customers' understanding of their electricity consumption by offering real-time, device-level insights. It would encourage self-reflection and support behavioural changes, such as shifting high-consumption activities to cheaper time periods. Transparency and education were described as central benefits, with the app offering a level of detail previously unavailable to most end users.

From the energy provider's perspective, the COO emphasized that the app would enable improved forecasting of energy demand through fine-grained consumption data. This, in turn, could lead to more efficient and cost-effective energy purchasing. He also noted that the insights generated by the app could be used to advise customers more effectively, for example by identifying inefficient appliances. Furthermore, he pointed out that the tool could serve as a foundation for innovative business models such as gamification elements or dynamic pricing. In summary, the COO sees the app as a valuable resource for reducing operational costs while strengthening customer engagement and service quality.

Description of Study Setting: The usability evaluation of the ÖtziStrom demonstrator was conducted as a controlled lab study using a semi-structured interview framework. Sessions were held either online or onsite, depending on participant availability and location. Online sessions were conducted via Zoom. During each session, participants were asked to share their screens. Audio and screen recordings were made to capture their interactions and feedback. Participants were encouraged to think aloud while completing the tasks, describing their actions, expectations, and any confusion they encountered. Each session lasted on average 55 minutes, with a duration ranging from 35 to 70 minutes.

The study involved ten end-user participants. They were recruited through convenience sampling from the researchers' personal network. The group included participants from

Austria, Romania, Italy, Germany, and the United Kingdom. Their ages ranged from 26 to 32 years, with an average age of 31. Most participants (70 percent) reported using smart home devices and generally indicated a high level of comfort with technology, averaging 4.5 out of 5 on a self-assessment scale. For most participants, the main motivation for energy saving was financial, specifically the desire to reduce costs.

Participants were guided through 14 distinct usability tasks, which corresponded to items 22 to 35 in the interview guideline[115]. These tasks were designed to assess participants' ability to navigate the application, use its main features, and understand energy consumption information. The tasks addressed several areas including account creation and profile management, device management (adding, editing, deleting devices), usage logging through tagging, dashboard exploration and trend recognition, smart meter data interpretation and peak usage identification, interactive graph analysis (e.g. identifying high-consumption devices), and exploration of additional visualizations. All participants provided signed informed consent before participating in the study. The data gathered from the sessions was primarily qualitative and analysed using thematic analysis.

Identified Usability Issues: The qualitative analysis of the transcripts revealed several salient issues related to the demonstrator's usability. Participants encountered various problems when interacting with the app, such as not understanding certain features, being unable to locate them, or misinterpreting their function. In the following, we report the most notable issues identified during the study.

Issues with Device Creation and Predefined List Management (items 23 and 26): A consistent pain point during device creation (item 23) was users not knowing the power consumption in Watts of their devices. When adding predefined standard devices (item 26), some users (P3, P5, and P7) were unsure if they could select one device or if all were added by default, stating comments like "Should I check all of them or some of them?"

Issue with Real-time and Manual Usage Logging (item 24): Some users (P2, P3, and P4) had minor confusions about whether the "Active" state referred to "currently in use" or to an "active device in the household inventory". P4 remarked: "I would understand it's an active device which is still in the apartment." The overall requirement for repeated manual logging was consistently highlighted as a significant deterrent to long-term use.

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[115] https://flo.cosylab.at/docs/Oetzistrom_Guideline.pdf

Issues with the Dashboard (items 28, 29, and 30): Key dashboard figures like "Current Consumption" and "Running Price" were sometimes difficult for users to locate immediately or were perceived as too small. Users also expressed a desire for more information or tooltips for elements like the "Smart meter reads overview".

Issues with Interactive Graph Analysis (items 33 and 34): The clickable nature of labels for filtering devices in graphs was not always immediately obvious. Colour differentiation in stacked bar charts for devices was sometimes problematic (P5 suggested using icons). Suggestions for improving graph tooltips included reordering the information or showing only the hovered item (P9), and P4 wanted click-to-filter behaviour. P2 expressed a preference for price information to appear directly on consumption graphs instead of having to navigate to a separate page.

Beyond Usability - The Broader Use Value of Ötzistrom's Demonstrator:
The most revealing insights uncovered through the evaluation did not primarily concern usability issues within the demonstrator's interface. Rather, they offered a broader perspective on the user experience, highlighting deeper expectations, assumptions, and contextual factors that shape how users engage with energy data and digital tools in general. This section explores four key themes (see Figure 3.14) that emerged from the user interviews, going beyond specific usability issues to examine the broader value users associate with the Ötzistrom demonstrator. These themes reveal what users consider important when engaging with energy-saving technologies.

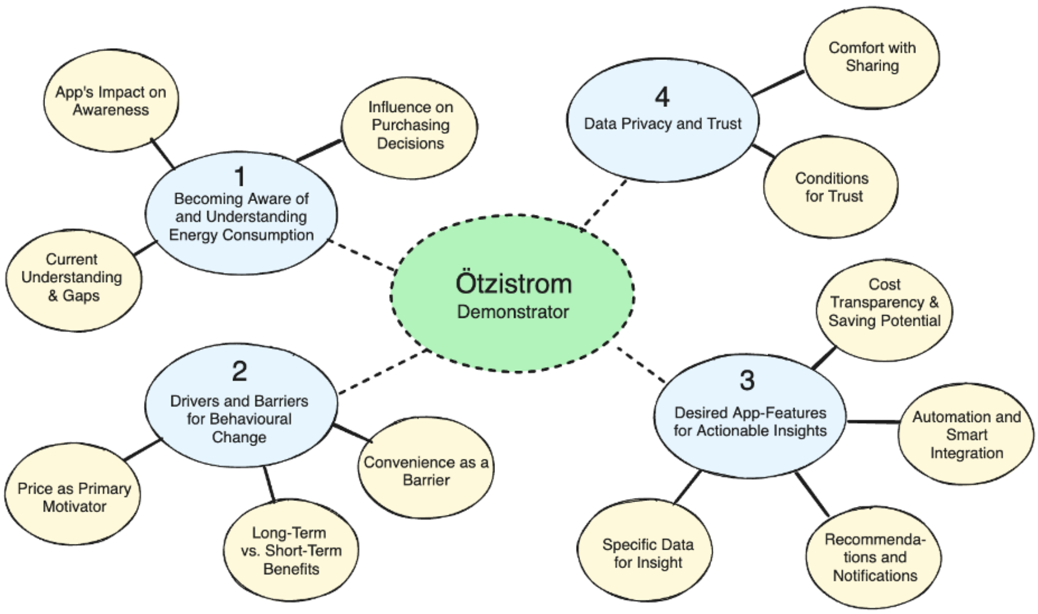

Figure 3.14: Four salient themes (plus sub-themes) emerged from the interviews about the Ötzistrom demonstrator.

Theme 1: Becoming Aware of and Understanding Energy Consumption. Participants generally had only a basic understanding of their energy usage, often based on confusing annual bills. They lacked insight into what devices used how much energy and when. The app helped increase awareness and understanding by making energy use more visible and concrete. Users reported that the app made them think more carefully about their consumption and consider behavioural changes. Some participants were also influenced to think about future appliance purchases, opting for more energy-efficient models based on what they learned through the app.

Theme 2: Drivers and Barriers for Behavioural Change. Saving money was the most important driver for behaviour change. Participants wanted to understand their exact costs and were willing to shift energy use to cheaper time zones if the app provided this information clearly. Sustainability and environmental protection were also valued, though less strongly than financial incentives. A key barrier was the manual tagging of energy use. Users found this process too demanding and time-consuming for daily life. They strongly preferred automation for long-term use.

Theme 3: Desired App Features for Actionable Insights. Users wanted features that deliver specific, useful insights. Automation was a high priority, such as smart integration that automatically detects and logs appliance use.
They also asked for detailed, device-specific, and time-based consumption data, broken down by cost and usage trends. Cost transparency was crucial. Users wanted clear estimates of what each device costs per hour or day, and how those costs are calculated.
Suggestions and notifications were also requested, such as alerts for cheaper time periods or government programs supporting energy efficiency.

Theme 4: Data Privacy and Trust. Most participants were comfortable sharing their energy data, especially since they felt energy providers already collect this type of information.
However, they wanted clear boundaries. Data should stay within the app and not be shared with third parties. Transparency was essential, and users wanted to see how their data is used, with privacy policies available to review. This reflects a balanced attitude toward privacy, where users are open to sharing data if they understand the purpose and maintain control over its use.

Conclusion: Evaluation of the Ötzistrom Demonstrator. One of the most striking findings was the enthusiastic response from the COO of Ötzistrom, who described the concept of their demonstrator as a potential "gamechanger." This reaction highlights the perceived business value of the application and its potential to enable innovative customer engagement strategies.

Another key insight was the recurring emphasis on saving money as the primary motivator for behavioural change among end users. While environmental reasons were frequently mentioned prior to testing, financial incentives increasingly took centre stage during the usability sessions. Many participants explicitly stated that their main reason for wanting to optimise energy consumption was the potential to reduce costs and better understand their "saving potential".

A further important finding was the resistance to manual data input for long-term engagement. Although the application can deliver detailed insights, the need for users to manually log or tag device usage was consistently flagged as a drawback. Comments such as: "If you have to manually add all the logs, it will be a lot of work for most people." Or "If it was automated… it would be a revolution." illustrate a gap between the current interaction model and user expectations regarding convenience and efficiency in energy management. This underscores the importance of prioritising automation and smart integration in future iterations to support sustained user adoption across a broader audience.

Evaluation of D4G's "Flexibility Dashboard" (EV3)

The demonstrator of D4G is the product of a co-design process between D4G and Univie (WP7), established to generate synergies between (commercial) development and academic insight. The deep integration of Univie throughout the design and development stages allowed for the entire process to be closely monitored and analysed, adopting a methodology closely aligned with 'research through design.' Building on this, the collaborative approach was essential for translating D4G's work into a tangible and 'experienceable' UX. Although their efforts in the EDDIE project centred on elements hidden from the end-user (like backend algorithm design and system logic), the co-design process turned these complex foundations into something perceivable and meaningful within the UX. The demonstrator, an energy flexibility dashboard, is a user-centric application developed for operating in the energy flexibility market. Its primary purpose is to serve as an intermediary platform, connecting end-users (specifically homeowners with distributed energy resources like solar panels, batteries, and EVs) with flexibility providers. The application's core goal is to empower these users by offering a transparent, comprehensive overview of their personal energy ecosystem. It moves beyond simple monitoring by enabling active participation in the energy market. By identifying opportunities to sell surplus energy or provide demand-response services, the dashboard allows users to monetize their assets, effectively transforming them from passive consumers into active market participants who contribute to grid stability while generating personal revenue. We go on to describe the demonstrator's main features as developed during the co-design process.

Key Features of D4G's Flexibility Dashboard: Upon launching the application, the user is greeted by the "Home Dashboard" (see Figure 3.15), which functions as a central hub for at-a-glance information. This main screen provides a real-time snapshot of the most critical metrics, including the fixed purchase price for grid electricity, the feed-in price for exported surplus, and the crucial, dynamic flexibility price, which rewards users for their on-demand support. The dashboard also displays the charge levels of home batteries and EVs, a live breakdown of consumption by major appliances like heat pumps, and a log of recent activities such as PV production cycles. To help users plan, a location-specific weather forecast predicts potential solar energy generation, contextualising the current and upcoming energy situation.

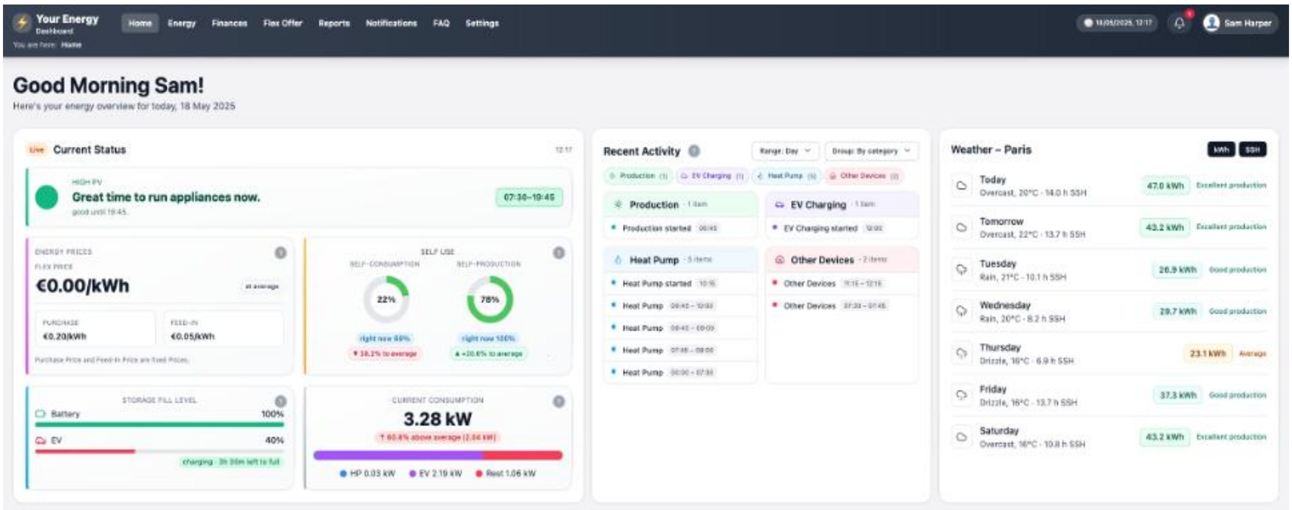

Figure 3.15: D4G's home dashboard (detail view)

For users wishing to delve deeper into their data, the dedicated "Energy Page" offers more granular analytical tools. Here, individuals can review historical data for a specific day, week, or month, examining detailed charts that juxtapose their energy production against consumption. This section clearly visualizes the flow of energy to and from the grid, illustrating periods of grid import and export. Complementing this technical analysis is the "Finance Page", which translates these energy flows into tangible financial outcomes. This area is focused on monetization, detailing the costs of imported energy against the revenue generated from both feed-in tariffs and, most importantly, the premium payments earned from flexibility events.

To ensure users can act on opportunities, the application incorporates a proactive "Notifications Page" that transforms it from a passive monitoring tool into an active assistant. This system alerts users to key events, such as upcoming periods of high solar production, favourable flexibility prices, or direct activation requests from flexibility providers. Furthermore, it provides smart recommendations, suggesting optimal times to run energy-intensive appliances to maximise the use of self-generated power. To support the user's journey and clarify complex topics, the dashboard also includes an integrated "FAQ Page" with definitions and answers derived from direct user feedback workshops.

Evaluation of D4G's Demonstrator: The D4G demonstrator was evaluated through a usability test[116] using synthetic data. It was not possible to study the demonstrator in a natural setting, i.e., within real households in France, because the necessary technical infrastructure to integrate the complex, multidimensional household data streams into the demonstrator was not yet available for this kind of user study.

Seven participants were recruited for the test (see Table 3.5). Participant 1 (25, male, business administration) had advanced technical skills, frequently used digital tools, and was open to flexible energy practices, though his household did not use renewables. Participant 2 (62, male, IT manager) showed advanced skills, monitored energy use weekly, and lived in a renewable energy household. Participant 3 (60, female, banker) had beginner-level skills, rarely used digital tools, but lived in a renewable energy household and consciously reduced consumption. Participant 4 (56, male, sales trainer) had intermediate skills, rarely monitored usage, but his household used renewable energy. Participant 5 (61, male, electrical engineer) showed advanced skills, lived in a renewable energy household, and had experience with dashboards, though his monitoring was irregular. Participant 6 (26, male, software developer) had advanced competence, used dashboards, but his household did not rely on renewable energy. Participant 7 (68, male, retired) combined advanced skills with daily monitoring and renewable energy, representing the highest level of routine engagement.

[116] Full description of the tasks of the usability test as well as the features under test: https://flo.cosylab.at/docs/D4G_Usability_Tasks_Happe.pdf.

ID	Age	Gender	Occupation	Technical Competence
P1	25	Male	MSc in Business Administration	Advanced
P2	62	Male	IT Manager	Advanced
P3	60	Female	Bank Clerk	Beginner
P4	56	Male	Sales Trainer	Intermediate
P5	61	Male	Electrical Engineer (Automotive)	Advanced
P6	26	Male	Software Developer	Advanced
P7	68	Male	Retired	Advanced

Table 3.5: Participant of the usability test of D4G's demonstrator.

Results of the Usability Test: The task performance of P1–P7 was systematically assessed. Each task was categorized as fully solved, partially solved (~, approx. 50% correct), or not solved. These tasks focused on testing how users interact with the D4G energy platform, mainly exploring energy production and consumption data, monitoring connected devices (like EVs, heat pumps, and batteries), and engaging with flexibility features such as setting prices or viewing rewards.

Overall, participants achieved 110 correct answers (71.4%), 29 partial (18.8%), and 15 incorrect (9.8%), which corresponded to an overall success rate of 80.84%. Section averages were 69.39% for 'Homepage & Energy Page,' 88.78% for 'Notifications,' 92.85% for 'Energy & Finance,' and 78.57% for 'Flexibility.' At the individual level, P6 performed best (90.91%), followed by P2 (86.36%) and P5 (84.09%). P7 (79.55%), P4 (78.26%), and P1 (72.73%) formed a mid-group, while P3 showed the lowest score (70.45%). Task 1 served as onboarding and was not scored.

Participants demonstrated very strong comprehension of historical and aggregate information once they reached the relevant pages. Tasks 12–16 (yesterday's situation, weekly consumption/production, profit, buy/sell times, and cost/revenue timing) were completed correctly by all participants (100%). Likewise, Task 23 (identifying todays and yesterday's flexibility actions) reached 100%. Core notification interactions were also robust: checking EV-charge notifications (Task 9) reached 92.86%; adjusting settings (Task 10) 85.71%; and scanning the notification bar (Task 11) 100%. These outcomes suggest that retrospective analytics, KPIs, and message flows were learnable and reliably recoverable across users.

In contrast, three areas emerged as usability pain points. First, rapid situational awareness on the Homepage was uneven. Task 2 (forming a quick view of the current energy status and "next best time" to consume) had a success rate of only 28.57%. Task 3 (understanding the distribution of current consumption by device) reached 35.71%. These results indicate that real-time status cues and device-level context were not immediately legible for several participants, especially P1, P2, and P3. Second, conceptual metrics around self-consumption and self-production (Task 18) were difficult: the success rate was 35.71%, with multiple partial answers. This points to terminology, labelling, or visual encoding that did not fully support quick recall and application. Third, aspects of flexibility configuration were only moderately successful. While participants could identify provider offers (Task 19, 71.43%) and the current flexibility price (Task 22, 71.43%), setting a personal flex price (Task 20) achieved just 57.14%, indicating uncertainty around thresholds and controls.

Other tasks around device and schedule decisions performed well. Participants were highly confident about weather-based production outlooks (Task 6, 92.86%) and EV-related planning and history (Tasks 7 and 8 at 100.00% and 71.43%, respectively). Battery-state queries (Task 17) were mostly successful (85.71%), though a few partial responses suggest opportunities to clarify time resolution or labelling. Data export (Task 21) was also straightforward (92.86%).

In sum, P1–P7 handled historical analytics, notifications, and general navigation effectively, and they could answer EV/battery questions with high accuracy. The main opportunities appear to lie in improving immediate, at-a-glance comprehension on the Homepage (Tasks 2–3), clarifying self-consumption/production concepts (Task 18), and making flex-price configuration more self-explanatory (Task 20). Strengthening these areas should lift performance for the lower-scoring participants and narrow the spread between the top (P6) and bottom (P3) performers, while preserving the strong results observed for notifications and finance/energy summaries.

Findings From the Thematic Analysis: In our thematic analysis of interviews or spoken words during the usability test, we found that the system provided a solid and structured foundation, while at the same time offering several opportunities for refinement. To structure our findings, we organised the results into five themes: linguistic clarity, design and layout, navigation and information flow, informational value, and motivation and interaction.

Regarding **linguistic clarity and comprehensibility**, we observed that elements such as the FAQ section and the “Why it matters” boxes supported understanding effectively. Participants also reported that the menu navigation and the icons were largely intuitive, and they valued the availability of tooltips for on-demand explanations. However, we also noted that technical terms and abbreviations reduced accessibility, and that some tooltips were formulated in a way that made them difficult to use. Legends occasionally caused confusion as well.

In terms of **design, layout, and visual structure**, we found that most participants perceived the dashboard as well organised and not overloaded, even though it contained a high density of information. The use of tiles and the thematic separation of content areas supported orientation, and the colour palette was generally seen as functional. At the same time, some participants wished for a less text-heavy presentation, clearer distinctions in certain charts, and a more responsive layout for small screens.

The theme of **navigation and information flow** showed that participants were generally able to move between sections without difficulty and that the menu structure was considered logical. The home page often served as the main entry point. Nevertheless, several participants described the initial impression as overwhelming. In addition, the boundaries between “Current Status” and subpages were not always clear, back-navigation was sometimes cumbersome, and certain information, such as battery data or dynamic pricing, was not always found in the expected place.

Concerning **informational value** and relevance, we identified a generally positive assessment. After a short period of familiarization, participants considered the dashboard useful for identifying trends and correlations. Weather forecasts and reports were highlighted as particularly practical. At the same time, participants expressed a need for more concrete, action-oriented recommendations, as well as clearer presentation of forecasts in terms of time and units. Many also suggested adding comparisons between predictions and actual outcomes to strengthen trust in the data, and some pointed out that additional context, such as average values or storage capacities, would be helpful.

Finally, regarding **motivation and interaction**, our analysis showed that the presentation of profit values encouraged engagement and created incentives for participation in flexibility mechanisms. Many participants valued the sense of control the dashboard provided. Still, we observed that interaction design could be improved, for example by offering clearer feedback after saving settings, expanding export functions, and enabling more personalization as well as integration into external devices.

In summary, our analysis indicated that the energy dashboard already offered a clear structure, a functional design, and motivating elements that users appreciated. At the same time, the study highlighted specific areas where targeted improvements could reduce initial complexity, simplify language, and provide more actionable and contextualized information. Overall, we consider the system a strong foundation with considerable potential for further optimization.

3.4.4 B.IV Integrative Framework FR2 (FutureUC.energy)

The FutureUC.energy Framework offers a structured synthesis of key themes emerging from qualitative interviews and presentations conducted as part of Research Strand B. Using Braun and Clarke's thematic analysis approach, a diverse range of stakeholder insights (spanning technology providers, utilities, and platform developers) were systematically re-analysed and consolidated into five overarching thematic areas. Table 3.6 shows the different stakeholders or companies represented by the interviewees. The companies from the consortium are mentioned by name, while the identity of the additional external companies and energy providers will not be disclosed. To preserve anonymity, specific identifiers for individuals have been intentionally omitted. Identifying the individuals is not necessary for interpreting or applying the insights offered by the FutureUC.energy Framework.

These themes of this framework reflect both recurring challenges and promising directions for the digital transformation of the energy sector in Europe. Rather than presenting isolated observations, the framework organises the perspectives of practitioners and experts into actionable categories that capture the structural, technical, and social dynamics currently shaping the field. Each theme, ranging from data access and smart meter infrastructure to regulatory complexity and market scalability, represents a core domain of concern and innovation. Together, they outline a multi-layered picture of what might be required to build more interoperable, scalable, and user-centred energy ecosystems across borders.

By framing these insights as a cohesive analytical model, the FutureUC.energy Framework serves as both a diagnostic and strategic tool: it helps stakeholders understand where friction arises and where intervention is most needed to enable a truly digital, inclusive, and flexible energy system in Europe (see Figure 3.16).

ID	Phase	Description of Participant / Participating Organization
P1	B.I	Founder of a company that specializes in digital energy optimization for commercial and public buildings, offering a cloud-based tool that uses smart meter data and third-party API integration to provide automated analysis and prioritized recommendations for reducing energy consumption and CO_2 emissions. With a focus on scalability and accessibility (especially for smaller building owners) the participant monitors a significant share of national electricity use and demonstrates measurable savings through a data-driven approach.
P2	B.I	Co-founder of a small startup focused on empowering households to make smarter energy decisions through a user-centric app. Their app provides live electricity prices, usage notifications, a 7-day price forecast using machine learning, real-time and historical consumption tracking, cost estimates, and insights into the environmental impact of personal electricity use. Built on publicly available energy data, the app helps shift user behaviour toward cheaper and cleaner consumption times. Operating on a freemium model with ads and partnerships, the company gained rapid traction during the 2022 energy crisis and became one of the most downloaded apps nationally by the end of that year.
P3	B.I	Founder of a software company developing SaaS solutions for renewable energy communities and local energy markets. Their platform and app facilitate the digital management of energy communities by automating complex administrative processes and

		enabling coordination with grid operators and authorities. Key features include tariff and invoicing management, KPI monitoring, visualization of hourly energy flows, support for dynamic tariffs, and integration with grid stability monitors. The solution relies on high-quality data from DSOs and TSOs, with the main challenge being data availability and standardization. The company advocates for improved data regulations and aims to expand into mobility-energy integration, gamification, and benchmarking.
P4	B.I	Head of Digital Services of a regional energy provider and infrastructure company with a strong focus on renewable electricity generation, especially hydropower. The company operates large-scale hydroelectric plants and is involved in grid infrastructure, electricity trading, and innovative energy services. It plays a key role in regional energy transition strategies and supports sector coupling through projects in areas such as green mobility, heating, and digitalization. With a strong emphasis on sustainability and regional value creation, the company combines traditional utility expertise with new digital tools to support smart energy use and system flexibility.
P5	B.I	Product Developer of the same regional energy provider and infrastructure company as described above (see P4).
P6	B.I	Head of Measurement Technology of the same regional energy provider and infrastructure company as described above (see P4).
P7	B.I	Energy Data Manager of the same regional energy provider and infrastructure company as described above (see P4).

P8	B.I	Head of Customer Service of the same regional energy provider and infrastructure company as described above (see P4).
P9	B.I + B.II	FlexiDao
P10	B.I + B.II	D4G
P11	B.II	ÖtziStrom/SEV
P12	B.II	ETA+
P13	B.II	Univie (the team of Univie working on WP6)

Table 3.6: Participants involved in interviews, informing the FutureUC.energy framework. These interviews took place either during phase B.I, phase B.II, or during both phases.

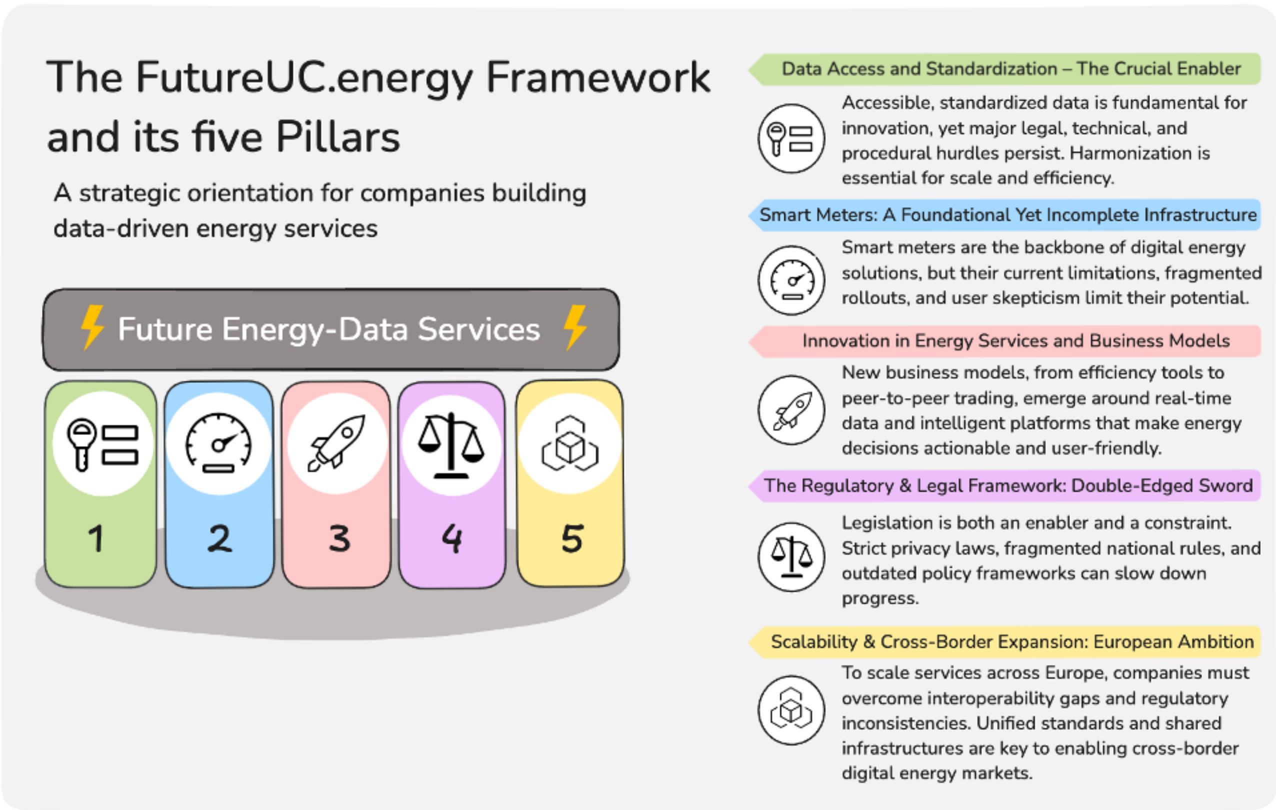

Figure 3.16: The FutureUC.energy Framework and its five Pillars.

The FutureUC.energy Framework defines five essential themes or pillars that companies should address when developing scalable, user-centric services based on digital energy data. These themes/pillars highlight the key technical, regulatory, and market-related dimensions shaping innovation in the energy sector.

Theme 1: Data Access and Standardization - The Crucial Enabler. This overarching theme highlights the critical importance of accessible and standardized energy data for innovation, alongside the significant technical, legal, and procedural barriers currently impeding it.

Sub-theme 1.1: Barriers to Data Accessibility: A recurring frustration among participants is the difficulty in accessing and integrating energy data. P9 points out, "Collecting metering data directly on behalf of clients. This is challenging - we're a software provider, not a data integrator". They emphasize that "Integrating with different systems across regions (e.g. data hubs or DSOs) is time-consuming and resource-intensive". P1 also notes a specific challenge: "In our country, we have a national database controlled by the TSO. If that's not available or systems are distributed, we need standards for data format and access". Furthermore, access to historical data is crucial for building accurate models, but P1 observes, "Some systems only have limited history. This is something we'd like to see improved". The manual nature of consent management also poses a significant hurdle: P9 highlights that "consent management … it's not always digitalized, and in many regions, we still rely on manual authorization letters". From the perspective of utilities, P4, the Head of Digital Services, states that smart meters are "not real-time, onboarding is complicated", limiting the ability to offer granular insights.

Sub-theme 1.2: Need for Harmonization: The consensus among participants is a strong demand for unified data standards. P9 explicitly states a "big need for normalized, validated data sources … and a unified approach would allow us to focus on our core offering". They further ask, "How can we align on a common format, and what are the other companies' needs?". P2, echoes this, asserting that they "need standardized frameworks across Europe for collecting, storing, and accessing energy data". P3 shares this sentiment, expressing enthusiasm for a "European data exchange platform". P10 emphasizes that "CIM-based data exchange is critical. It's standards-based, consent-based, cyber-secured, and compatible with partner apps", and they are frustrated by the "lack of harmonized TSO-DSO data". The goal, according to P10, is "harmonized interfaces enabling revenue stacking" across various market services, as "Currently, every country has its own APIs - a nightmare. The market is completely fragmented".

Sub-theme 1.3: Historical vs. Real-time Data: A significant point of discussion revolves around the granularity and timeliness of data. P5 notes that smart meter data "gets transmitted the next day. So, you're always looking at historical data". While this 15-minute interval data is "legally sufficient" for energy communities, there's a debate for more advanced use cases: "For real-time steering like load shifting or automation some argue we need real-time data". P4 highlights that "current data intervals … quarter-hourly, once a day … are too slow" for effective optimization, and "Real-time data would be great, but it requires massive bandwidth and infrastructure". P10 strongly advocates for a move beyond smart meters, as they are "not fit for real-time needs", and stresses the need for "real-time data sharing" for applications like AI-based microtransactions. This leads to the next theme.

Theme 2: Smart Meters - A Foundational Yet Incomplete Infrastructure. This theme explores the dual nature of smart meters as essential building blocks for energy digitalization, juxtaposed with their current limitations in functionality, operational challenges, and varying customer acceptance.

Sub-theme 2.1: Core Infrastructure Role: Participants universally acknowledge smart meters as the bedrock of digital energy services. P5 clearly states that "smart meters are simply the technical prerequisite to participate at all" in energy communities. P6, Head of Metering Technology, refers to the smart meter as "the foundation for all future data" and "the key to" knowing "in real time what the load situation is" in the grid. P4 sees them as "a basic infrastructure, like the internet was for smartphones". Indeed, P7 confirms that smart meters have led to an "immense shift" from coarser to "very granular values … daily or even quarter-hourly data," significantly increasing the data volume handled by grid operators.

Sub-theme 2.2: Technical and Operational Hurdles: Despite their foundational role, smart meters present numerous practical challenges. P5 describes the rollout as a "massive logistical challenge … scheduling appointments, travelling to remote places, doing manual installations". P6 highlights that the technology "didn't yet exist" when the rollout began, making it "a patchwork of systems" requiring "constant updating and adjusting". Technical issues include the existence of "maybe 48" different firmware versions, and the fact that "systems aren't interoperable" across regions, even within a country. P4 bemoans that smart meters are "rudimentary" and "can't retrieve real-time data on demand". Data quality issues, such as "replacement values, data availability, and delayed intervals," are a common problem for DSOs, causing confusion for customers and affecting downstream processes like billing. P6 even notes that the "devices are limited by design" and are essentially "first-generation tech, designed 10–12 years ago".

Sub-theme 2.3: Customer Engagement and Perception: Customer acceptance and engagement with smart meters vary widely. P8, Head of Customer Service, observes that "Homeowners who generate electricity, or have switched to heat pumps, or use electric vehicles tend to be more engaged". However, "tenants in apartments generally show less interest in detailed data". P4 reports that "The majority are indifferent" to smart meters, and that "customers lose interest quickly unless prices spike" because "Electricity just isn't a top priority for many". During the rollout, P8 recalls, "Customers feared surveillance, especially with GDPR [...]. The media also raised concerns about hacking and blackouts". P6 confirms that "90% of people don't care" about the technology, with only "5% love the tech" and "3% are outright hostile". P5 summarizes the situation by stating, "Most customers don't care. Especially the 80% of household users who just want electricity to work".

Theme 3: Innovation in Energy Services and Business Models. This theme highlights the diverse range of new digital services and business models emerging across the energy sector, from optimising consumption in buildings to enabling peer-to-peer energy trading, all driven by increasing data availability.

Sub-theme 3.1: Energy Efficiency & Optimization: A core application of digital energy data is driving efficiency. P1 states that their company focuses on "how highly available energy data already is a driver for a lot of the work with energy optimization - both inside of companies and cities and municipalities". Their system provides a "ranked list of improvements across their building portfolio" and "automatically verifies what happened, forming a feedback loop". P2's app "helps people make better energy decisions," offering "Live and historical consumption tracking" and "Cost calculations and early bill estimates". P4 emphasizes the need for data interpretation, for example, asking: "Is your base load at night okay?". P1 also highlights the potential of data analysis to "help drive toward zero-carbon buildings" through recommendations for solar PV or heat pumps.

Sub-theme 3.2: Local Energy Markets & Communities: Digitalization is crucial for the burgeoning trend of energy communities. P5 asserts that for energy communities, "Without digitalization, nothing works", as it enables everything from "measurement of energy data, to the transmission [...] its processing, allocation to individual energy communities, and automated data handover". P3 offers a platform for "renewable energy communities and tenant energy models - basically local energy markets", allowing communities to manage "user tariffs, invoicing, KPI monitoring [...] all based on data transmitted by DSOs". Their platform offers "customizable visual dashboards" that let users "monitor total production and consumption data daily, see coverage percentages for each participant". P8 confirms that their company "could offer services like a portal showing production and usage in such communities".

Sub-theme 3.3 Dynamic Tariffs & Flexibility Management: The ability to leverage real-time or near real-time data for pricing and grid management is a significant area of innovation. P2's app provides "Live electricity prices and notifications on when to run appliances" and a "7-day price forecast based on machine learning". P3's platform "support[s] dynamic tariffs, allowing different rates at different times, or even weather-based tariffs". P4 discusses offering "dynamic tariffs based on quarter-hour intervals" and developing an app to give customers insights and suggest actions. P10 envisions "a real-time energy trading app, enabling second-by-second, AI-based microtransactions for residential users". The concept of "emissionality APIs," tracking avoided emissions based on grid behaviour, is also gaining interest. P10 highlights the importance of creating a "flexibility data space" to provide grid operators with the "same confidence and granularity as they have for conventional generation plants" for demand response.

Sub-theme 3.4: User-Centric Digital Platforms: A strong emphasis is placed on making complex energy data intuitive and actionable for end-users. P2's mission is to "accelerate the transition to sustainable energy through a user-centric app that helps people make better energy decisions", demonstrating that "tracking energy prices and habits is not just a niche, it's mainstream". P3 aims for an "intuitive" experience where users "not need a manual". P4's company is developing an app "that gives customers insights based on their usage and suggests actions, without them needing to analyse anything themselves". P9 also believes the "user interaction layer should be standardized" and advocates for a "user-friendly front end, for example, pages for authorization management, data visualization, etc.".

Theme 4: The Regulatory and Legal Framework - A Double-Edged Sword. This theme examines how existing and proposed regulations both enable and constrain the development and scaling of digital energy solutions, particularly regarding data access, privacy, and market design.

Sub-theme 4.1: Enabling Legislation: Legislation often serves as the initial impetus for smart meter rollouts and the development of new energy models. P3 mentions that in their country, "the implementation of the EU Renewable Energy Directive has taken legal form" for energy communities. P5 notes that smart meters are "the technical prerequisite" due to regulations, and that the rollout in Vorarlberg is "to be completed by the end of the year by Vorarlberg Netz and other operators". P6 confirms they met the "legal minimum rollout requirement" for smart meters. P8 also states that "Starting next year, dynamic pricing must be offered".

Sub-theme 4.2: Privacy Concerns & Data Governance: Despite the potential benefits of data, privacy regulations significantly restrict its use. P6 highlights that "For now, these advanced features are locked down due to privacy concerns". They add that "Strict privacy laws limit innovation". P7 confirms that due to "privacy laws, they only see their own data" within energy communities, not total production. P10 raises a critical question: "How do we test this in multi-tenant environments while protecting data privacy? We handle private user data and are trusted by them. How can we guarantee privacy across parties, including TSOs and DSOs?". P8 recalls that during the smart meter rollout, "Customers feared surveillance, especially with GDPR coming into effect in 2018".

Sub-theme 4.3: Fragmented National Regulations: Inconsistent regulations across countries pose a significant barrier to scaling solutions. P2 explains that they "operate mainly in one country because only there do we have access to the necessary energy data. In other countries, there's no comparable platform or integration point". They explicitly state, "different countries have different TSOs, data access rules, and no unified integration process". P6 confirms this, stating that "Smart Meter specs differ across countries" and "systems aren't interoperable". Each country "builds on their own IT infrastructure," making integration a major challenge.

Sub-theme 4.4: Challenges in Policy Development: The pace of regulatory change struggles to keep up with technological advancements and market needs. P6 notes that a "draft energy law includes this [use of voltage data for grid analysis], but it wasn't passed before the government term ended". P5 expresses disappointment that an "updated ElWOG law" enabling default 15-minute readings with opt-out "didn't pass in time". P7 points out that "Current regulations limit what we can do with the data. We hope future revisions will grant us more flexibility". P10 also expresses frustration with "lack of harmonized TSO-DSO data" within the flexibility code development process, underscoring that while "CIM-based real-time trading is technically feasible," the "challenge is the business model and contracts". P6 notes that "Roles are shifting drastically in the market [...] grid operators now have to act like service providers, and that's a major structural and cultural change".

Theme 5: Scalability and Cross-Border Expansion: The European Ambition. This theme captures the strong desire among innovators to scale their solutions across Europe and the inherent challenges posed by the fragmented energy landscape, emphasising the critical need for a unified approach.

Sub-theme 5.1: Scaling Digital Solutions: The goal of quickly expanding digital energy services is paramount for many. P1 emphasizes, "We focused on proving scalability". P9 highlights that "in some edge cases, like a telecom firm with thousands of sites, onboarding becomes a major challenge". P2's aspiration is to "scale more easily beyond our national borders", noting that as a "two-person team, we face major challenges" expanding across

Europe due to inconsistent data access. P4 acknowledges that "Accessing data through standardized interfaces isn't the problem. The challenge is building and scaling digital services".

Sub-theme 5.2: Interoperability Challenges: The lack of seamless integration between different national systems significantly hinders scalability. P6 states that smart meters from one region "can't be used in our grid. And we can't just swap out meters due to the deeply integrated IT architecture behind them". Even within Austria, "each network operator has different back-end systems". P2 laments that in Norway, their TSO is "very hard to connect to. There's no easy API, and integration requires local company registration. These are huge hurdles and exactly the kind of challenges a European standard could help solve". P10 stresses the need for standards to ensure "no vendor lock-in" and for "real-time device streaming" to enable broader data exchange.

Sub-theme 5.3: Call for European Harmonization: A clear call for unified European frameworks resonates across the interviews. One of P1's main concerns is about "system architecture [...] how to ensure central availability, even with decentralized setups". P2 explicitly states, "We need standardized frameworks across Europe for collecting, storing, and accessing energy data" and desires a "standardized access protocol that works across borders". P3 "really believe[s] in the benefit of centralized, standardized platforms. They make scalable, cross-border applications possible". P10 urges EDDIE to "expand beyond smart metering as a data exchange framework" and to "influence future framework development" towards broader standards. The long-term vision includes cross-border energy communities, which are "... Technically feasible, sure. But regulatory and economic challenges are huge" and require "Harmonising market processes, data formats, and legal frameworks".

3.5 Conclusion

The work conducted within Task T7.2 has provided substantial insights into how user experience (UX) and behavioural economics (BE) principles can inform the design and implementation of energy-data-driven services. By systematically combining primarily qualitative and quantitative methodologies within two complementary research strands, the task has generated both empirically grounded findings and conceptual contributions. The BEUX.energy Framework, developed under Strand A, synthesizes these findings into a theoretically informed model for designing user interactions with energy data. It demonstrates that meaningful engagement arises when energy information is made comprehensible, situated within everyday contexts, and framed to support users' sense of agency and motivation.

Strand B expanded this perspective to the systemic level, exploring how interoperable data infrastructures and emerging business models can support innovation in the evolving energy-data ecosystem (cf. The FutureUC.energy Framework). Together, the results emphasize that technological advancements alone do not guarantee adoption or impact; rather, they must be coupled with human-centred approaches that address cognitive, emotional, and ethical dimensions of data interaction. The findings underscore the transformative potential of the EDDIE framework: by combining UX, behavioural insight, and interoperable data infrastructures, it can enable more informed, participatory, and environmentally responsible energy use.

The work carried out for this task has so far resulted in two accepted peer-reviewed papers,[117] with additional manuscripts currently under review.

Future research should build upon this foundation to test these concepts at scale and further explore how energy data can empower both individual users and organisations within a connected, data-driven energy ecosystem.

[117] https://flo.cosylab.at/docs/IoT_Conference_Energy_Inspectors.pdf
https://flo.cosylab.at/docs/DIGIHUM_Digital_Capitalism.pdf

4 LEGAL RESEARCH ON METERING AND CONSUMPTION DATA SHARING

4.1 Introduction and background

This chapter investigates the EU legal framework governing the exchange of electricity metering and consumption data with eligible parties, with a view to understanding whether and how this framework enables a wide range of energy services for consumers.[118] These services include, among others, energy sharing, participation in renewable and citizen energy communities, demand-side management, and tailored energy efficiency solutions. The legal discipline surrounding data access and sharing is therefore analysed not in isolation, but as a foundational enabler of the EU's twin transition towards a decarbonised and digitalised energy system. By clarifying the legal conditions under which electricity metering and consumption data can be accessed and shared, this chapter supports the technical and governance architecture of project EDDIE and contributes to the broader goal of fostering a competitive, interoperable, and consumer-oriented energy market.

The chapter proceeds in four sections. Section 4.2 outlines the research questions and methodology which this chapter follows. Section 4.3 provides a systematisation of the relevant EU legislation, covering both data and energy law. On the data side, it examines the General Data Protection Regulation (GDPR), the ePrivacy Directive, the Data Act, and the EU's policy initiative on Common European Data Spaces. On the energy side, it analyses the Electricity Directive, the Electricity Regulation as amended by the Electricity Market Design

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[118] This chapter focuses exclusively on electricity metering and consumption data, as these are central to enabling consumer-oriented energy services in the EU electricity market and constitute the product scope of project EDDIE. The Gas Market Directive mandates Member States to strongly recommend that also natural gas undertakings optimise the use of natural gas by, inter alia, providing energy management services, and introducing smart metering systems gas (art 17); moreover, Member States shall ensure the deployment of smart metering systems for hydrogen that can accurately measure consumption and provide information on actual time of use, and that are able to transmit and receive data for information, monitoring and control purposes using a form of electronic communication (art 18). However, natural gas and hydrogen consumption data fall outside the scope of this analysis. Directive (EU) 2024/1788 of 13 June 2024 on Common Rules for the Internal Markets for Renewable Gas, Natural Gas and Hydrogen, Amending Directive (EU) 2023/1791 and Repealing Directive 2009/73/EC (Recast) [2024].

Reform, the Interoperability Implementing Act on Data Access (IADA), the amended Renewable Energy Directive and the Common European Energy Data Space initiative (CEEDS).

Section 4.4 explores the interaction between electricity and data law, focusing on whether and how these frameworks align. It considers the implications of different legal bases for data processing, the roles and responsibilities of various actors, and the potential for regulatory fragmentation across Member States resulting from the interaction between different pieces of EU electricity law and the electricity-relevant content of the Renewable Energy Directive and from the interplay between the two bodies of legislation. Recent Commission guidance on the scope and applicability of 'building systems data' under the Energy Performance of Buildings Directive is discussed as a promising case study of how greater clarity could be provided by the EU institutions.

Through this multi-layered analysis, the chapter aims to identify legal gaps and overlaps, ultimately contributing to a more coherent and enabling legal environment for energy data exchange in the EU.[119]

4.2 Methodology

The attainment of the objectives of project EDDIE relies on the presence of a clear and functioning legal framework enabling the exchange of electricity metering and consumption data. The principal research question for this chapter consequently is:

RQ: What is the EU legal framework for the sharing of electricity metering and consumption data?

To answer the research question, the chapter relies on legal-doctrinal methods to construct a comprehensive picture of this legal framework. This is a complex task given that the legal instruments examined have been adopted at different points over time, and within different fields of law.

The legal framework is situated at the intersection of two legal fields: energy and data law. A first step thus involves identifying the relevant legislative acts and policy initiatives within each field, as well as the specific provisions within these acts that are of relevance to the research question. The sub-questions (SQs) that guide this part of the analysis are as follows:

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[119] The topic has been explored since 2023, when project EDDIE started, and takes into consideration EU legislative developments until 1 July 2025.

SQ1: Which EU legal acts and policy initiatives in data and energy law are relevant for the exchange of electricity metering and consumption data?

SQ2: What specific provisions within these acts and policy initiatives are most relevant for the exchange of electricity metering and consumption data?

Figure 4.1 shows this selection of legislative acts and policy initiatives and their appurtenance to either energy or data law. The analysis at this initial stage takes a rather broad approach, capturing all legal acts and policy initiatives directly relevant to the exchange of electricity metering and consumption data.

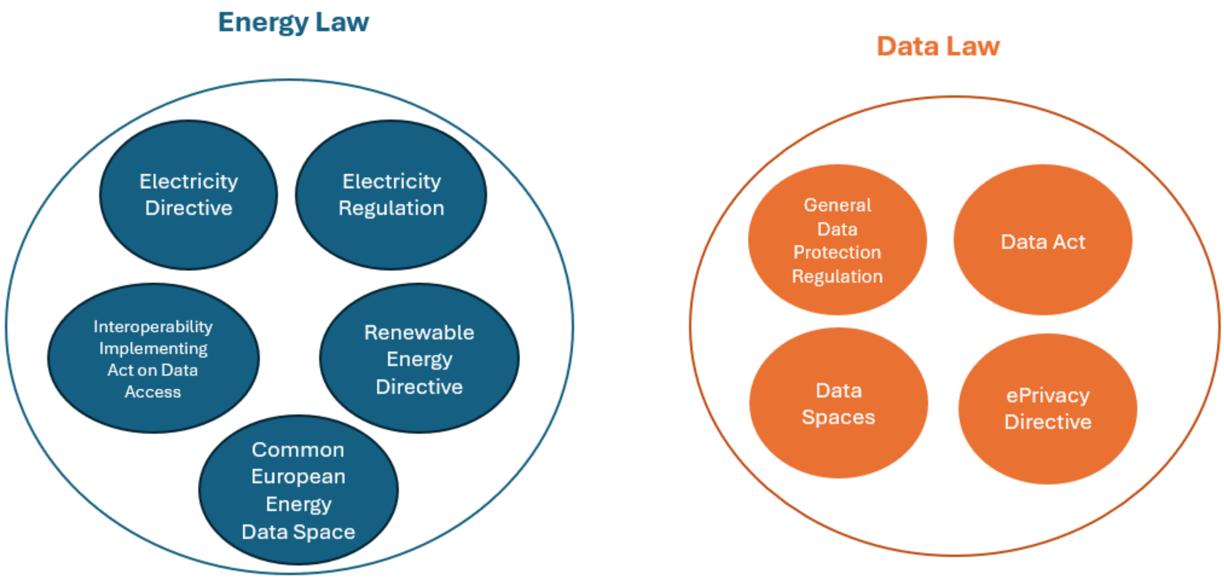

Figure 4.1: Energy and Data Legislation covered in Section 4.3.
Source: Own elaboration.

This broad mapping enables a selection of the most pertinent legal provisions. Within electricity law, interactions between the legislative acts identified are particularly intricate since provisions governing the process of sharing of metering and consumption data are contained in several interlinked pieces of legislation. This gives rise to the following sub-question:

SQ3: How do the principal components of EU electricity law interact regarding the exchange of electricity metering and consumption data?

The analysis conducted to answer SQ3 is illustrated in Figure 4.2 below.

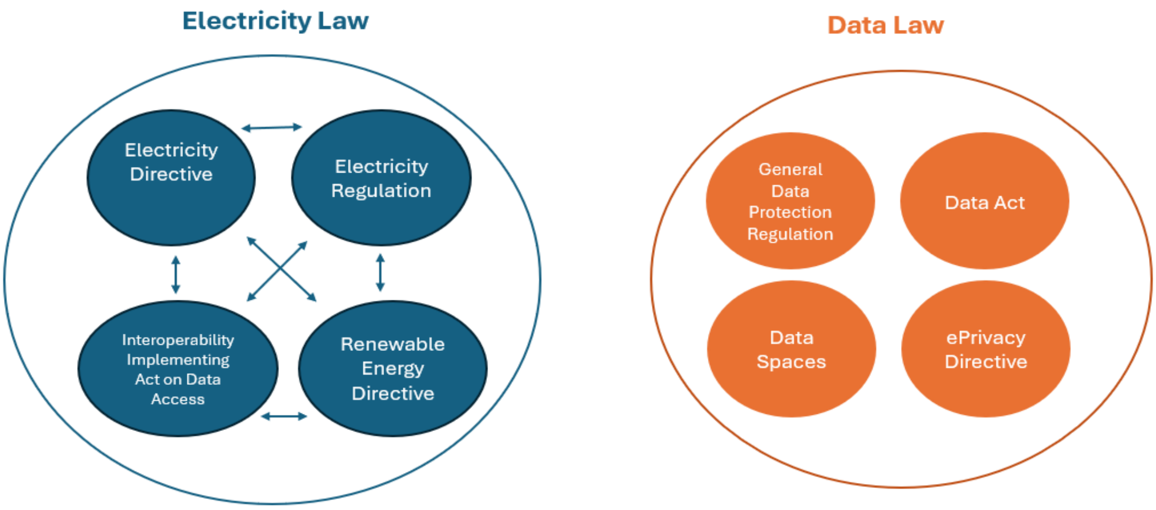

Figure 4.2: Interaction between Electricity Law Acts covered in Section 4.4.
Source: Own elaboration.

The mapping of these interactions was the key to the selection of data law which has direct impact on the electricity law framework for metering and consumption data sharing as shown in Figure 4.3. Data law was here treated as the general, overarching legal framework, while electricity law was conceptualised as sector-specific rules elaborating on this general framework. The sub-question for this step was:

SQ4: How do the cross-cutting provisions of the Data Act and General Data Protection Regulation interact with the electricity law framework for the exchange of electricity metering and consumption data?

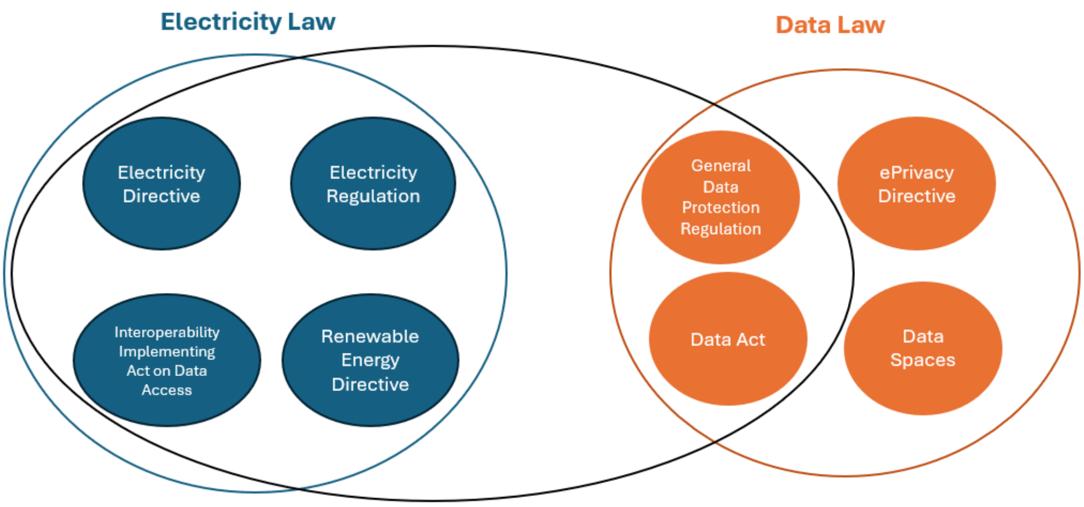

Figure 4.3: Interaction between Electricity and Data Law Acts covered in Section 4.4.
Source: Own elaboration.

4.3 EU Legislation Relevant for Access to and Sharing of Electricity Metering and Consumption Data

In this section, we provide an overview of EU law relevant for access to and the sharing of electricity metering and consumption data.[120] We first investigate data legislation and then move to the relevant energy legislation. This is a necessary foundation for Section 4.4 of this chapter, which focuses on the consequences of the interaction between these pieces of legislation.

4.3.1 Data Legislation

We begin our analysis by examining EU data law that is of relevance for access to and sharing of electricity metering and consumption data. Specifically, we focus on the General Data Protection Regulation (GDPR) (Regulation (EU) 2016/679) and the Data Act (Regulation (EU) 2023/2854). Both legislative acts provide horizontal, cross-cutting frameworks for data sharing and processing. The GDPR applies to the processing of personal data, whereas the more recent Data Act is concerned with access to data generated by internet of things devices. Examining the GDPR and the Data Act also requires a brief consideration of other relevant legislative and policy instruments to provide a comprehensive contextualisation of these legal acts. We thus also consider the ePrivacy Directive (Directive 2002/58/EC), which complements the GDPR by addressing the processing of data in the field of electronic communications. In connection with the Data Act, we briefly discuss the EU's recent Data Spaces policy, which aims to facilitate data sharing across various sectors and is closely linked to the objectives of the Data Act. We identify the provisions within these legislative frameworks that are most relevant to accessing and sharing electricity metering and consumption data generated by smart meters and Dedicated Measurement Devices (DMDs, see Section 4.3.2). Their precise interaction with sector-specific legislation is examined in greater detail later in this chapter, in Section 4.4.

4.3.1.1 The General Data Protection Regulation (GDPR)

Household electricity metering and consumption data generated by smart meters are personal data (European Data Protection Supervisor, 2022, note 6; Baumgart and Espinosa Apráez, 2024, p. 514). If the same would also apply to such data generated by Dedicated

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[120] We use 'data sharing' and 'data exchange' as synonyms, following the way these terms are used in EU electricity legislation.

Measurement Devices (DMDs),[121] both would be subject to the EU's flagship data privacy law, the General Data Protection Regulation (GDPR). The GDPR was adopted in April 2016 with full application from 25 May 2018 (GDPR, Article 99). The principal objective of the GDPR is to streamline data protection laws and to fully realise the protection of the fundamental rights of persons whose data are processed in the EU.

The following key definitions of the GDPR are of relevance for metering and consumption data sharing. First, the Regulation broadly defines personal data as 'any information relating to an identified or identifiable natural person ("data subject")' (GDPR, Article 4(1)). Secondly, the action of processing this data, meanwhile, is defined as:

> *"any operation or set of operations which is performed on personal data or on sets of personal data, whether or not by automated means, such as collection, recording, organisation, structuring, storage, adaptation or alteration, retrieval, consultation, use, disclosure by transmission, dissemination or otherwise making available, alignment or combination, restriction, erasure or destruction." (GDPR, Article 4(2))*

Thirdly, the actor which decides how and why personal data are processed is termed the data controller under the GDPR (GDPR, Article 4(7)). Fourthly, the controller may delegate the actual act of processing to a data processor (GDPR, Article 4(8)). Fifthly, the GDPR foresees the role of a 'third party', which, acting under the direct authority of the controller or processor, also processes personal data (GDPR, Article 4(9)). Finally, any natural or legal person, public authority, agency or body to which personal data are disclosed, is considered a 'recipient' (GDPR, Article 4(10)).

For data processing to be lawful under the GDPR, at least one of six justifications contained in Article 6 must be met. These are: (1) consent of the data subject (Article 6(1)(a)); (2) performance of a contract to which the data subject is party (Article 6(1)(b)); (3) the existence of a legal obligation to which the controller is subject (Article 6(1)(c)); (4) protection of the vital interests of the data subject or of another natural person (Article 6 (1)(d)); (5) the performance of a task carried out in the public interest or in the exercise of official authority vested in the controller (Article 6(1)(e)); and (6) legitimate interests pursued by the controller or by a third party (Article 6(1)(f)). Regarding this final justification, the legitimate interest of a controller or third party can 'be overridden by the interests or fundamental rights and freedoms of the data subject which require protection of personal

[121] The definition of DMDs is discussed in more detail in Section 4.3.2.

data, in particular where the data subject is a child'. The assessment required must be conducted on a case-by-case basis.

4.3.1.2 The Directive on Privacy and Electronic Communications (ePrivacy Directive)

While not as important as the GDPR for the analysis in this chapter, Directive 2002/58/EC on Privacy and Electronic Communications (ePrivacy Directive) should also be mentioned in this overview of applicable law. The ePrivacy Directive concerns the processing of personal data and the protection of privacy in the electronic communications sector. It also seeks to ensure the free movement of such data. While pre-dating the GDPR, the ePrivacy Directive now can be considered complementary to it, providing more specific rules as to the application of the GDPR in the electronic communications sector (European Data Protection Board, 2019). It mandates the compliance with rules aiming at ensuring security in the processing of personal data, the notification of personal data breaches and confidentiality of communications, banning communications where the user has not provided consent.

For the purposes of this chapter, the ePrivacy Directive is primarily relevant because the Interoperability Implementing Act on Data Access (IADA), in Recital 16, recognises smart meters as 'terminal equipment' under the ePrivacy Directive and thus foresees its applicability to smart meter data access. However, the ePrivacy Directive itself does not provide a definition of 'terminal equipment'. Further clarification of this concept within the ePrivacy Directive seems unlikely since the Commission's Work Programme for 2025 stated that a planned recast of the ePrivacy Directive has been dropped due to a lack of agreement between co-legislators (COM/2025/45 final, Annex IV, p. 26).

4.3.1.3 The Data Act (DA)

A more recent EU legal act relevant for the sharing of electricity metering and consumption data is the EU Data Act (DA), which was adopted in November 2023 (Regulation (EU) 2023/2854). The Data Act's main objective is to give individuals and businesses greater control over the data that is generated using 'connected products'. These are defined in Article 2(5) of the DA as:

"an item that obtains, generates or collects data concerning its use or environment and that is able to communicate product data via an electronic communications service, physical connection or on-device access, and whose primary function is not the storing, processing or transmission of data on behalf of any party other than the user."

The DA stipulates that these connected products must: (1) obtain, generate or collect data concerning their use or environment; (2) be able to communicate these data; (3) not primarily serve these purposes for a party that is not the 'user' as defined by the DA (DA, Article 2(5)). Data generated by these products that are designed to be retrievable are considered product data and thus come within the scope of the Act (DA, Article 2(15)).

Several of the most important concepts and roles defined in the DA are interconnected and potentially of relevance to electricity metering and consumption data sharing.[122] Indeed, the definition of who qualifies as the user of a connected product also has an impact on the definition of the device itself. As mentioned above, DA specifies that connected products should not have, as their primary function, 'the storing, processing or transmission of data on behalf of any party other than the user'. Article 2(12) of the DA provides that a user is 'a natural or legal person that owns a connected product or to whom temporary rights to use that connected product have been contractually transferred, or that receives related services. A 'user', according to the DA, must thus be able to satisfy at least one of three conditions: (1) he or she owns the connected product; (2) he or she has contractual rights to use the product; or (3) he or she receives a related service.

As to the service provided via the connected product, the DA, in Article 2(6), defines such a related service as:

> *"a digital service, other than an electronic communications service, including software, which is connected with the product at the time of the purchase, rent or lease in such a way that its absence would prevent the connected product from performing one or more of its functions, or which is subsequently connected to the product by the manufacturer or a third party to add to, update or adapt the functions of the connected product."*

The DA thus provides two alternative avenues for a service using data from a connected product to come under its scope. This is either when: (1) the service is integrated in the product from the start and is essential for the device to perform one or more of its functions; or (2) the service is connected at a later point to enhance the functionality of the product. Regarding the latter criterion, Recital 17 of the DA clarifies that:

> *"[s]ervices which do not have an impact on the operation of the connected product, and which do not involve the transmitting of data or commands to the connected product by the service provider should not be considered to be related services."*

[122] For details regarding the applicability of the definitions, see Nicolai & Münchmeyer (2025).

The Commission's *Frequently Asked Questions* document breaks this down into two further criteria, stating that a related service (1) must entail a 'bidirectional exchange of data between the connected product and the service provider', and (2) 'the service must affect the connected product's functions, behaviour, or operation' (European Commission, 2024c, p. 9).

A final definition of the DA relevant for the purposes of this discussion is that of 'data holder', defined in Article 2(13) as:

> *"a natural or legal person that has the right or obligation, in accordance with [the DA], applicable Union law or national legislation adopted in accordance with Union law, to use and make available data, including, where contractually agreed, product data or related service data which it has retrieved or generated during the provision of a related service."*

It is data holders that are the primary subject of the obligations imposed by the DA, which are further discussed in their interaction with sectoral law in Section 4.4 below.

4.3.1.4 Data Spaces

While not specified in a single legal act, the EU's objective of setting up Common European Data Spaces (CEDS) is of potentially significant relevance for the sharing of electricity metering and consumption data. The purpose of these Data Spaces is 'to foster an ecosystem of companies, civil society and individuals that provides easy and secure access to shared data. Companies and others could then use this data to create new products and services, optimise supply chains and simplify administration' (SWD/2021/247 final, p.50).

CEDS are conceptualised as sectoral initiatives to make the best use of digital technologies in strategic sectors of the EU economy: 'Common European data spaces are infrastructures designed to create data-sharing platforms: their main leverage will be the possibility to reuse data' (CEPS 2022). The EU Data Strategy (COM/2020/66 final) initially introduced the development of ten common European data spaces; in 2024, work was ongoing across 14 sectors/domains.[123] These sectoral initiatives considered together will constitute the Single European Data Space (SEDS).

EU institutions opted for a bottom-up approach for setting up CEDS, mirroring the necessities highlighted by stakeholders across sectors, who 'emphasize the need for coordinated investment to create common European data spaces in strategic sectors' (SWD/2021/247 final, p.50). This is also in line with the intentions expressed by the European Commission in 2021: 'In the first phase, common support actions will lay the basis for the development of each of the data spaces through community building and preparatory work on interoperability and governance' (SWD/2021/247 final, p.88).

The legislation pertaining to data in the EU discussed above goes beyond the electricity sector and is intended to contribute to providing an overarching architecture for data governance in the EU. This is especially true for the Commission's most recent push in the data domain, which has resulted in initiatives such as the Data Act and the CEDS. These developments at Union level provide the background against which to view the sector-specific law on energy metering and consumption access and sharing, to which we now turn.

4.3.2 Electricity Legislation

In this section, we analyse how sharing electricity metering and consumption data with eligible parties is regulated in the sector-specific legislation for electricity to clarify the roles and responsibilities of the actors involved in the process. As illustrated in Figure 4.1, we start with the Electricity Directive (Directive (EU) 2019/944), we then move to the Electricity Regulation (Regulation (EU) 2019/943) as amended by the Electricity Market Design Reform (by Regulation (EU) 2024/1747), the IADA, the Renewable Energy Directive (Directive (EU) 2018/2001) and we conclude with the Energy Data Space.

4.3.2.1 The Electricity Directive

The Directive on Common Rules for the Internal Market for Electricity (Directive (EU) 2019/944), hereafter the Electricity Directive, as recast by the 2019 Clean Energy Package, aimed at providing consumers with additional ways to engage in the decarbonisation of the energy sector, boosting retail market competition. With this objective in mind, Article 23 introduced an obligation for Member States or designated competent authorities, usually the national

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[123] Data spaces are currently envisaged for agriculture, cultural heritage, energy, finance, the European Green Deal, health, industry, language, media, mobility, public administration (subdivided into four separate data spaces), research and innovation, skills and tourism. For more information, see SWD/2024/21 final.

regulatory authority, to 'specify the rules on the access to data of the final customer by eligible parties in accordance with this Article and the applicable Union legal framework', with 'data' being metering and consumption data as well as data required for customer switching, demand response and other services. The European approach does not push for a harmonisation of national practices regarding the management of this type of data but simply mandates the interoperability of those practices (see the analysis of the IADA in Section 4.3.2.4), leaving the choice of the model to Member States (see Chapter 5 for a more detailed overview of Data Management Models).

Therefore, the Electricity Directive obliges Member States to establish the rules enabling metering and consumption data sharing with 'eligible parties', which were later defined by the IADA (IADA, Article 2(6), see Section 4.3.2.4) as entities:

> *"offering energy-related services to final customers, such as suppliers, transmission and distribution system operators, delegated operators and other third parties, aggregators, energy service companies, renewable energy communities, citizen energy communities and balancing service providers, as far as they offer energy related services to final customers."*

This definition is broad enough to include all the different entities which could in principle offer energy services to consumers.

Overall, the Electricity Directive provided for the objective to be implemented, i.e., metering and consumption data sharing with eligible parties, designating Member States and designated competent national authorities as the actors in charge of taking the necessary steps to achieve it. It offered guidelines for the organisation of the data management, which must 'ensure efficient and secure data access and exchange, as well as data protection and data security' (Electricity Directive, Article 23(2)). Data protection and security are of crucial importance when considering metering and consumption data, since these data can reveal sensitive information about customers' behaviour and financial means. For example, from an analysis of energy consumption data it is possible to infer which type of home appliances consumers own, for instance more or less efficient ones, and, in turn, this can provide indications on their disposable income. Moreover, consumption data could allow for the identification of times when consumers wake up and when they are at home (Huhta, 2020).

Moreover, Article 23 states that there should be no discrimination between the eligible parties and that data must be shared simultaneously with all those entitled to receive it (Article 23(2)). Charges for the access to data can be set by Member States and they should be reasonable and duly justified (Article 23(5)).

4.3.2.2 The Electricity Regulation

After the 2022 Russian invasion of Ukraine and the subsequent energy crisis, discussions on the design of European electricity markets gained momentum, triggering reflections on the resilience and preparedness of markets to disruptions and changes in energy demand and supply dynamics, especially considering the net zero target by 2050 enshrined in the EU Climate Law (Regulation (EU) 2021/1119). Therefore, after a series of interventions to address the immediate effects of the energy crisis, the European Commission, in March 2023, proposed a reform of the electricity market design, which entered into force in July 2024 (see Regulation (EU) 2024/1747 and Directive (EU) 2024/1711).[124] The reform aimed to boost the penetration of renewable energy in the EU's energy mix, to better protect consumers and to enhance industrial competitiveness. Moreover, it expanded the tools for electricity consumers to take part specifically in flexibility solutions for local congestion management, introducing a definition of flexibility and a specific role for DMDs.

Firstly, flexibility is now defined, by the revised Regulation (EU) 2019/943, hereafter the Electricity Regulation, as 'the ability of an electricity system to adjust to the variability of generation and consumption patterns and to grid availability, across relevant market timeframes' (Electricity Regulation, Article 2(79)). Secondly, DMDs are 'devices linked to or embedded in an asset that provides demand response or flexibility services on the electricity market or to system operators' (Article 2(78)). In a nutshell, DMDs are devices embedded into or separate but connected to, for example, EV charging points, storage and heating systems and home appliances such as a washing machine, which enable the measurement of the electricity consumption of that specific appliance, in addition to the measurement, by conventional or smart meters, of the aggregated consumption at the customer's metering point. These data can be used by system operators and relevant market participants for the observability and settlement of demand response and flexibility services, upon the consent of the final customer (Electricity Regulation, Article 7b(1)). The participation in flexibility markets through smart meter data remains the default option. The option to use DMD data has been introduced to accommodate the different roll out rate of smart meters across

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[124] For a broader overview of the reform, refer to Emma Menegatti, Ellen Beckstedde, Max Münchmeyer and Leonardo Meeus, 'How Comprehensive is EU Electricity Market Design Reform?: Exploring the Full Scope of Measures, Objectives, and Future Directions', Working Paper (Florence School of Regulation 2025). The reform also included the revision of Regulation (EU) No 1227/2011 of 25 October 2011 on Wholesale Energy Market Integrity and Transparency [2011] OJ L 326/1 via Regulation (EU) 2024/1106 of 11 April 2024 Amending Regulations (EU) No 1227/2011 and (EU) 2019/942 as Regards Improving the Union's Protection Against Market Manipulation on the Wholesale Energy Market [2024], which entered into force in May 2024.

Member States (Electricity Regulation, Recital 18). This option becomes an obligation to use such data when a consumer does not have a smart meter installed or the smart meter does not deliver the necessary data for demand response or flexibility.

However, uncertainty persists as to the definition of DMDs and their usage, due to the non-comprehensive framework offered by the reform. SmartEn, for example, in its 2023 'Policy Recommendations on the Electricity Market Design Revision' (SmartEn, 2023), suggested to improve the definition by specifying the ownership and operation of such devices, but those details have not been included. Furthermore, it is unclear whether the applicable legal framework is the same as that in place for smart meter data sharing (see Section 4.4.1).

4.3.2.3 The Renewable Energy Directive

The Directive on the Promotion of Energy from Renewable Sources (Directive (EU) 2018/2001), as amended by Directive (EU) 2023/2413, hereafter the Renewable Energy Directive, is the key EU legal act for promoting the use of energy from renewable sources. In order to achieve the binding target set in Article 3 of at least a 42.5% share of energy from renewable sources in the Union's gross final consumption by 2030, it mandates the Commission to support Member States through an enabling framework comprising the enhanced use of Union funds to, among other things, develop 'projects and programmes for integrating renewable sources into the energy system, for increasing *[its]* flexibility, for maintaining grid stability and for managing grid congestions' (Renewable Energy Directive, Article 3(5)(b)). This directive is, in a sense, complementary to the Electricity Directive. In fact, the latter, as amended by the 2019 Clean Energy Package, aimed to support active consumers and foster consumer engagement in the decarbonisation of the energy sector, as stated in Section 4.3.2; the Renewable Energy Directive strengthens the Electricity Directive's commitment to this objective, supporting the role of renewables self-consumers and renewable energy communities.[125]

In fact, Article 21 on renewables self-consumers aims at making consumers an active part of the energy system, entitling them to generate renewable energy, including for their own consumption, as well as to store and sell the excess production and to receive remuneration for the self-generated renewable electricity fed into the grid. To enable these use cases, consumers should not only have access to their own consumption data (electricity withdrawn and injected into the grid), but they also need to be able to share the data, since

[125] For an overview of policies regarding renewable energy communities, refer to Nicolò Rossetto, 'Beyond Individual Active Customers: Citizens and Renewable Energy Communities in the EU', IEEE Power and Energy Magazine, 2023, Vol. 21, No. 4, pp. 36-44.

consumers' installation may be owned by a third party or managed by a third party for installation, operation, including metering and maintenance (Renewable Energy Directive, Article 21(5)). Additionally, data sharing proves relevant to grant renewables self-consumers non-discriminatory access to all electricity market segments (Article 21(6)(e)), among which we can include flexibility markets.

The access to electricity market segments is also mentioned concerning citizen energy communities (as regulated by the Electricity Directive, Article 16) as well as renewable energy communities, which, in addition to sharing, within the community, the renewable energy produced, should be able to access all suitable energy markets both directly or through aggregation in a non-discriminatory manner' (Renewable Energy Directive, Article 22(2)(c)). The directive's provisions discussed above contribute to expanding the rights of consumers when engaging in the different participative forms to contribute to the decarbonisation of the energy sector.

4.3.2.4 The Interoperability Implementing Act on Data Access (IADA)

The European Commission, in order to reduce the administrative burden for eligible parties active in different Member States and to boost competition in retail markets, has been tasked by Article 24 of the Electricity Directive to adopt implementing acts specifying interoperability requirements and non-discriminatory and transparent procedures for access by consumers and eligible parties to data required for customer switching, demand response and other services. In the context of smart metering, interoperability is 'the ability of two or more energy or communication networks, systems, devices, applications or components to interwork to exchange and use information to perform required functions' (Electricity Directive, Article 2(24)). Interoperability should make it easier to share metering and consumption data between different actors in different countries.

In June 2023, the first Interoperability Implementing Act was adopted (Commission Implementing Regulation (EU) 2023/1162).[126] It introduced a 'reference model' at the disposal of Member States for the procedures to access and share metering and consumption data with eligible parties, as well as for the access to the data by consumers themselves (Implementing Act on Data Access – IADA). The Act leaves a margin for existing national practices and allows for national customisation. The implementation of the model is also the

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[126] As of July 2025, a second interoperability implementing act on electricity supplier switching is in preparation, after the public consultation ended in June 2025. See https://energy.ec.europa.eu/news/have-your-say-call-feedback-technical-rules-smoothly-switching-electricity-supplier-2025-05-21_en.

object of a mapping effort that Member States shall carry out at national level and then report to the Commission (IADA, Article 10). Reports are then made publicly available through a repository to ensure the transparency of and non-discrimination in national procedures.

The IADA clarifies the definitions, roles and responsibilities of different actors when sharing the type of data described; for example, in addition to the definition of eligible party mentioned in Section 4.3.2, it introduces the 'metered data administrator' as the 'party responsible for storing validated historical metering and consumption data and distributing these data to final customers and/or eligible parties' (IADA, Article 2(7)). Additionally, via Article 5, it outlines the responsibilities of the metered data administrator, for instance, to make validated metering and consumption data available to final customers and eligible parties through an online or through another appropriate interface, on request, in a non-discriminatory way, and without undue delay (IADA, Article 5(1)(a)).

In EU electricity law, the IADA is the most comprehensive document on the sharing of metering and consumption data with eligible parties. It also offers clarity on the concepts of 'validated historical' and 'near real-time' metering and consumption data (IADA, Articles 2(3) and (5)). In fact, electricity metering devices can produce both validated historical and near real-time data. The former is the data generated and integrated to complement gaps due to times of meter unavailability; the latter is the data generated and shared continuously by a smart meter or a smart metering system in a short time period. Both play a crucial role for the provision of energy services for consumers.

In the annex of the IADA, specific use cases are identified and the required steps to enable them are highlighted. The use cases, all relevant for the provision of flexibility services to energy consumers are: termination of service by an eligible party; revocation of an active permission by the final customer; activation of near real-time data flow from a smart meter or smart metering system; reading of near real-time data from a smart meter or smart metering system; access to validated historical metering and consumption data by the final customer and by an eligible party.

4.3.2.5 The Common European Energy Data Space (CEEDS)

The concept of 'data spaces' has been introduced in Section 4.3.1.4, together with the sectoral ramifications foreseen by the EU Data Strategy (COM/2020/66 final), which led to the design and development, among others, of a Common European Energy Data Space (CEEDS), whose implementation started via a cluster of EU-funded projects, the Energy Data Space Cluster, comprising: Omega-X, Enershare, Data Cellar, EDDIE, Synergies and Int:net. The CEEDS has not been inserted in Figure 4.2 and Figure 4.3 due to the current lack of a legislative act specifically shaping it, unlike, for example, the European Health Data Space Regulation (EHDS) (Regulation (EU) 2025/327). However, it is a policy initiative to develop concrete projects and build on legislation, such as the IADA, which, by facilitating energy data sharing among trusted parties, would make it possible for innovative, digital services to enter the energy market and would strengthen interoperability among different systems (ETIP SNET, 2024).

4.4 The Complementarities and Uncertainties of the Electricity Legislation and the Interaction with the EU Legislative Framework on Data

After having provided an overview of both EU data and electricity legislative initiatives relevant for electricity consumer metering and consumption data sharing with eligible parties, this section analyses their interaction. As shown in Figure 4.2 and Figure 4.3, numerous legislative acts have a role to play in the data exchange for different energy services for consumers and the intersection between those belonging to the electricity domain and the data domain deserves careful consideration. Given that these EU laws have been adopted over a considerable span of time, under different EU competences and with varying lead Directorates-General, European Parliament Committees, and Council of the EU configurations, it is important to consider whether and how they are designed to work together in practice in the case of sharing of and access to electricity metering and consumption data. We start our analysis more narrowly, asking how the different components of electricity legislation discussed above interact, before broadening out our scope to enquire into the relationship between electricity and data law.[127]

4.4.1 The Interplay of the Different Electricity Legislation Pieces

As highlighted in Section 4.3, different components of electricity legislation combine to define the legislative framework for consumer participation in the decarbonisation of the energy sector. We find that some of the sector-specific legislative acts align, but other interactions between legislative acts result in uncertainties as to whether and how they are integrated and complement each other.

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[127] Despite the description of the Data Spaces initiative in Section 4.3.1 and, in particular, of the Common European Energy Data Space in Section 4.3.2, by virtue of the lack of a specific a legislative act on CEEDS, the latter will not form part of the analysis of this section. Additionally, the section will not include the ePrivacy Directive, due to its principal scope of application focusing on the electronic communications sector.

The starting point of this analysis is the shared objective in the electricity legislation to allow all final consumers to be offered and take part in different energy services without being discriminated against by well-established, larger actors with more market power and knowledge. An example is Article 21(6)(e) of the Renewable Energy Directive, which states that Member States should enable, for renewables self-consumers, non-discriminatory access to relevant existing support schemes as well as to all electricity market segments. One could imagine flexibility markets for local congestion management as a market segment to which renewables self-consumers should have the same access as incumbents. This interpretation would align with the obligation imposed under Article 32 of the Electricity Directive on Distribution System Operators (DSOs), when establishing the specifications for the flexibility services procured, to ensure the:

"effective and non-discriminatory participation of all market participants, including market participants offering energy from renewable sources, market participants engaged in demand response, operators of energy storage facilities and market participants engaged in aggregation."

Moreover, the electricity market reform imposed the obligation on system operators and relevant market participants not to discriminate against a final consumer relying on DMD data instead of smart meter data for taking part in flexibility services (Electricity Regulation, Article 7b(2)). Evidently, the reform aimed to provide additional tools to boost participation in flexibility mechanisms in different Member States characterised by varying smart meter rollout rates.

However, despite the equivalence, in certain circumstances, of smart meters and DMDs for the purpose of Article 7b(2), there is currently no uniform EU legal discipline explicitly covering both. A first reason certainly stems from the recent introduction of DMDs via the 2024 electricity market design reform. It is therefore not surprising that just a few details on these devices are provided: the definition of DMDs, the indication of the actors entitled to use the data and the objectives of the usage.[128] Clarity is also offered as to the legal basis for DMD data management, but, given the direct link to the GDPR, this aspect is addressed in Section 4.4.2.1.

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[128] As of July 2025, work is ongoing on the Network Code on Demand Response, which could provide further clarity on DMDs usage. See https://www.entsoe.eu/news/2024/05/08/dso-entity-and-entso-e-submit-joint-network-code-on-demand-response/.

Additional details on DMDs usage as well as on the coherence of the EU legislative framework are needed. On this last point, reflections can be brought forward considering the IADA. A *priori*, the subject matter of the IADA seems to exclude the access to and sharing of DMD data. In this regard, Article 1 states that:

"This implementing Regulation lays down interoperability requirements and rules for non-discriminatory and transparent procedures for access to electricity metering and consumption data by final customers and eligible parties in accordance with Directive (EU) 2019/944."

Electricity metering and consumption data comprise 'validated historical data and non-validated near-real time data' (IADA, Article 2(2)), which, according to their definitions, are those collected or provided by a smart meter or a smart metering system (IADA, Article 2(3) and (5)). DMDs are not smart meters; one may wonder whether they qualify as smart metering systems. A smart metering system is defined by Article 2(23) of the Electricity Directive as:

"an electronic system that is capable of measuring electricity fed into the grid or electricity consumed from the grid, providing more information than a conventional meter, and that can transmit and receive data for information, monitoring and control purposes, using a form of electronic communication."

The qualification of a DMD as a smart metering system and, therefore, the applicability of the IADA, seems to depend on the ability of the device to measure the electricity fed into or consumed from the grid, while there is no doubt that the device can transmit and receive data. However, a DMD, as defined in the electricity market design reform, does not seem able to provide such measurement, the purpose of its usage being the measurement of one component of the total amount of electricity fed and withdrawn from the grid, favouring the interpretation that the IADA is applicable to smart meters, but not to DMDs.[129]

Therefore, there is currently no sector specific discipline explicitly applicable both to smart meter and DMD data sharing, except for the general indications provided by the Electricity Directive. The overarching legal framework appears to be the data legislation, functioning as *lex generalis*. Moreover, uncertainties intensify when inquiring into the coherence between the different legal acts regulating the two measurement devices.

[129] For further elaboration on this topic, see Nicolai & Münchmeyer (2025).

A first such uncertainty relates to the definition of 'eligible parties', highlighted in Section 4.3.2. Curiously, the Electricity Regulation, as revised by Regulation 2024/1747, does not reference the concept of 'eligible parties' and, instead relates to system operators and 'relevant market participants including independent aggregators' as actors entitled to use the DMD data (Electricity Regulation, Article 7b(1)). The choice leads to a difference in the categories of actors allowed to use smart meters and DMDs data, even though all the potentially relevant market participants seem to be comprised in the broad definition of eligible parties provided by the IADA. Differences in the identification of the legal basis for the processing of data from smart meters and DMDs also exist and are tackled in the following subsection.

4.4.2 The Interplay between the Electricity and Data Legislation

We now turn to the ways in which electricity and data law interact when it comes to sharing of and accessing to electricity metering and consumption data. We focus on two particularly relevant nodes in the interaction between both legal disciplines. First, we examine the interplay between electricity legislation and the GDPR. We then turn to whether and how these rules are affected by the relatively recent introduction of the Data Act.

4.4.2.1 Electricity Legislation and the General Data Protection Regulation

The intersection between sector-specific electricity law and data law that has generated the most scholarly attention is that of how individuals' right to privacy and control over their data can be guaranteed in an electricity system whose efficient functioning will increasingly rely on the data from smart meters and DMDs, which can be classified as personal data. Even before the coming into force of the Electricity Directive, which strengthened pre-existing provisions meant to accelerate and harmonise smart meter roll-out across the European Union (particularly in Articles 19-21), Huhta cautioned against this conflict in general orientation between the Union's data and electricity law (Huhta, 2020). While electricity law sees the use of personal data as essential to electricity sector decarbonisation, data law emphasises the primacy of the individual right to privacy of the concerned electricity consumers (Huhta, 2020, p. 8). Adding to this fundamental tension of guiding objectives are specific legal challenges related to the roles and grounds for processing under the GDPR as discussed in Section 4.3.1 and the EU electricity *acquis*.

A first challenge, highlighted by Baumgart and Espinosa Apráez (2024, pp. 520–522) is the identification of the data controller and data processor. These roles, as defined in the GDPR, are not easy to match to the definitions provided in the IADA. Further, it is challenging to identify precisely who the data subject should be, since multiple individuals whose electricity consumption patterns constitute personal data may often live behind the same meter.

Baumgart and Espinosa Apráez thus posit that it is insufficient to only consider the consumer who has a contractual relationship regarding smart meter data processing, for example through an agreement with their supplier, as the sole data subject.

This latter point, in turn, is connected to the question of how legal grounds for the processing of data as per Article 6 GDPR are construed in the context of the processing of metering data. Article 7b(1) of the Electricity Regulation, which was introduced in the electricity market design reform, specifically mentions the need for the customer's consent for DMD data processing. While the amending Regulation (EU) 2024/1747 makes a broader and subtly different claim as to the basis for metering data processing in Recital 19, stating that the Regulation establishes 'a legal basis for the processing of personal data in accordance with Regulation (EU) 2016/679', the wording of Article 7b(1) of the Electricity Regulation does not leave space for any action without the customer's consent, leading to a reinforced legal basis for the processing of data from DMDs.

The IADA does not make explicit reference to consent for data access and sharing, but to 'permission', defined as 'the authorisation given by a final customer for an eligible party on the basis of a contractual agreement they have with this party, to access their metering and consumption data [...] for the provision of a specific service'. From this definition, it is possible to infer that the preferred legal basis for energy consumer data sharing with eligible parties, for smart meters and smart metering systems data, is Article 6(1)(b) GDPR, relating to the necessity of data processing for the performance of contractual obligations, while the Electricity Regulation, concerning DMD data sharing, nominates consent (Article 6(1)(a) GDPR).

4.4.2.2 Electricity Legislation and the Data Act

An analysis of the Data Act has been provided in Section 4.3.1. Due to its status of *lex generalis*, the DA must interact with the electricity legislation as sector-specific framework. It is therefore valuable to assess the interplay between these legal acts to evaluate the need for further clarity or to confirm their legislative consistency. For this purpose, the main elements of the analysis conducted by Nicolai and Münchmeyer (2025) are recapitulated.

Overall, there seems to be no conflict between the way the DA and the EU electricity legislation regulate energy consumer data sharing with eligible parties. On the contrary, an analysis of Chapter II (Business to consumer and business to business data sharing) and Chapter III (Obligations for data holders obliged to make data available pursuant to Union law) of the DA, the most relevant chapters for data exchange for energy services, reveals a relationship of consistency and complementarity.

Concerning the element of consistency, there are provisions of the DA which mirror the content of the earlier, sector-specific obligations for accessing and sharing energy consumption data. Article 3 DA states that data shall be accessible in a 'structured, commonly used and machine-readable format', as also provided by Article 5(1)(b) of the IADA. The common terminology ensures an alignment which derives from the concept of data portability as defined in Article 20 of the GDPR: 'The data subject shall have the right to receive the personal data concerning him or her, [...], in a structured, commonly used and machine-readable format and have the right to transmit those data [...]'.

Additionally, alignment occurs for what concerns the means of compensation for accessing to and sharing the data. In fact, according to the DA (Articles 3(1), 4(1), and 9), the user should have access to the connected product data free of charge, and the data recipient and the data holder (i.e., the natural or legal person that has the right or obligation to use and make available the product data (DA, Article 2(13))) should settle the compensation for making the data available. Similarly, the Electricity Directive foresees no additional costs to final customers for accessing their data or requesting to make them available (Electricity Directive, Article 23(5)).

Concerning the complementarity element, some gaps left in the sector-specific legislation seem to be filled by the DA. Firstly, the IADA does not outline the responsibilities of the eligible party with which the data is shared, while obligations on the third party receiving the data are set by the DA. Third parties must access the data only under the conditions and for the purposes agreed with the user and they must not make the exercise of choices or rights of the user unduly difficult (DA, Article 6). In case of applicability of the DA to energy consumers data sharing with eligible parties, GDPR provisions on data protection would be reinforced, for example avoiding unagreed profiling practices unless and to the extent necessary to provide the service requested by the user.

Secondly, concerning the information to be shared with consumers on the functioning of electricity smart meters, in 2012, the Commission published Recommendation 2012/148/EU, specifying a list of details to be communicated when preparing the roll-out of smart meters. The list is included in paragraph 29 of the Recommendation, which foresees information on: (a) the data controller; (b) the period of the data processing; (c) the purposes of the data processing; (d) the right to ask the controller for access to and rectification or erasure of the personal data; (e) the right to lodge a complaint in front of a supervisory authority; (f) the recipients of the data; and (g) any further information necessary to guarantee fair processing in respect of the data subject. However, that recommendation is not binding, and Member States were not obliged to implement it.

On the other hand, the DA mandates the connected product seller or lessor to convey: '(a) the type, format and estimated volume of product data which the connected product is capable of generating; […] (d) how the user may access, retrieve or, where relevant, erase the data, including the technical means to do so […]' (Article 3(2)). The sectoral applicability of the DA would legally oblige sellers or lessors of measurement devices to communicate details on their functioning to consumers, who would be more aware of the type of data generated and shared and of the procedures to access or erase it, on the one hand imposing more obligations on sellers and lessors of measurement devices, and, on the other, fostering consumers' control over the processing of their data, reinforcing, also in this case, the GDPR framework. However, to achieve this result, uncertainties about the application of the definitions of the DA to the electricity sector (e.g., connected product, user), should be clarified. Furthermore, it proves not straightforward to state whether consumers own or lease a measurement device and from which entity, due to the different contractual qualifications which exist in different Member States and to the variety of energy data management models in the EU (see Chapter 5).

Lastly, concerning the justiciability of the rights attributed to consumers when it comes to data access and sharing, the Electricity Directive does not refer to the right to lodge a complaint and, in general, to dispute settlement procedures relevant for energy consumption data sharing with eligible parties; in fact, the directive refers to the resolution of disputes between the consumer and the electricity supplier or against system operators, not the eligible party (see Articles 10, 25, 59). Article 26 seems to provide a general right to out-of-court dispute settlement:

"Member States shall ensure that final customers have access to simple, fair, transparent, independent, effective and efficient out-of-court mechanisms for the settlement of disputes concerning rights and obligations established under this Directive, through an independent mechanism such as an energy ombudsman or a consumer body, or through a regulatory authority."

Nevertheless, the Electricity Directive, as highlighted before, provides very general indications on metering and consumption data sharing with eligible parties; therefore, the provisions and the related obligations which could constitute the core of a complaint are very limited. On the other hand, the DA foresees for natural and legal persons the right to lodge a complaint in front of national competent authorities 'if they consider that their rights under this Regulation have been infringed' (DA, Article 38(1)). The DA offers more provisions and of a more detailed nature concerning connected product data sharing with third parties;

therefore, Article 38(1) provides a wider spectrum of protection, partially making up for the lack of judicial remedy in the IADA, the most detailed piece of sectoral discipline.

4.4.3 Building Systems Data: a Case Study for Clarifying the Applicability of Overlapping Legislative Frameworks

An instructive example of how the relationship between different legal acts from different legal fields which could, however, be interpreted to apply to the same set of data, could be clarified is the case of 'building systems data', which was the subject of a dedicated Commission Guidance in 2025 (C/2025/4132 final, Annex 6).

This issue is particularly salient considering the overlapping scopes and definitions found in the IADA, the Energy Performance of Buildings Directive (Directive (EU) 2024/1275, EPBD), and the Data Act. Each of these legislative instruments addresses aspects of data access and sharing, yet they do so from distinct sectoral standpoints—energy, buildings, and data governance respectively.

The concept of 'building systems data' was introduced in the recast EPBD, the EU's principal legislative framework for enhancing the energy efficiency of buildings. Adopted in 2024, the revised directive includes a dedicated provision—Article 16—on the exchange of building-related data. This provision is particularly relevant given the increasing integration of smart technologies, such as smart meters and DMDs, within multi-apartment buildings, where they become embedded components of the building ecosystem.

Article 16 mandates that Member States ensure building owners, tenants, and managers have direct access to their building systems data. This data is broadly defined to include:

> *"at least all readily available data related to the energy performance of building elements, the energy performance of building services, the projected lifespan of the heating systems, where available, building automation and control systems, meters, measuring and control devices and recharging points for e-mobility (emphasis added)."*

Furthermore, the provision stipulates that these stakeholders must be able to share such data with, or grant access to, third parties. [130]

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[130] To facilitate it, Member States are mandated to ensure the 'full interoperability of services and of data exchange within the Union' (EPBD, art 16(1)). The Commission must adopt an implementing act setting out more detailed requirements for such exchange and interoperability by the end of 2025 (art 16(5)).

This raised important questions about the interaction between the EPBD and the DA, particularly regarding the management of energy consumption data generated within buildings. The EPBD's definition of 'building systems data' appeared to align conceptually with the DA's definition of 'product data', which refers to:

> *"data generated using a connected product that the manufacturer designed to be retrievable, via an electronic communications service, physical connection or on-device access, by a user, data holder or a third party, including, where relevant, the manufacturer" (DA, Article 2(15)).*

Smart meters and DMDs likely fall within this definition, even if they do not fully conform to the DA's notion of a 'connected product' (Nicolai & Münchmeyer, 2025). It therefore seemed reasonable to consider building systems data as a potential subset of 'product data' under the DA.

A key point of legal ambiguity was the scope of Article 16 EPBD: did it encompass all metering and consumption data generated by smart meters and DMDs, or only data related to specific building functions such as heating, cooling, ventilation, lighting, and domestic hot water? The definition in Article 16(1) references 'building elements'—defined in Article 2(17) as 'a technical building system or an element of the building envelope'—but also explicitly includes 'meters' without clarifying whether this refers to all metering data or only that linked to energy performance functions. The wording of Article 16 seemed to blur the line as to what data should be included in or excluded from the umbrella of Article 16 EPBD, creating interpretative uncertainty.

The IADA adds another layer of complexity. As a *lex specialis*, it governs the access and sharing of electricity metering and consumption data (see Section 4.3.2.4), particularly in relation to building sub-units, e.g., the different apartments within it. However, electricity data represents only one component of a building's overall energy consumption profile. Consequently, the IADA's applicability appeared limited to the subset of building data concerning electricity, leaving other types of building systems data governed by the EPBD and potentially the DA.

In the absence of clear legal boundaries, this legal overlap generated uncertainty for stakeholders—building owners, tenants, managers, and third-party service providers—who must navigate these intersecting regimes (see Figure 4.4).

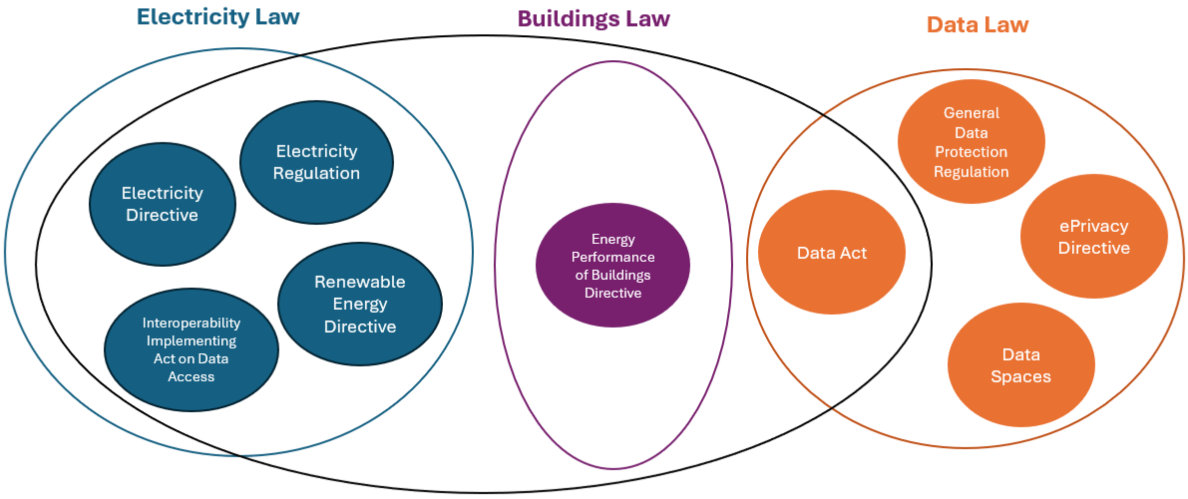

Figure 4.4: Interaction between Electricity, Buildings and Data Law Acts.
Source: Own elaboration.

The ambiguity surrounding the scope of 'building systems data' under Article 16 EPBD, and whether it includes all metering data or only data tied to specific functions, underscored the urgent need for interpretative guidance and legal clarification, which was provided in June 2025 by the European Commission.

In a comprehensive guidance document issued on 30 June 2025 as part of a broader support package on the EPBD, the Commission clarified the scope of Article 16 (C/2025/4132 final, Annex 6). Recognising the need for precision regarding the application of energy, data and buildings law, the Commission here specified that Article 16 EPBD applies to access to data regarding non-connected products and 'basic/static data on connected products', in the meaning of that term under Article 2(5) DA. However, the 'dynamic' data that is generated by these connected products falls solely under the jurisdiction of the DA. In the case of meters mentioned as part of building systems data in Article 16 EPBD, the guidance draws a distinction between what it terms 'regulated meters for the purpose of billing of electricity and gas consumption' and 'other types of meters, for instance sub-meters for gas that are not used for the purpose of billing'. The guidance clarifies that the term 'building systems data' used in Article 16 EPBD covers both static and dynamic data pertaining to these other types of meters (C/2025/4132 final, Annex 6, p. 7), but specifies that Article 16 EPBD covers static data only, for example regarding the presence and number of sub-meters. Meanwhile, data generated by 'regulated utility meters (including smart meters)' are bracketed out entirely, since the guidance specifies that these are covered by the Electricity and Gas Directives (C/2025/4132 final, Annex 6, pp. 3–4).

The issuance of this guidance is a useful case study for present purposes in two principal ways. First, it shows that the Commission, once cognisant of uncertainties as to the scope and applicability of different legal regimes to the same data, does not hesitate to provide comprehensive and clarifying guidance on how exactly legal provisions should interact in the implementation by Member States. As our analysis above has shown, there may be need for a similar guidance regarding the relationship between electricity and data law. A complicating factor that should be acknowledged here is that, while the guidance on Article 16 of the EPBD was issued before the Directive's transposition deadline of 29 May 2026, the IADA and DA, as Regulations, have been directly applicable since their entry into force. Secondly, this guidance shows that, at least in the case of buildings, the Commission seems to prefer an arrangement in which the scope of application of all three areas of law is exclusive and clearly defined without overlap. In issuing the guidance, the Commission thus does not seem to endorse the more layered idea of the DA as *lex generalis* with buildings and energy law as *leges speciales* providing additional, more detailed rules for these specific sectors.

4.5 Conclusion

The ability to securely and efficiently share electricity metering and consumption data with authorised parties—from grid operators to energy service providers—enabling demand response, congestion management, and greater consumer participation in decarbonisation efforts lies at the heart of the European twin transition towards a decarbonised and digitalised future. Yet, as the regulatory landscape evolves, the interplay between energy and data law presents both opportunities and challenges.

This chapter provides a mapping of the principal EU legal framework(s) applicable to the access to and sharing of electricity metering and consumption data. While it primarily focuses on the EU's data law and sector-specific electricity law, the chapter also highlighted an example of the interaction with buildings law. This mapping will already be a valuable resource for further research into this complex legal landscape. However, it is also possible to draw three main conclusions from the above analysis, both as regards the individual sectors examined and their interplay.

Firstly, we analysed the electricity sector legislation relevant for electricity metering and consumption data exchange with eligible parties for the provision of energy services for consumers to map the existing rights and obligations of the actors involved in the process. We highlighted how the Electricity Directive sets the stage by requiring Member States to facilitate fair and non-discriminatory access to consumer data, empowering market players to offer innovative services. Complementing this, the IADA introduces common rules to streamline data exchange, promoting interoperability across borders. Meanwhile, the electricity market design reform expands the options to participate in flexibility services by recognising the role that can be played by DMDs; this is a welcome step, though questions remain about how these devices fit into the existing regulatory structure compared to smart meters. Finally, via the Common European Energy Data Space, the EU is laying the groundwork for a unified approach to energy data sharing, though its full legal and operational framework is still taking shape.

Secondly, our mapping of the relevant data law has shown that, while the application of the GDPR to electricity metering and consumption data is a relatively straightforward and well-researched issue, the same cannot be said for the DA. Here, definitional uncertainty exists as to whether smart meters and DMDs fall within the scope of the DA, particularly due to the specific ownership structure regarding smart meters, which renders it difficult to discern if these devices, which *prima facie* seem to conform to the type of product that the DA targets, can be said to be 'connected products' under it, and, more crucially, whether electricity consumers can be considered the 'users' of their smart meters. Clarification from the EU legislator seems to be necessary to resolve this question, which will become particularly pertinent for future revisions and recasts of relevant sector-specific electricity law. These recasts, revisions, and indeed potential additions to the EU's energy *acquis* would be legislative instruments post-dating the DA and thus fall more squarely within its legal framework. The case of 'building systems data' is exemplary in this sense. It shows how the European Commission, aware of the potential definitional uncertainty as to whether, and indeed which, data from smart meters and DMDs falls within the scope of Article 16 EPBD was able to intervene with a soft law instrument clarifying the boundaries of the *lex generalis* (data legislation) and the *leges speciales* (electricity law and the EPBD).

Finally, the perhaps most important conclusion that we can draw from this comprehensive mapping of EU law is that a systematic integration of the two legal areas examined is missing, at least to some extent. This stems partly from the abovementioned definitional uncertainties, an unclear relationship between *lex generalis* and *lex specialis*, as well as a lack of explicit cross-references in the legislation itself. As our analysis above has shown, so far this does not seem to have resulted in any outright contradictions between the legal regimes examined. However, the potential for conflict is clear. The lack of clarity as to how the legal regimes relate to each other, if at all, seems to open the door to fragmented national implementation of these rules regarding electricity metering and consumption data, as well as legal challenges before national and European courts and, potentially, data protection authorities. Such uncertainty about when and which rules apply risks ultimately introducing an element of confusion for service providers, especially if offering services cross border, as well as, crucially, for the consumers' understanding of an already complex regulatory and technical area that has historically been fraught with distrust and concerns as to data protection. For instance, while smart meters benefit from detailed interoperability rules, DMDs operate in a regulatory grey area, leaving market participants uncertain about compliance.

In conclusion, the benefits of data sharing to consumers, such as lower energy costs and personalised services, must be balanced against privacy concerns. Simplifying consent mechanisms and improving transparency will be key to building trust and encouraging their participation. In parallel, to get to a decentralised, data-driven energy system, policymakers must ensure that EU energy and data law evolve in synchrony, closing regulatory gaps while fostering innovation. Clear definitions, a harmonised and simplified approach where possible and relevant, and robust consumer protection will be essential to unlocking the full potential of energy data sharing.

5 RESEARCH ON REGULATION OF DATA SHARING INFRASTRUCTURE

5.1 Introduction

This chapter starts from Article 23 of Directive (EU) 2019/944, which requires Member States to organise the management of data to ensure efficient and secure data access and exchange but does not prescribe a specific approach to achieve this.[131] Instead, the Directive recognises that no single solution might fit all national contexts and sets out a series of obligations that Member States must comply with when developing data management models (DMMs). As a result, different approaches to organising the management of final customer data persist across Europe.[132]

The possible negative consequences of heterogeneity in DMMs were anticipated by Article 24 of the Directive, which requires Member States to facilitate the full interoperability of energy services within the Union and mandates the European Commission to adopt interoperability requirements and non-discriminatory, transparent procedures for access to data by means of implementing acts. The first of such implementing act, Commission Implementing Regulation (EU) 2023/1162, was published in June 2023 and aims to promote the interoperability of energy consumer data management models by developing a reference model for access to metering and consumption data. Our investigation of how this implementing act may foster interoperability of energy consumer data access and exchanges aligns with the objectives of the EDDIE project, which seeks to develop a decentralised, open-source data space for seamless and secure energy data exchange across Europe. It must be noted that similar analyses might be performed for other implementing acts on topics such as customer switching, energy communities and demand response that are expected in the coming months and years. However, this chapter focuses

[131] Article 23 of Directive (EU) 2019/944 also specifies that "data shall be understood to include metering and consumption data as well as data required for customer switching, demand response and other services". These data can be further distinguished in validated, historical data and near real-time data.
[132] A description of how data management is organized in several European countries is available also in Deliverable 5.2 of the EDDIE project.

on Commission Implementing Regulation (EU) 2023/1162, as the others were not available in a finalised version at the time of writing.[133]

The main contribution of this chapter comes from the mapping of nine frontrunner European DMMs against the reference model introduced by Commission Implementing Regulation (EU) 2023/1162. Our analysis suggests that the traditional taxonomy, which used to classify data management models into centralised, hybrid and decentralised models, may be insufficient to capture the variety of national practices that have emerged across Europe. Therefore, we propose a richer taxonomy that distinguishes models based on the specific roles that are centralised and the entities that take up the responsibility of those centralised roles. This detailed mapping of national DMMs aims to make the specific roles and responsibilities for access to data clear and understandable for market participants, thereby fostering competition in retail markets and avoiding excessive administrative costs across borders. Beyond the richer taxonomy, we also discuss the main challenges ahead and lessons learned from the interviews with the selected frontrunner countries.

The content is organised around five main sections. Section 5.2 describes the adopted research methodology in more detail. Section 5.3 discusses different models for organising access to and sharing of energy consumer data and proposes a richer taxonomy to classify them. Section 5.4 examines the main arguments influencing the level of centralisation of data management models, with particular attention to cost efficiency. Section 5.5 provides further insights into data-sharing governance and stakeholder involvement. Finally, Section 5.6 introduces some of the future regulatory challenges that energy consumer data management models might face.

5.2 Methodology

The scoping of the research presented in the next sections started with a desk review of the relevant legislation, stakeholder reports and academic literature on European data

[133] A draft of a second implementing act on customer switching was published on 21 May 2025 and subject to public consultation. At the time of writing the act was under comitology. For more information on the public consultation, see https://energy.ec.europa.eu/news/have-your-say-call-feedback-technical-rules-smoothly-switching-electricity-supplier-2025-05-21_en. A third implementing act on demand response was under preparation by the Joint Working Group on Data Interoperability by ENTSO-E and DSO Entity. Its publication is expected in 2026, together with the Network Code on Demand Response. For an overview of this and other recent developments, see FSR (2025b).

management models for consumer data. A summary of the review was presented in a research note that identified a knowledge gap concerning the advantages and disadvantages of centralised versus decentralised models and highlighted the need for more empirical evidence to better understand how different data management models are being implemented across Europe.

In the context of this Deliverable, we aimed to contribute to these open research questions by conducting online semi-structured interviews with 14 national entities involved in various roles in the data management models of 9 European countries. The interviews, which took place between January and March 2025, covered Austria, Belgium, Estonia, Finland, France, Italy, Norway, Spain, and the Netherlands. While these countries apply different approaches to data management, they all demonstrate advanced practices in ensuring access to metering and consumption data for final customers.

The interviews were structured around six main parts: (1) introduction, (2) mapping the EU reference model, (3) implementation barriers and solutions, (4) past and future evolutions of data management models, (5) cost and performance parameters, and (6) closing remarks. To give an indication of the interview process, Table 5.1 summarises the questions and duration of each part. The research findings were subsequently discussed with some of the interviewees (and additional experts) during a workshop held on 12 February 2025 in Brussels, organised in cooperation with Vlerick Business School. A first consolidation of the main findings and policy recommendations from this workshop was published as an FSR Policy Brief in June 2025, which was presented and discussed in an online debate on 2 July 2025 (FSR, 2025a).[134] Therefore, the following sections contain some fragments of Beckstedde and Rossetto (2025), complemented by additional literature review and insights from the interviews.

Structure	Interview questions
Introduction (5 min)	Presentation of the people in the meeting. Clarification of the structure of the interview. Interviewees were invited to share relevant references and websites.

[134] The highlights of the online debate are available in FSR (2025b).

	Interviewees were asked if they were fine with the recording of the meeting to facilitate the preparation of the workshop; they were also informed that the recording would have remained private and that it would have been deleted afterwards. Interviewees were informed that high-level, anonymized results of the interviews and the workshop might contribute to Deliverable 7.2 of the EDDIE project.
Mapping the EU reference model (10 min)	Presentation of the DMM for metering and consumption data in the country as understood by our desk research (focus on the roles of metered data administrator, data access provider and permission administrator). Did we correctly understand the identity of the different actors taking up these roles in your country? Potential bonus question: What were the main reasons to implement this type of DMM in your country?
Implementation barriers and solutions (15 min)	Did you face any particular barriers or delays during the implementation of the DMM? What were the main reasons behind those barriers or delays? Are these challenges specific to the DMM solution selected in your country? What were the main lessons learnt during the implementation process? Are these lessons specific to your DMM solution or can they be applied more broadly?

Past and future evolutions of data management models (15 min)	Has the DMM in your country already undergone substantial updates since its first implementation? What were the main drivers behind these updates (e.g., implementation of new functionalities, regulatory requirements, technical limitations)? What will be the most important evolution DMMs will face in the coming years (e.g., energy communities, flexibility registers, (near) real-time data)? Are the current design and operation of the DMM in your country (sufficiently) agile to support this evolution?
Cost and performance parameters (10 min)	Are the different actors taking up the DMMs roles in your country subject to any audits or benchmarks? If so, what are the main performance parameters used in these evaluations? What were/are the main cost drivers during the implementation and operation of the DMM in your country? Who pays for those costs and how? Is any form of incentive regulation in place?
Closing remarks (5 min)	Do you have any questions for us? Do you have any questions about the workshop in Brussels?

Table 5.1: Overview of the interview structure and questions.

5.3 Different models to organise access to energy consumer data

First, we explain the traditional taxonomy and the role model that is part of the reference model introduced by Commission Implementing Regulation (EU) 2023/1162.[135] Second, we propose a richer taxonomy to classify data management models for validated, historical metering and consumption data and describe the two observations leading to this proposal.

[135] Note that the reference model of Commission Implementing Regulation (EU) 2023/1162 also contains an information and process model, but this chapter solely focuses on the role model.

Third, we elaborate on three nuances in the classification of DMMs that arise from this richer taxonomy but were difficult to discern when using the traditional taxonomy. Finally, we describe the status of the Joint Working Group on Data Interoperability repository that was developed by ENTSO-E and DSO Entity in the context of Commission Implementing Regulation (EU) 2023/1162.

5.3.1 The traditional taxonomy and the new role model

Depending on the architecture chosen for storing and distributing the data, DMMs have been traditionally distinguished as centralised, decentralised or hybrid (see, among others, CEER, 2016; Thema, 2017; GEODE, 2020; European Commission, 2024d).

- In a **centralised model**, all data are sent and stored in a data hub, operated and developed by a specific party or service provider. All processes run on the data hub and results are sent back to the relevant actors. Market participants use the functionalities of the data hub to exchange data.
- In a **decentralised model**, data are stored at the source or close to it, and market participants communicate directly with each other to exchange data for specific purposes. Standardised market communication is normally developed together by the various actors to facilitate bilateral data exchange.
- In a **hybrid model**, elements of both centralised and decentralised models are present. Market participants typically communicate bilaterally, but task-specific centralised structures are present to support some specific use cases. Accordingly, data are copied sparingly and only in the context of those use cases.

Instead of referring to the traditional taxonomy, the role model introduced by Commission Implementing Regulation (EU) 2023/1162 specifies a set of roles, detailing their responsibilities and interactions. The model is agnostic about the identity of who performs each role. A role can be assigned to different actors, and the same actor can perform more than one role. Some roles are naturally assigned to the same actor across most of the EU Member States. An example is the meter operator, who is responsible for installing, maintaining, testing and decommissioning physical meters. For final customers connected to the distribution grid, this role is generally assigned to distribution system operators, even in centralised DMMs. For other roles, variability among countries is apparent. In this chapter, we mainly focus on three roles that are typically taken up by actors of different nature across Member States:

1) The **metered data administrator**, who is responsible for storing validated, historical metering and consumption data and distributing these data to the final customer and eligible parties.
2) The **permission administrator**, who is responsible for managing data access permissions.

3) The **data access provider**, who is responsible for facilitating the access by the final customer or eligible parties to metering and consumption data.

Other roles that are outside the scope of this analysis are the final customer, the competent authority, the eligible party, the metering point administrator, the identity service provider, the meter operator, the smart meter and the near real-time data consumption system. A definition of these roles can be found in Table II of the Annex of Commission Implementing Regulation (EU) 2023/1162.

5.3.2 Two observations calling for a richer taxonomy

Although intuitive and valuable for orientation, we find that the traditional taxonomy may not fully capture the different nuances between national implementations of DMMs. This limitation was also expressed by the European Commission in its Guidance for the Reporting of National Practices in accordance with Commission Implementing Regulation (EU) 2023/1162 (European Commission, 2024d). More specifically, two observations emerged from the interview conducted in the context of this deliverable, both indicating the need for a richer taxonomy.

First, we observe that different interpretations of the three categories of the traditional taxonomy can exist. Some experts, for instance, refer to DMMs as centralised not when a data hub is present, but when a standardised data exchange framework is managed by a single entity and used by all market participants. This ambiguity associated with the traditional taxonomy can be overcome by specifying which roles of the Commission Implementing Regulation are centralised and assigned to a single entity.

Second, we notice that the entity taking up the centralised role(s) in data management can consist of various actors, such as distribution system operators (DSOs), transmission system operators (TSOs), third parties or a combination of them. Depending on the nature of the involved actors, centralised entities can have differences in available resources, commercial interests and obligations within the energy system. Assigning the same role to an entity of a different nature can thus potentially have varying implications, which, in turn, can call for alternative forms of regulation. Again, the traditional taxonomy can be refined by specifying the nature of the entity that takes up the centralised role(s) in data management models.

Based on these two observations, we propose the taxonomy of Figure 5.1 and map the nine European countries considered during the interviews accordingly. The vertical axis describes which of the DMM's roles are centralised. The more you move up along this axis, the more roles are assigned to a single entity. The horizontal axis specifies the nature of the entity taking up the centralised role(s). The more you move to the right on this axis, the more data management is taken away from DSOs and, eventually, from all system operators.

It must be noted that this mapping reflects the national DMMs for access and exchange of validated, historical metering and consumption data of final customers connected to distribution grids. As a result, the flags may appear in different positions when considering near real-time data or customers connected to the transmission grid. Moreover, the mapping represents the situation in these countries up to February 2025, when the main research for this deliverable was conducted. Since then, some national models might have evolved along both axes. Nevertheless, the figure offers a useful indication of how a richer taxonomy may help to more accurately reflect the diversity of national approaches.[136]

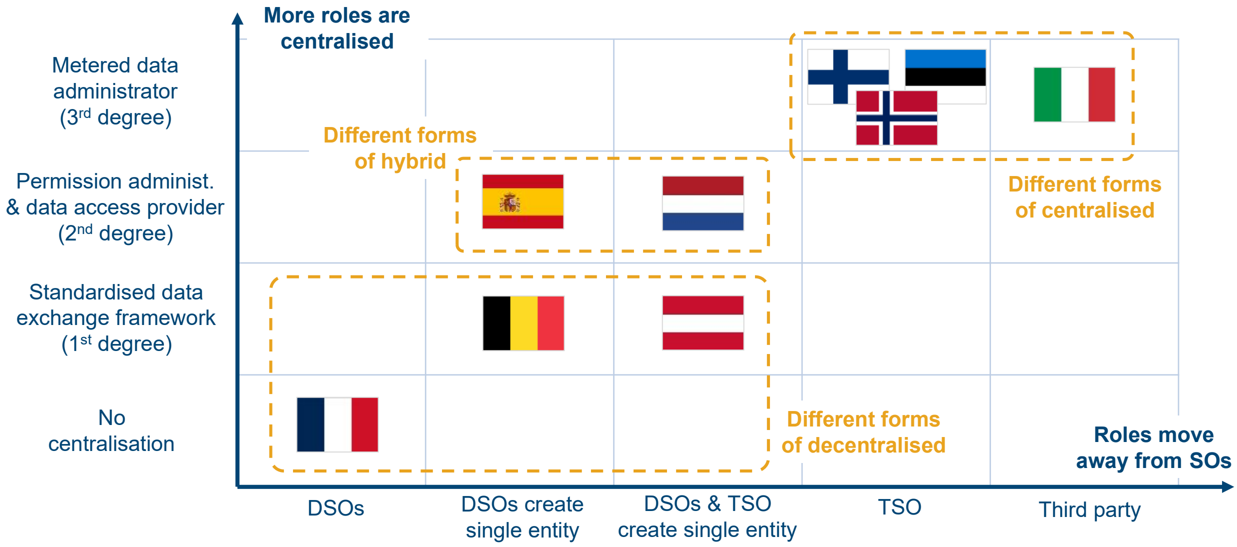

Figure 5.1: A richer taxonomy of data management models for the access and exchange of validated, historical metering and consumption data of final customers connected to distribution grids.
Note: The taxonomy is applied to a selection of established data management models in Europe and reflects the situation up to February 2025.

[136] As mentioned later in Section 5.3.4, more updated information can be found on the repository of national practices in the Joint Working Group on Data Interoperability website (https://www.data-interoperability.eu/).

5.3.3 Three nuances previously hidden

The proposed, richer taxonomy reveals at least three nuances to the traditional classification of data management models.

First, different forms of decentralised DMMs exist. Decentralised models typically do not centralise any of the roles of the reference model: each DSO collects and stores metering and consumption data, manages permissions and provides data access for the customers connected to its own grid. Nevertheless, we observe that a first degree of centralisation might already occur in some decentralised models when countries develop a standardised framework of communication protocols, data formats and processes to support the access and exchange of data. This is the case in Belgium, where Atrias was developed as a joint initiative of national DSOs, and Austria, where EDA was established by DSOs in collaboration with the TSO.[137] On the contrary, a national, standardised data exchange framework does not exist in France: in addition to the data hub put in place by Enedis, the largest electricity DSO, other processes have been developed in parallel by the other French DSOs.[138] This finding contrasts with the common perception of France as having a centralised DMM, since Enedis serves roughly 95% of continental metropolitan France. However, according to our taxonomy, France should be considered decentralised rather than centralised. It is worth noting that in countries characterised by a more diverse DSO landscape, such a fully decentralised configuration could lead to greater fragmentation than is currently observed in France.

Second, different forms of hybrid DMMs are possible. Hybrid models are generally placed at a second degree of centralisation as the storage of metering and consumption data remains with the DSOs, but the data exchange framework, the role of permission administrator and the role of data access provider are coordinated nationally by a single entity. Again, our mapping shows that there might be differences in the nature of the entity taking up these activities. In Spain, the Datadis platform, which facilitates data access for final customers and eligible parties based on customer consent, was created by all DSOs and is operated by

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[137] Status February 2025. More information about Atrias and EDA is available, respectively, at https://www.atrias.be/ and https://www.eda.at/.

[138] Status February 2025. More information about Enedis' data hub is available at https://datahub-enedis.fr/.

Aelēc, an association of electricity companies.[139] BAS performs a similar role in the Netherlands but, unlike Datadis, it involves not only the Dutch DSOs but the TSOs as well.[140]

Third, different forms of centralised DMMs exist. In the case of DMMs characterised by a third degree of centralisation, the storage and distribution of metering and consumption data, i.e. the role of metered data administrator, is also performed by a single entity. The nature of this single entity can again be different. In several Nordic countries, such as Estonia, Finland and Norway, the TSO was tasked with the establishment of a data hub.[141] On the contrary, the Italian data hub, called Sistema Informativo Integrato (SII), is managed by Acquirente Unico, a public company owned by the Italian Ministry of Economy and Finance and independent from the energy system operators.[142]

5.3.4 The Electricity Data Interoperability Repository

Beyond introducing the reference model, Commission Implementing Regulation (EU) 2023/1162 required EU Member States to report on the national practices for metering and consumption data access by 5 July 2025. In addition, the Commission Implementing Regulation mandated the establishment of a Joint Working Group (JWG) by ENTSO-E and the DSO Entity to guide Member States in their reporting, collect the national reports, and maintain a publicly available repository where the reports are published and updated (art. 11 and 12).

The JWG on Data Interoperability launched the Electricity Data Interoperability Repository on 7 July 2025 (ENTSO-E, 2025). The repository serves as a single point of access for stakeholders to obtain the up-to-date information on national practices of current and forthcoming implementing acts on data interoperability. As of October 2025, the national reports of 12 Member States are available on the website, of which the reference models of 10 Member

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[139] Status February 2025. More information about Datadis is available at https://datadis.es/home.
[140] Status February 2025. More information about BAS is available at https://www.mffbas.nl/. BAS has been recently renamed as Het Normo. More information about Het Normo is available at https://hetnormo.nl/.
[141] Status February 2025. More information about the data hubs in Estonia, Finland and Norway is available, respectively, at https://elering.ee/en/electricity-data-exchange, https://www.fingrid.fi/en/electricity-market/datahub/, https://elhub.no/.
[142] Status February 2025. More information is available at https://www.acquirenteunico.it/attivita/sistema-informativo.

States are already accessible and comparable on an interactive tool (DSO Entity and ENTSO-E, 2025).[143]

It must be noted that the main research supporting this chapter was conducted before the reporting deadline and the creation of the Electricity Data Interoperability Repository. To connect our results with the efforts of the JWG and Member States, an FSR Online Debate was organised on 2 July 2025 to discuss stakeholders' expectations for the repository and future activities of the JWG. The recording and highlights of the debate are available at FSR (2025a) and FSR (2025b) respectively.

5.4 Arguments determining the level of centralisation of data management models

Figure 5.1 indicates a tendency towards a minimum degree of centralisation in European data management models. While this does not necessarily entail the creation of a national data hub, it is apparent that most countries have at least standardised the data exchange framework to foster interoperability and reduce transaction costs associated with the exchange of data between the different actors of the energy system.

The extent to which this trend towards centralisation, particularly for roles such as permission administrator, data access provider and meter data administrator, will continue remains an open question. In what follows, we first provide insight into the different arguments that might influence the decision of moving towards a more centralised or decentralised model, before exploring one of the dimensions in more detail. Finally, it should be noted that even when the decision is made to establish a central data hub, some roles associated with data management are likely to remain decentralised. This is the case, for instance, for the metered data collector and the metered data responsible, two roles respectively in charge of the sourcing and validation of metering and consumption data, which are typically assigned to DSOs.[144]

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[143] More specifically, the national practices on electricity metering and consumption data of Austria, Belgium, Czech Republic, Denmark, Finland, France, Malta, Poland, Portugal, Romania, Slovenia and Sweden are accessible in the Repository (Status: October 2025).

[144] The roles of metered data collector and metered data responsible are not included in the Commission Implementing Regulation (EU) 2023/1162. However, their definitions, together with that of other roles, are provided by the Harmonised Electricity Market Role Model (HEMRM), which ENTSO-E, EFET and ebIX have developed and maintained over time. The HEMRM aims to "facilitate

5.4.1 Key dimensions influencing the level of centralisation

The degree of centralisation of data management roles is typically evaluated at the national level in terms of four dimensions:

- **Cost efficiency** or minimising the costs for all stakeholders and consumers by streamlining processes, reducing transaction costs, and leveraging economies of scale.
- **Consumer centricity** or empowering customers by unlocking their access to metering and consumption data and enabling their active participation in both retail and wholesale energy markets.
- **Data integrity and security** or ensuring that all data is protected according to relevant privacy regulations and that its quality, accuracy, and reliability are maintained.
- **Agility** or facilitating the adaptation of data exchange systems to future needs, new use cases, and forthcoming technological developments.

Because gains in one dimension may come at the expense of another, national decision regarding the DMM to adopt are typically shaped by the priority given to each dimension. For example, according to the experts interviewed, consumer-centricity was seen as an important argument to adopt a data hub in Finland, while cost-efficiency and agility in supporting new business processes have been mentioned as important drivers to standardise the data exchange framework but not to establish a national data hub in Austria. Also, the broader context in which a DMM operates, such as the concentration of DSOs and the roll-out of smart meters, influence the level of centralisation of data management roles.[145]

Furthermore, we find that the same dimensions might be used to support the adoption of either centralised or decentralised approaches depending on the stakeholders interviewed and the context in which they operate, suggesting that differences in the considered scope

the dialogue between the market participants from different countries through the designation of a common name for each role and associated responsibilities towards other roles and objects that are prevalent within the European electricity market information exchange. It focuses essentially to enable a common terminology for IT supported information exchange." The latest version of the HEMRM, now prepared by ENTSO-E and DSO Entity is available in ENTSO-E and DSO Entity (2025).

[145] For the concentration of DSOs and the roll-out of smart meters in the various European countries, see for example Eurelectric (2020), ACER and CEER (2024), and DSO Entity (2025).

and interpretation of cost efficiency, consumer centricity, data integrity and security, and agility can exist across countries. Table 5.2 illustrates some of these contrasting arguments based on insights from experts across various Member States and a review of the traditional literature on the classification of data management models, including CEER (2016), Thema (2017), and GEODE (2020).

	Arguments in favour of greater centralisation	Arguments in favour of greater decentralisation
Cost Efficiency	Centralisation reduces transaction costs and interface costs	Decentralisation avoids development and maintenance costs of a central database
Consumer Centricity	Centralisation provides a single point of contact for end-users, making the system inherently user friendly	Decentralisation can ensure consumer centricity by designing protocols with the consumer at the centre
Data integrity and security	Decentralisation requires strict enforcement of security standards across multiple interfaces	A central database forms a single point of attack and failure, and requires data replication which may undermine integrity
Agility	The potential complexity of add-ons of decentralised models can be reduced to some extent	The potential lengthy implementation of changes in centralised models can be avoided by resorting to decentralised solutions, at least to some extent

Table 5.2: Illustration of arguments related to cost efficiency, consumer centricity, data integrity and security, and agility that are used in favour or against the centralisation of data management roles.

5.4.2 A closer look at cost drivers and cost allocation of DMMs

The interviews conducted with the experts from national data management models and the review of the existing academic and non-academic literature suggest the absence of a shared understanding of how cost-efficiency, consumer-centricity, data integrity and security, and agility should be defined and assessed in the context of consumer data sharing in the energy sector. Therefore, leveraging on the evidence collected, we now focus on exploring one of these arguments in more detail. We concentrate on cost-efficiency because it is generally less discussed in the literature, as also mentioned earlier in Chapter 2 (see Section 2.5.4). A more detailed discussion of the dimension data integrity and security can be found in Chapter 6 of this Deliverable.

To better understand the cost aspect related to data management, we examined:

- the primary cost drivers associated with implementing and facilitating data access, and
- the main parties to whom these costs are allocated.

This scoping exercise provides an initial overview of the cost dimension of data management based on expert interviews, without claiming to capture the full range of possible cost factors.

First, the cost drivers. As already discussed in Section 2.5.4.1, we observed that the primary cost components can be grouped into development costs, which are generally larger one-off expenditures, and operational costs, which are typically, smaller but recurring payments. Table 5.3 summarises the most common cost elements mentioned during the interviews. Overall, experts indicated that these costs are relatively small compared to the total costs of the energy system, but they may pose challenges for smaller actors such as local DSOs.

Development costs	Operational costs
- Agreement with all system users on the data management model, communication standards and interfaces - Design of (new) functionalities and associated processes - Implementation of IT solutions (custom-built or purchased from external providers)	- Personnel and software licenses - Maintenance of platforms and IT systems - Data storage and cloud services, where applicable - Auditing of data access permissions, where applicable

Table 5.3: Main cost elements of data management models, as reported during the interviews.

Second, the cost allocation. We observed two main approaches for recovering the costs of facilitating access to energy consumer data. In about half of the analysed countries, the costs are recovered solely through system operator(s). In the other half of the cases, the costs are recovered from a combination of system operator(s), suppliers, energy service providers and other third parties accessing the data management interface. Here it must be noted that the contribution to the recovery of data management costs is generally based on a fixed fee (e.g., euro/month), possibly differentiated on the basis of the type of actor, or on a combination of a fixed fee and a metering point-dependant fee (e.g., euro/metering point/month). In the latter case, a market participant is typically charged based on the number of metering points that falls under its responsibility (e.g., in the case of an energy supplier, this would be the number of final customers he supplies). Finally, two observations can be made regarding cost allocation: a) the costs paid by system operators are typically passed on to final users via network charges; b) the emergence of new actors interested in accessing consumer data and the appearance of new use cases that require such access are inducing a reflection on the way costs associated with data management are allocated, eventually leading to a redefinition of the actors that must contribute.[146]

[146] For a more detailed description of cost allocation in six European countries (Austria, Belgium, Italy, Norway, Spain and the Netherlands), see Section 2.5.4.2.

5.5 Insights on stakeholder involvement and performance monitoring

Article 23 of Directive (EU) 2019/944 does not specify the governance of data management nor the way stakeholders must be involved. Still, both are relevant for at least three reasons. First, inclusive governance can build trust and support consensus among the diverse stakeholders involved in data management. Second, stakeholder involvement can mobilise technical expertise and support the smooth implementation of new rules and processes. Third, stakeholder consultations help to align future DMM developments with the evolving data access and exchange needs of final customers and market participants.

Reflecting these needs, various governance approaches and forms of stakeholder involvement have emerged across European countries, regardless of the DMM in place. While some countries rely on more ad-hoc arrangements, others have started to formalise governance and apply stakeholder interactions more systematically.[147] To what extent countries should formalise stakeholder involvement and assign control to market participants remains an open question.[148] Two aspects are worth mentioning here. First, the stakeholder landscape can be more or less complex, depending on the number, size and capabilities of market participants, making it important to consider how all perspectives can be equally represented, including those of the smaller and less capable stakeholders. Second, stakeholder involvement can be lengthy, making it essential to designate a final decision-maker – be it a ministry, regulator, or market party – which intervene in case no consensus is reached on a certain topic within a reasonable timeframe.

Monitoring the performance of the data exchange framework of a country can support trust among stakeholders and could potentially be used to incentivise increased cost efficiency or higher quality in data management. However, this aspect of data governance seems to

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[147] The Marktfaciliteringsforum (MFF) in the Netherlands, for instance, manages consultations and facilitates discussion among stakeholders on the energy data exchange framework. To involve all actors of the fragmented Italian market, changes in technical specifications and rules governing data sharing are subject to public consultation, respectively by Acquirente Unico and ARERA. Another example is the Data Development Plan published by Flemish DSOs in Belgium, which provides stakeholders with an overview of the data management functionalities that are prioritised for the next 10 years.

[148] It is possible that the appropriate answer to this question depends on the specific "use case" considered: definition of data formats and processes; supporting the implementation of agreed rules and data-exchange solutions; definition of the new functionalities to develop.

be not yet mature at the moment nor explicitly linked to the remuneration of the actors that are responsible for the management of metering and consumption data. National practice is in this regard quite heterogeneous. In some countries, formal oversight of a regulatory authority is in place and the entities involved in data management are accurately monitored. This is the case, for example, of Norway, where Elhub, is subject to an external audit every three years, with the results made available to the public (Vista Analyse og Vali, 2025).[149] Other countries rely more on self-regulation, with the regulator intervening only in case of complaint by one of the stakeholders. This can occur, for example, when the entity managing data access fails to fulfil the requirements specified in the service level agreement that is typically signed with the relevant market participants. An example in this regard is Spain, where Aelēc monitors a series of Datadis parameters and perform audits with external service providers on topics such as cybersecurity and the compliance of third parties with the consent management rules.

While there is an expectation of more formal oversight of data management in the future, attention must be paid to the indicators used to monitor performance. The choice of these indicators must consider the fact that data management typically involve several actors.[150] Moreover, the achievement of high levels of service quality naturally requires higher levels of investment in the metering and communication infrastructure. Setting targets that are not achievable or that do not consider the sequence of processes leading to data being made available to final customers and eligible parties may have negative implications in terms of transparency and trust.

5.6 Future challenges of data management models

The implementation of a data management model adequate for the energy system is not a result that you can considered as achieved forever. Energy systems are constantly evolving, with new data-related needs emerging over time (Rossetto and Reif, 2021). Data management models are called to adapt and be able to support the fulfilment of those needs.

[149] The report on the results of the audit includes a chapter dedicated to user satisfaction.
[150] For example, a data hub, which performs the role of metered data administrator, can support access to metering and consumption data only once it has received the validated data from the meter data collector and the meter data responsible, two roles that are normally performed by the DSOs.

Three needs are visible today. First, more granular (historical and validated) h metering and consumption data are needed to expose energy consumers and prosumers to the changes in the value of electricity over time. The current deployment of smart meters In Europe and beyond enables the production and transmission of those data with a granularity of up to 15 minutes. Second, metering and consumption data are used to support an increasing variety of market processes and business models that is hard to predict in advance. If DMMs were originally designed with in mind the traditional activities of consumer billing and supplier switching, we see today several new use cases, such as the provision of electricity from multiple suppliers, including energy sharing and peer-to-peer exchange within energy communities, the provision of automatic discounts targeting certain categories of consumers, the participation in flexibility markets, and so on (Glachant and Rossetto, 2021). Third, and related, not only there is an interest in more granular data, but also there is a growing interest in having access to data closer to real time, as it enables more advanced services that dynamically react to market prices or to the specific conditions of the electricity system. In this context, the data exchange framework is expected to handle more data, to support a broader and possibly expanding set of market processes and business models, potentially outside the traditional data validation process.

In what follows, we provide some insights emerged during the conversation with the experts about the challenge posed by increasing data volumes and the growing interest in near-real time data.[151] We also mention other challenges that were identified but not explored in detailed and that may justify further research in the future.

The challenge of increasing data volumes

As smart meters increasingly support the measurement of consumers at the same resolution of the imbalance settlement period (i.e., every 15 minutes), DMMs must deal with growing volumes of validated, historical metering and consumption data.[152] This evolution may challenge the sustainability of the existing data management solutions, depending on how many consumers request or accept to be metered at this granularity, how fast those data must be validated and made available, and how long those data must be stored for future use.

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[151] Near real-time data are typically non-validated and provided continuously in a short time period, down to seconds or up to the imbalance settlement period in the relevant market.
[152] Art. 20, letter g of Directive (EU) 2019/944 says the "smart metering systems shall enable final customers to be metered and settled at the same time resolution as the imbalance settlement period in the national market". At the same time, Regulation (EU)2019/943 states that the imbalance settlement period cannot be longer than 30 minutes from 2025 (art. 8(4)).

Anticipating this challenge, some countries have started to update their data management systems by redeveloping their technical infrastructure or moving to a cloud-based solution. An example of the former is the Estfeed data hub in Estonia, an example of the latter is Elhub in Norway. Here, an important consideration is whether to keep the data sharing infrastructure and its development in-house or not, which will again be a trade-off between cost-efficiency, agility, and data security.[153]

5.6.1 The growing interest in near real-time data

Directive (EU) 2019/944 gives consumers not only the right to access and exchange validated, historical metering and consumption data, but also near real-time data. Near real-time data are typically non-validated and provided continuously in a short period, down to seconds or up to the imbalance settlement period. Although near real-time data are perceived as increasingly relevant to engage final customers in energy markets, their use is currently still limited and their collection is often done locally, directly from the smart meter via an adapter.[154]

It is not yet clear who will be responsible for the management of near real-time data and the development of the relevant data access and sharing infrastructure. In this context, two approaches are possible.

- The task can be regulated and assigned to the same entities that support the management of validated, historical data. These entities can then integrate the management of near real-time data into existing platforms or establish new platforms. In Spain, for instance, Aelēc is setting up a dedicated platform called SIORD to support the exchange of data between distributed generation units and DSOs close to real-time. Moreover, the French DSO Enedis has tested a cloud-based platform for real-time data as part of the Interconnect project.
- Commercial entities could develop data-sharing services on a purely market-based logic. While the efficiency and availability of near real-time data might increase, customers might be locked in and the level playing field might be negatively affected to the detriment of other service providers.

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[153] The use of cloud-based solutions can potentially reduce costs but may raise issues regarding data protection and security.
[154] See Deliverable 5.2 of the EDDIE project for overview of the accessibility of near-real time data in several European countries.

5.6.2 Additional challenges identified during the interviews

In addition to the above-described challenges, interviewees raised a range of further considerations related to the practical implementation and evolution of data management models. These observations can be grouped into three categories: institutional and governance challenges, operational and technical challenges, and emerging and future developments of DMMs. Table 5.4 summarises some of the challenges raised in each of these categories.

Institutional and Governance Challenges
• Developing an appropriate legal framework • Engaging with regulators and competent ministries • Organising a public procurement for large-scale projects • Addressing the complexity of a diversified DSO landscape • Ensuring access to the necessary expertise and technical know-how
Operational and Technical Challenges
• Shortening delivery periods for validated historical metering data • Ensuring data quality, integrity, and availability • Enhancing the usability and user experience of data platforms • Verifying third-party eligibility and access rights • Integrating with the EU Digital Identity and wallet systems • Managing the complexity and pace of IT innovation • Assessing the risks and opportunities of cloud-based solutions
Emerging and Future Developments
• Defining roles and responsibilities in flexibility registers • Extending data management practices to other sectors, such as natural gas • Aligning with European data spaces and the EU Data Act

Table 5.4: Other challenges concerning the development and evolution of data management models, as reported during the interviews.

5.7 Conclusion

This chapter starts from the implementation experience of data management models in nine European countries that demonstrate advanced practices in ensuring access to validated, historical metering and consumption data of final customers.

When mapping these frontrunners on the role model introduced by Commission Implementing Regulation (EU) 2023/1162, it appears that the traditional taxonomy used to classify data management models into centralised, hybrid and decentralised models might be insufficient to navigate the different national practices that have emerged across Europe. A richer taxonomy is then proposed that distinguishes those models based on the specific roles that are centralised and the entities that take up those centralised roles. By classifying national practices along these dimensions, it is possible to reduce ambiguities and reveal additional nuances. The repository of national practices established by the JWG on Data Interoperability in Summer 2025 can ideally provide, over the coming years, the information necessary to further populate the taxonomy and test its robustness.

Based on the experience of the considered frontrunners, four reflections about the evolution of data management models in Europe were presented in the chapter.

First, a tendency towards a minimum degree of centralisation in data management models is visible, as most of the examined countries established at least a standardised data exchange framework. The extent to which more roles will be centralised in the future is nonetheless uncertain. Various arguments can be made both in favour and against centralisation, based, among others, on cost efficiency, consumer-centricity, data integrity and security, and agility. While it is clear that the context matters, the current lack of consensus suggests that more empirical research is needed.

Second, inclusive governance plays an important role in ensuring trust, mobilising technical expertise and identifying the evolving data needs of stakeholders. Both ad-hoc and systematic stakeholder involvement are being implemented in the analysed countries, but the optimal level of formalisation and stakeholder control remains an open question. Monitoring the performance of the data exchange framework in a country can support trust among stakeholders and possibly be leveraged to incentivise increased efficiency or quality of the service. However, this aspect seems currently to be not yet mature nor explicitly linked to the remuneration of the actors involved the management of metering and consumption data.

Third, the metering of final customers at the resolution of the imbalance settlement period significantly increases the volume of validated, historical data. Although updating the IT infrastructure of existing data management models seems to be sufficient to deal with this challenge, countries are considering different technologies and development strategies.

Fourth, the interest in near real-time data is growing and the current practice of collecting these data directly from the smart meter via an adapter might become inefficient. Whether data access and exchange infrastructures for near real-time data will be developed by commercial entities or the regulated entities that manage validated, historical data is an open question.

6 SECURITY AND SAFETY ANALYSIS OF DATA-SHARING INFRASTRUCTURE OPTIONS

6.1 Introduction

This chapter provides an overview of extended work done in task T7.4 on cybersecurity topics. It includes an overview and a brief introduction to the NIS 2 Regulation (see section 6.3), a description of the cybersecurity questionnaire used for the cybersecurity analysis (see section 6.4), and a summary of central and decentral data storage in relation to the General Data Protection Regulation (GDPR) (see section 6.5).

6.2 Methodology

Two different methods were used to create the content of this chapter. For the content of Section 6.3 (introduction to the NIS 2 Regulation) and for the content of Section 6.5 (centralized and decentralized data storage), existing knowledge was summarized within the team and updated through additional literature research. Section 6.4 (Cybersecurity Questionnaire) describes the development and use of a questionnaire for determining the cybersecurity status during system development (HW and SW). This questionnaire was further developed in the EDDIE project, adapted to the requirements of the energy sector, and used in the development of the EDDIE framework.

6.3 Network and Information Systems (NIS2) Directive

This section explains the Network and Information Systems (NIS2) Directive, issued by the European Union

6.3.1 The NIS2 Directive – What it is and how to implement it

NIS2 stands for “Network and Information Systems version 2” and replaces its predecessor NIS1. The goal of the NIS2 Directive is to enhance cybersecurity across the EU's economic zone, a much-needed move. Key and critical companies will now have to implement stricter security protocols, which will also extend to their suppliers. Consequently, this directive will have an impact on businesses outside of the explicitly mentioned sectors. This section presents some of the most important steps for achieving compliance with NIS-2.

Excerpt from the European Commission website for digital strategies about NIS2[155]:

> ***"NIS2 Directive: new rules on cybersecurity of Network and Information Systems (NIS) --*** *The NIS2 Directive establishes a unified legal framework to uphold cybersecurity in 18 critical sectors across the EU. It also calls on Member States to define national cybersecurity strategies and collaborate with the EU for cross-border reaction and enforcement. Cybersecurity aims to protect Network and Information Systems (NIS), their users, and other affected individuals from cyberthreats and incidents. In response to the growing exposure of Europe to such risks, Directive 2022/2555, known as NIS2, replaced its predecessor, Directive 2016/1148 (NIS1)."*

The text of the NIS2 Directive can be downloaded on the European Commission website[156].

NIS2 raises the EU's cybersecurity standards by expanding its scope, providing clearer regulations, and introducing stronger supervision tools. It requires Member States to strengthen their cybersecurity capabilities, implement risk management measures, and meet reporting obligations for entities across more sectors. Additionally, it establishes rules for cooperation, information sharing, supervision, and enforcement of cybersecurity protocols.

Various implementation steps are necessary for the implementation of the NIS2 Directive. The following recommended steps for a smooth introduction of the NIS2 Directive have been compiled from various literature sources as well as statements from NIS2 and security experts.

About the NIS2 Directive, the interior ministries of the European member states have set up their own information websites, which provide information to companies on which required activities are to be implemented. For example, the Austrian Federal Ministry of the Interior provides useful information on the website[157].

[155] https://digital-strategy.ec.europa.eu/en/policies/nis2-directive
[156] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2555
[157] https://www.nis.gv.at/

The following information was taken from this website[158]:

The NIS2 Directive defines the following: • the obligation for all Member States to adopt national cybersecurity strategies (**Art. 7**) • the obligation for all Member States to appoint or establish competent national authorities (**Art. 8**), cyber crisis management authorities (**Art. 9**), central contact points for cybersecurity (**Art. 8**) and computer emergency teams (**Art. 10**) • Obligations regarding cybersecurity risk management (**Art. 20 ff**) and reporting obligations (**Art. 23**) for affected institutions • Rules and obligations for the exchange of cybersecurity information (**Art. 29 f**) • Supervisory and enforcement obligations for the Member States (**Art. 31 ff**)

The following collection of process step descriptions for the implementation of the NIS2 Directive was particularly inspired by the eBook from Security-Insider[159][1]and compiled from various literature sources.

Implementation Step 1: Clarify whether the company is affected by NIS2.

NIS1 defined six critical sectors, while NIS2 extended this number to 15 sectors. On the website[160], curated by Uniqkey, lot of detail information for NIS2 will be provided.

A distinction is made, firstly, between "**Essential Sectors**" such as (1) **Energy,** (2) Health, (3) Transport, (4) Finance, (5) Water Supply, (6) Digital Infrastructure, (7) Public Administration and (8) Space, and, secondly, between "**Important Sectors**" such as (9) Digital Providers, (10) Postal Services, (11) Waste Management, (12) Food, (13) Production, (14) Chemistry and (15) **Research**.

In addition, a distinction must be made as to whether the company is considered "important".

[158] https://www.nis.gv.at/nis-2-richtlinie.html.
[159] www.security-insider.de (only available in German)
[160] https://nis2directive.eu/

Source: https://www.nis.gv.at/nis-2-richtlinie.html

Number of employees and financial thresholds for defining the company classes:

1. The size class of micro, small and medium-sized enterprises (SMEs) consist of companies that employ fewer than 250 people and that either have an annual turnover of no more than EUR 50 million or whose annual balance sheet total does not exceed EUR 43 million.
2. Within the category of SMEs, a small company is defined as a company that employs fewer than 50 people and whose annual turnover or annual balance sheet does not exceed EUR 10 million.
3. Within the category of SMEs, a micro company is defined as a company that employs fewer than 10 people and whose annual turnover or annual balance sheet does not exceed EUR 2 million.

According to Art. 2 and Art. 3 of the NIS 2 Directive, however, entities can also fall within the scope of the NIS 2 Directive regardless of their size and the "size cap rule".

Implementation Step 2: Define the NIS2 implementation as a company internal project

The introduction of NIS2 in a company is not a one-person task and cannot be carried out on the side. It is therefore advisable to set up this undertaking as an internal project.

The managing director or CEO is ultimately the sponsor and project client of the working group, because he is also the project financier and the donor of the project budget. In addition to the management, the IT manager, the IT security and the data protection officer, the legal department must always be involved. As personnel security plays a major role in NIS2, the human resources department should or can also be included in the project team in an advisory capacity. From an expert perspective, however, it is mentioned not to make the project management team too big. If a quality management team, ideally for ISO 9001, is established in the company, this team is an important additional source of experience in quality and processes. This team is familiar with the installation and maintenance of processes, and this is a large part of the long-term establishment of NIS 2.

By definition, a project has a start and an end. A security quality process is a continuous process without a dedicated end. Therefore, the project defined at the beginning of this section should be set up as a chain of projects. Starting with the NIS2 introduction project and periodic project re-establishment with new budget and personnel approvals, which are fully supported by the management.

Implementation Step 3: Raising management awareness for cybersecurity.

This step includes the very important undertaking of raising management's awareness of NIS2. Usually, the management's focus is on the successful implementation of business activities and their economical and profitable financing. The implementation of NIS2 means a larger initial investment and requires a continuous budget for maintenance and adaptation work. The management should be invited to training courses and seminars to gain an overview of cyberthreats and to be able to classify them. Ultimately, the management should be able to assess where action is needed. General, the management is liable for the implementation of NIS2 in the company in two respects. Firstly, the decisions on risk management must be understandable and secondly, management is liable for the damages caused by neglecting NIS2 activities

Implementation Step 4: Involve the entire company in the strategy

A general security strategy must be established in the company, involving all employees and communicating the roles of each individual employee in the strategy process. Given today's high level of digitalization in the company IT sector, the entire company's operations must be examined to establish functioning cybersecurity. Another important aspect is to continuously inform employees about the cybersecurity measures implemented, ideally through a regular cybersecurity summary report as part of a periodic employee meeting of the company.

Implementation Step 5: Analyse your company's cybersecurity risk

An important goal of NIS2 is to evaluate all business processes for their criticality and dependency on the various IT functionalities. Unnecessary, but long-established, business processes should be eliminated or simplified to reduce the attack surface for cyberattacks and simplify the cybersecurity monitoring radius. This task poses a challenge to the scope of the analysis and the representation of the business processes. Finding the right level of sufficient detail and avoiding over-determination is not easy. To identify the different cybersecurity risks in the various business areas, the cooperation of all those involved is a necessity to adequately determine the appropriate scope and to determine the measures.

In the starting phase of the NIS2 implementation, a basic cybersecurity concept could be carried out by determining the most important IT infrastructure components (assets) in the company, which are required for the general basic business operations. Then it is necessary to analyse who has access to the components (login). Are all these accesses necessary? Are the components also visible from outside the company (e.g., via external communication interfaces). Are these interfaces sufficiently secured by authentication[161] and authorisation[162]? Are accesses recorded in a tamper-proof manner (monitoring)?

The analyses mentioned above can be made much easier using cybersecurity questionnaires. The questionnaires ask questions about the most important test criteria regarding cybersecurity measures. Project partner AIT has designed two cybersecurity questionnaires for this purpose. One questionnaire is of a general nature and can be filled out by non-cybersecurity experts in advance of a detailed analysis. It provides an initial basic assessment to determine the basic cybersecurity status of the company. The user also gets an idea of the expected scope of the test criteria to be considered. The second questionnaire will then be carried out in collaboration with a cybersecurity expert. The questionnaire is based on the cybersecurity standard IEC 62443 for industrial control systems (ICS). The strengths and weaknesses of the current cybersecurity situation are recorded in detail here. The questionnaire is also a good reference for comparisons after the implementation of cybersecurity measures.

The questionnaires, which are based on IEC 62443, define complementary requirements for NIS2 and provide profiles as a possible basis for the Network Code on Cybersecurity (NCCS).

A more detailed description of the questionnaires can be found in section 6.4 of this document.

Implementation Step 6: Implement an Information Security Management System (ISMS)

The measures in Implementation Step 5 address and implement one of the core requirements of NIS2. This requirement obliges the company to implement suitable and proportionate technical, operational and organisational measures to control and treat cybersecurity risks in mission-critical IT and network components and to be able to control these events even in a Cybersecurity emergency case.

Another core requirement describes the establishment and implementation of an Information Security Management System (ISMS). The certification of an ISMS according to ISO 27001 is very extensive, cost-intensive and labour-intensive because it is set up in detail. However, for small companies, very valuable additional information and practical examples can be found in ISO 27001 and ISO 27002 (implementation recommendations) as reference.

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[161] Who am I?

[162] Do I have the right access?

An effectively installed ISMS enables the Cybersecurity Officer (CSO) to create an overall picture of the IT- and network-structures. Established tools can help to describe and manage the complexity of the current IT architecture.

Project partner AIT offers a model-based threat assessment risk analysis (TARA) tool solution for this task with expert support. The advantage of such a tool is that it allows planned changes of the IT- infrastructure to be tested in advance by using the IT- and network-model of the company structure (Digital Cybersecurity Twin - DCST) through simulation. Potential weak points can be identified early before switching the updated installation to operation.

Implementation Step 7: Analysing supply chain risks

The NIS 2 Directive has a significant impact on industrial companies and their supply chains. NIS2 relevant companies are required by **Article 21.2d NIS2** Directive to ensure supply chain security and to continuously review the suppliers on which their products depend. Based on the risk in the supply chain, they must impose cybersecurity measures on their suppliers.

The IEC 62443 cybersecurity standard helps meet the new requirements of NIS 2 and provides a proven framework to remain competitive and secure in the long term.

A special case are software products that are partly built from open-source software. It is not easy or even impossible to demand an ISO 27001 certificate from this open-source supply chain. Nevertheless, the software manufacturer must ensure the cybersecurity quality of the used software components.

It is necessary to create a Software Bill of Materials (SBoM) list, an inventory list of all software components (in-house developed modules, third-party modules and open-source modules) and their dependencies.

All known external (and internal) software modules must be periodically monitored for vulnerabilities using a Common Vulnerability Scoring System (CVSS). If threats are reported by these databases, the software manufacturer is obliged to carry out its own product investigation as quickly as possible and deliver the necessary software updates.

Implementation Step 8: Strategies for managing cybersecurity crises

Cybersecurity Risk Management (**Art. 20 ff NIS2** Directive[163]).

[163] https://www.nis.gv.at/nis-2-richtlinie.html

After the ISMS has been fully installed and the supply chain risks have been assessed and identified, the next step is to define cybersecurity emergency processes. A cybersecurity incident can happen more quickly than you might expect. A good example is the cybersecurity incidents list on the data breaches, cyberattacks and vulnerabilities list website[164], started from 2008 until today.

An essential measure for a secure and useful IT and as a main part of the security strategy includes a complete and secure (inaccessible from the outside) backup of the entire data volume in a company. Due to the increasing volume of data, the fast and orderly access to digital data is becoming a key factor for a functioning IT landscape. And cybercriminals know this too, who try to steal, change or encrypt this data through ransomware attacks and try to extort a ransom for its recovery.

When it comes to data backup, a distinction is made between a full backup and an incremental backup. As the name suggests, a full backup means that the entire data set is backed up by copying it onto a backup medium. With an incremental backup, only the data that has been newly created or changed since the last backup is backed up. The incremental backup is carried out daily and the full backup once a month, for example. A full backup can take several hours for large amounts of data.

The golden **3-2-1 data backup rule** is recommended for protection in the event of a disaster. This means:

3 Make at least three copies of data on three physically independent backup media.

2 Use at least two different backup media (e.g. tape drive, hard drive, …).

1 Store a copy of data at a geographically different location (fire emergency).

An extension of the golden 3-2-1 data backup rule is the 3-2-1**-1-0 data backup rule**, which offers further recommendations:

1 Use a removable storage device for offline storage.

164 https://www.dsgvo-portal.de/sicherheitsvorfall-datenbank/

0 Controlled and verified data backup with a guaranteed zero-error goal.

Managing a cybersecurity crisis requires developing a crisis plan for all possible crisis scenarios, such as data theft, data manipulation, data encryption, and so on. Simulations should be carried out regularly for all these scenarios so that all responsible persons are precisely informed about their assigned tasks. Other IT crises that are not considered cybersecurity crises include power outages, fires, floods, earthquakes, and so on, for which emergency plans and responsibilities should also be developed.

Implementation Step 9: Register as a NIS2 relevant company

Companies must register themselves when the company fits the NIS2 classes.
Further information about the registration can be accessed on the following website[165]:

There is an incident reporting requirement. This means that if there is a cyber-incident, you must report it to the supervisory authority, according to **Art. 23** of the NIS2 Directive:

Each Member States established Computer Security Incident Response Teams (**CSIRT**) where each NIS2 relevant European company must report cyber-incidents.

On the website[166] there is given an informative overview of the CSIRTS Network Members, with detail information and contact information for each individual CSIRT Network Member.

Additional information will be available at the website[167].

[165] "Understanding the registration and reporting requirements of the EU NIS2 Directive" https://www.eversheds-sutherland.com/de/austria/insights/understanding-the-registration-and-reporting-requirements-of-nis2 or at: https://www.cyber-trust.at/nis/
[166] https://csirtsnetwork.eu/
[167] https://github.com/enisaeu/CNW

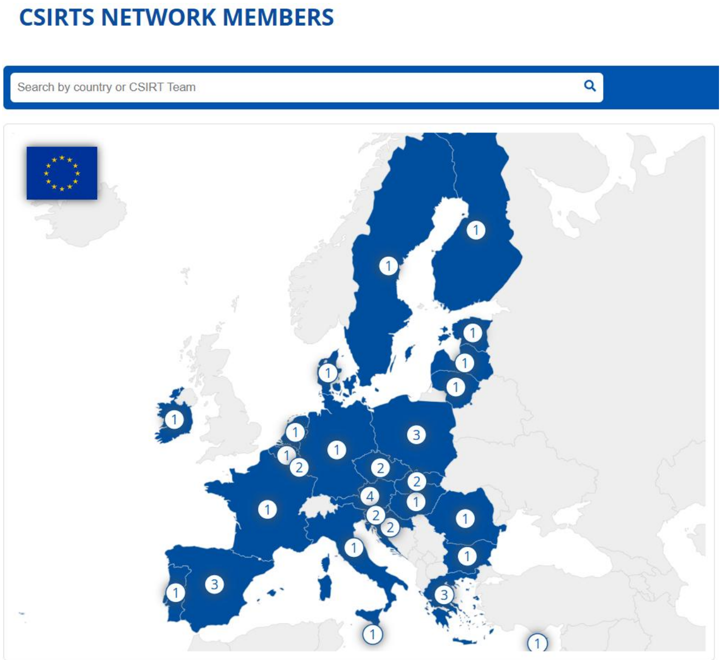

Figure 6.1: Overview of the CSIRT Network Members.
Source: Excerpt of the website https://csirtsnetwork.eu/.

Figure 6.2: Detailed information of CSIRT Network Member Austria.
Source: Excerpt of the website https://csirtsnetwork.eu/.

Implementation Step 10: The ever-repeating project – NIS2 wants a continuous process

As already mentioned in Step 2 the establishing and maintaining the NIS2 Directive is a project which must be continually updated. Each time, it is important to ensure that the cybersecurity team's staff and budget are adequately funded for the necessary activities. NIS2-relevant companies must demand appropriate cybersecurity evidence from their suppliers, e.g. an ISO 27001 certification, which is audited annually. Companies that work in this direction have done valuable preparatory work for the Cyber Resilience Act (CRA), which will come into force soon. Software manufacturers and software providers, which produce "products with digital elements" must then ensure that the products they sell does not contain any cybersecurity vulnerabilities and provide a maintenance guarantee for many years. More information about the CRA see the website[168].

Regulation (EU) 2024/2847 of the European Parliament and of the Council of 23 October 2024 on horizontal cybersecurity requirements for products with digital elements and amending Regulations (EU) No 168/2013 and (EU) 2019/1020 and Directive (EU) 2020/1828 (Cyber Resilience Act) see the website[169].

6.4 The cybersecurity questionnaire concept

This subsection presents the cybersecurity questionnaires developed and used for the cybersecurity analyses.

Starting a cybersecurity investigation requires the collaboration of an internal cybersecurity team with external cybersecurity experts if they are not available within the company. The start may sometimes require some persuasion to explain the scope of the cybersecurity investigation to the company. The cybersecurity questionnaire "Non-Expert" was created for this purpose. This cybersecurity questionnaire asks about the actual status of seven basic cybersecurity areas.

As shown in Figure 6.3, the cybersecurity questionnaire is filled out by the company internal cybersecurity team (USER). The cybersecurity questionnaire "Non-Expert" can be answered

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[168] https://digital-strategy.ec.europa.eu/en/policies/cyber-resilience-act
[169] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202402847

by non-experts. The evaluation of the questionnaire provides a preliminary representation based on the user's assessment of the situation. This result is a very important starting point for the cybersecurity experts, who now get a first impression of the company's cybersecurity status. In addition, the questionnaire gives the company's internal cybersecurity team an idea of the scope of a cybersecurity investigation by outlining the seven basic cybersecurity.

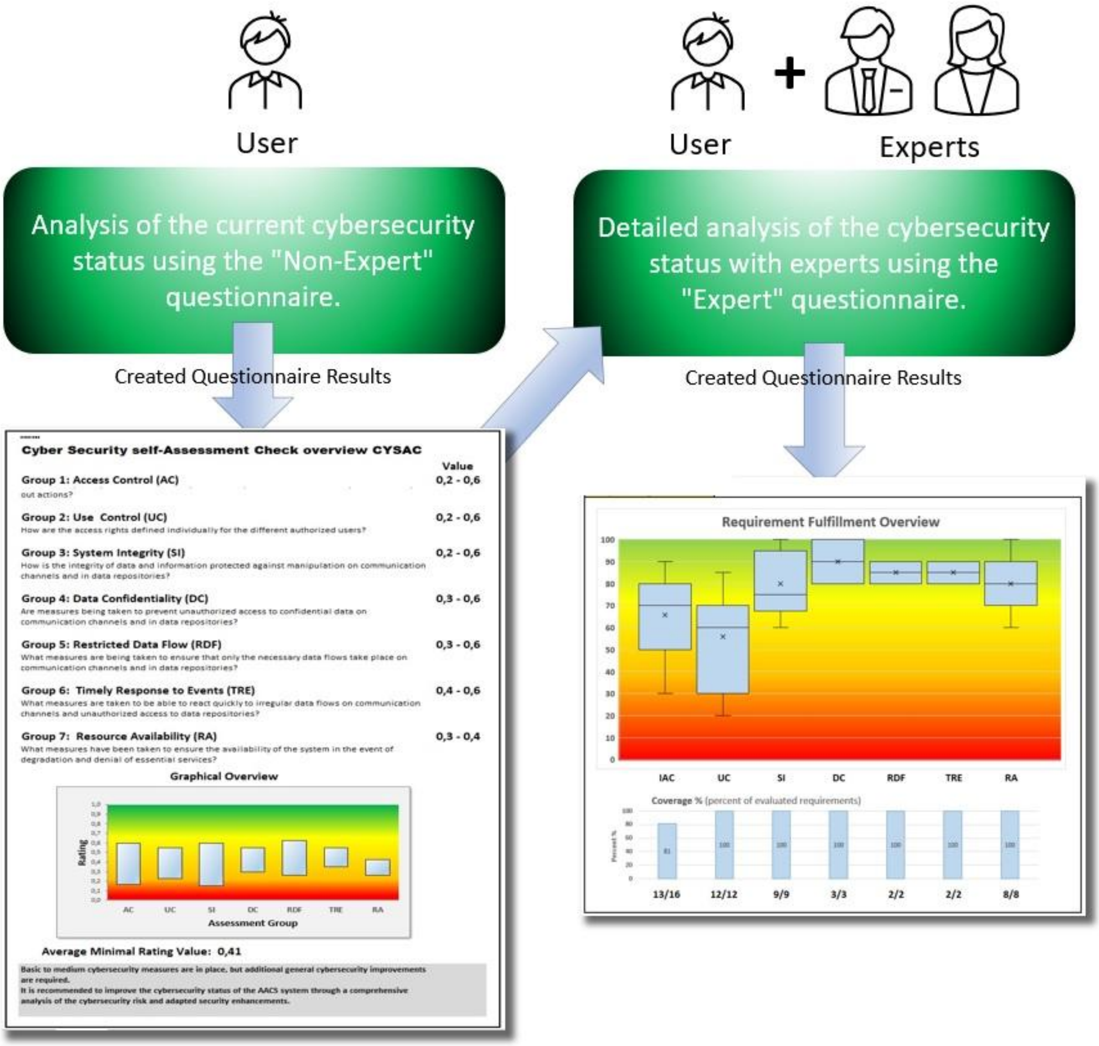


Figure 6.3: Cybersecurity questionnaire process.

After coordination between the company's internal cybersecurity team and the external cybersecurity experts, the cybersecurity questionnaire "Expert" is filled out together, thereby simultaneously determining the true cybersecurity status and initiating the first initial cybersecurity improvements.

The cybersecurity questionnaire is implemented by an MS-Excel worksheet. The evaluation and the result visualisation using MS-Excel functionalities.

6.4.1 Cybersecurity Questionnaire "Non-Expert"

The target audience for the security questionnaire "Non-Expert" are the asset owners, system developers and every cybersecurity non-expert employee of the company.
The questionnaire is designed for a Cybersecurity Level 2 (SL2) according to IEC 62443. This level defines the security requirements to ensure the confidentiality of information on communication channels and in data repositories to prevent the unauthorized disclosure of information by attackers who provide well-developed means with moderate resources, general skills and moderate motivation.

The questionnaire can be done by non-cybersecurity expert simple by evaluating the questions with a ranking between 0 to 9. The MS EXCEL work sheet calculates an average cybersecurity ranking value and gives a general assessment of the cybersecurity status, both with a rating value overview and a three-colour (red-yellow-green) graphical schema.

The questionnaire provides a set of questions related to the seven foundational requirements groups and prepare an informative report with an overview and a three-colour graphic, as shown in Figure 6.3, which shows where additional improvement must be performed according to fulfil the IEC 62443 cybersecurity standard.

The report provides an overview with average calculated assessment values (0,0 – 0,9) for each of the seven assessment groups Group 1 to Group 7. A graphical overview gives the distribution of the assessment values for each assessment group. Each bar notifies the range of the lowest and the highest average rating value.

Finally, a short assessment rating text summary evaluates the cybersecurity status with recommendations for security improvements, if necessary.

Each question is answered by giving a rating value between 0 and 9 with the following meaning:

Rate each question between 0 and 9 in the green coloured fields		
0:	not implemented	not available
1 - 7:	partially implemented	partially available
8 - 9:	full implemented	full available

In the current released version, which is a draft development version, a workaround between the meaning of "not relevant" and "not implemented" is provided in the following way:

For questions that are not relevant to the asset, enter the average rate of the question sets, e.g..: Q1: not relevant, Q2 = 5, Q3 = 6 -> Q1 rate = (5 + 6) / 2 = 5.5 -> round to the next whole number = 6.

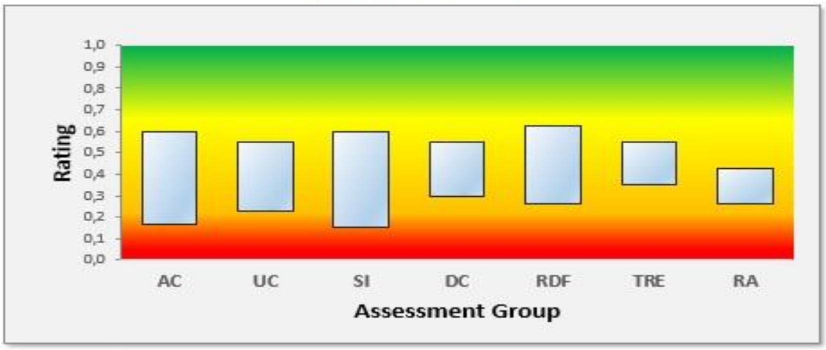
Never enter "0" as the default for "not relevant". The rate "0" stands for "not implemented", which has a different meaning than "not relevant".

The questionnaire generates the following evaluation report (see Figure 6.4).

Cyber Security self-Assessment Check overview CYSAC

	Value
Group 1: Access Control (AC) out actions?	0,2 - 0,6
Group 2: Use Control (UC) How are the access rights defined individually for the different authorized users?	0,2 - 0,6
Group 3: System Integrity (SI) How is the integrity of data and information protected against manipulation on communication channels and in data repositories?	0,2 - 0,6
Group 4: Data Confidentiality (DC) Are measures being taken to prevent unauthorized access to confidential data on communication channels and in data repositories?	0,3 - 0,6
Group 5: Restricted Data Flow (RDF) What measures are being taken to ensure that only the necessary data flows take place on communication channels and in data repositories?	0,3 - 0,6
Group 6: Timely Response to Events (TRE) What measures are taken to be able to react quickly to irregular data flows on communication channels and unauthorized access to data repositories?	0,4 - 0,6
Group 7: Resource Availability (RA) What measures have been taken to ensure the availability of the system in the event of degradation and denial of essential services?	0,3 - 0,4

Graphical Overview



Average Minimal Rating Value: 0,41

Basic to medium cybersecurity measures are in place, but additional general cybersecurity improvements are required.
It is recommended to improve the cybersecurity status of the AACS system through a comprehensive analysis of the cybersecurity risk and adapted security enhancements.

Figure 6.4: Cybersecurity Questionnaire "Non-Expert" report

As previously mentioned, the questionnaire consists of seven question groups. Each group has three question sub-groups which two to four dedicated questions each, as show in Figure 6.5 for Group1, the Access Control (AC) requirement group as an example.

Group 1: Access Control (AC)	Value:
How is the system protected so that only authorized persons can access the system and take actions? Authorize and authenticate the Automation Control System (ACS) users, define them for a predefined role and allow them access to the system and assets.	0,0 - 0,0
• Management of password and user authentication: Any access to the Automation Control System (ACS) must be protected by a mechanism which controls user identification and authentication. In Automation Control System (ACS) with security level 2, a combination of username and password is sufficient. Two-factor access protection is required for higher security levels.	
Is every access to the Automation Control System (ACS) and the parts of it, protected by a username and password?	0
Is the quality (strength) of the password checked during the password definition?	0
Is the password changed regularly after a predefined lifespan?	0
Is a separate password defined for each component?	0
• Account management: The asset owner must be able to create a new account, change accounts, suspend accounts and delete accounts in a uniform manner for all subsystems for authorized users.	
Is there a unified feature for installing new accounts for authorized users?	0
Is there a unified feature available to change accounts for authorized users, unified for all sub-systems?	0
Is there n unified account lockout feature available for authorized users (e.g.: administrator)?	0
Is there a unified feature available to delete accounts for authorized users?	0
• Management of failed login attempts: To prevent unauthorized access from being guessed by repeatedly trying out passwords, access must be blocked for a certain period of time after a certain number of attempts.	
Is there a password input attempt limiter activated?	0
Is a meaningful low number of attempts defined, for example three attempts?	0
Are access attempts recorded and an alarm triggered when the maximum access attempts are reached?	0

Figure 6.5: Example of the Questionnaire Group1: Access control.

6.4.2 Cybersecurity Questionnaire "Expert"

The cybersecurity questionnaire "Expert" presents all components requirements according to IEC 62443-Part 4.2 in one table, line by line, for a better overview organised around the seven foundational requirements groups.

Figure 6.6 shows an excerpt of the cybersecurity questionnaire table, showing four table lines with two active selected (relevant) requirements. The **Security Level mark** indicates the target SL. There are individual questionnaire tables for each security level (SL 1, SL 2, SL 3 and SL 4).

For each foundational requirements group an individual sub-table with the **Requirement group name** is presented. Finally, the **Requirements description** presents the dedicated requirement with a short overview title. These are fix defined parts of the table and cannot be changes by the user.

The difference to the cybersecurity questionnaire "Non-Expert" is that each question is rated with a fulfilment value between 0 and 100. In addition, a "Not relevant (NR)" selection box is implemented for each requirement. To be able to specify the degree of fulfilment in more detail, a more precise ranking value range with a granularity of 1% was chosen.

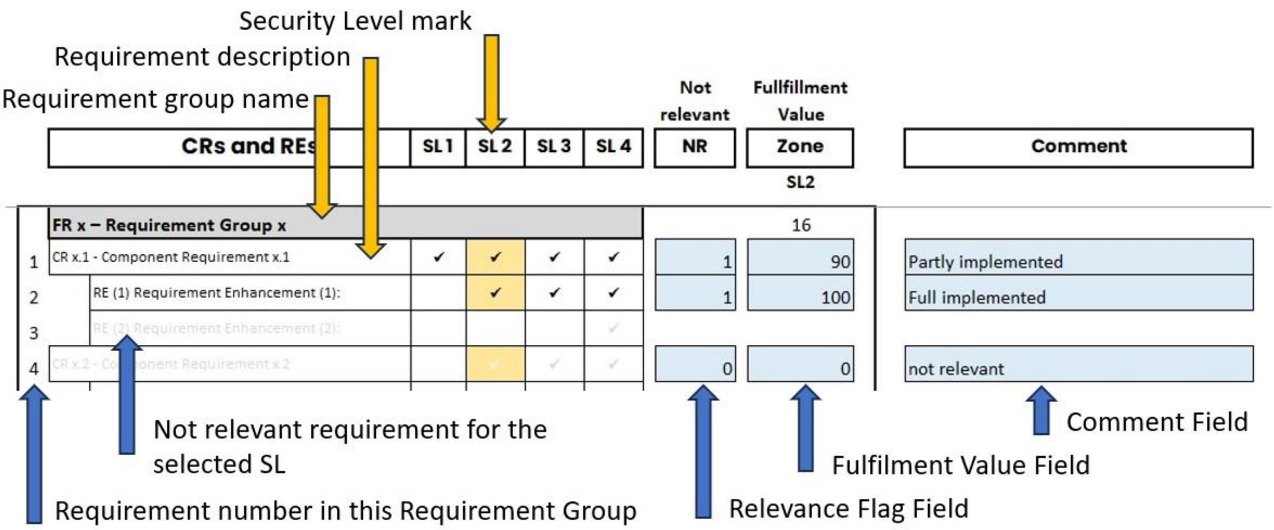


Figure 6.6: Excerpt of the Cybersecurity Questionnaire "Expert" Table.

For each specified Component Requirement (CRx.y) and for each Requirement Enhancement (RE) the questionnaire provides a **Fulfilment Value Field**, where the user fill in the level of requirement fulfilment in the range from 0 (not available) to 100 (fully fulfilled).

If the specified requirement is not relevant for the assessment object, the questionnaire contains a **Relevance Flag Field** to reflect this. Setting the field to 1 means that the requirement is relevant. Otherwise, setting the field to 0 means that this requirement is not relevant for the current assessment object. The effect of this flag is that the related requirement will be not involved in the overall fulfilment calculation, also when the Fulfilment Value is set to 0 (not available). Also, the Requirement description text is displayed in grey.

To capture the background of the decision, the user can enter a short description in the comment field. All field backgrounds of the table, which are alterable by the user are coloured in light blue.

For example, in Figure 6.6, the requirement CR x.1 (table line 1) is relevant and is fulfilled by 90%, while requirement RE (1) (table line 2) is fully fulfilled by 100%. Requirement RE (2) (table line 3) is not relevant for the selected SL2 and is displayed in grey and provide no user input boxes. Requirement CR x.2 (table line 4) is selected as "not relevant" by the user and has logically a fulfilment grade of 0%.

The cybersecurity questionnaire table only provides a brief and concise description of the requirements in one short sentence. More information about the requirements must be found in the specific section of the standards.
For example, the component requirement CR 1.1 from the foundational requirements group FR 1 with the Requirement group name: "Identification and authentication control (IAC)" (see Figure 6.7) specify the requirements under the title: "Human user identification and authentication". A very important requirement, which is specified for all four SL's.

More details give the explanation in the standard for this requirement: (excerpt from IEC CDV 62443-4-2 © IEC:2017)

"The component shall provide the capability to identify and authenticate all human users according to IEC 62443-3-3 [11] SR 1.1 on all interfaces capable of human user access. This capability shall enforce such identification and authentication on all interfaces that provide human user access to the component to support segregation of duties and least privilege in accordance with applicable security policies and procedures."

The standard provides additional explanations and justification as well as supplementary notes to inform the implementer of the component in an understandable and precise manner.

It is recommended to complete the cybersecurity questionnaire “Expert” together with the IEC 62443-4-2 standard. It would also be possible to include the explanations from this standard in the questionnaire. Unfortunately, the standard IEC 62443-4-2 is not open access, and a licence fee must be paid to the standardization body for the use of the standard.

To provide a first overview of the cybersecurity status for each foundational requirements group (FR 1 to FR 7) a boxplot-like diagram shows the fulfilment of the requirements in a clear and self-explanatory form. An example for such a representation is shown in Figure 6.7 for the foundational requirements group FR 1 (identification and authentication control (IAC)).

	Component Requirement CRx.y and Requirement Enhancement RE(x)	SL 1	SL 2	SL 3	SL 4	Relevant	Value Zone SL2
	FR 1 – Identification and authentication control (IAC)						16
1	CR 1.1 – Human user identification and authentication	✓	✓	✓	✓	1	80
2	RE (1) Unique identification and authentication:		✓	✓	✓	1	70
3	RE (2) Multifactor authentication for all interfaces				✓		
4	CR 1.2 – Software process and device identification and authentication		✓	✓	✓	1	90
5	RE (1) Unique identification and authentication			✓	✓		
6	CR 1.3 – Account management	✓	✓	✓	✓	0	0
7	CR 1.4 – Identifier management	✓	✓	✓	✓	0	0
8	CR 1.5 – Authenticator management	✓	✓	✓	✓	1	85
9	RE (1) Hardware security for authenticators			✓	✓		
10	NDR 1.6 – Wireless access management	✓	✓	✓	✓	1	70
11	RE (1) Unique identification and authentication		✓	✓	✓	1	70
12	CR 1.7 – Strength of password-based authentication	✓	✓	✓	✓	1	70
13	RE (1) Password generation and lifetime restrictions for human users			✓	✓		
14	RE (2) Password lifetime restrictions for all users (human, software process or device)				✓		
15	CR 1.8 – Public key infrastructure certificates		✓	✓	✓	1	75
16	CR 1.9 – Strength of public key-based authentication		✓	✓	✓	1	75
17	RE (1) Hardware security for public key-based authentication			✓	✓		
18	CR 1.10 – Authenticator feedback	✓	✓	✓	✓	1	80
19	CR 1.11 – Unsuccessful login attempts	✓	✓	✓	✓	0	0
20	CR 1.12 – System use notification	✓	✓	✓	✓	1	30
21	NDR 1.13 – Access via untrusted networks	✓	✓	✓	✓	1	30
22	CR 1.14 – Strength of symmetric key-based authentication		✓	✓	✓	1	30
23	RE (1) Hardware security for symmetric key-based authentication			✓	✓		

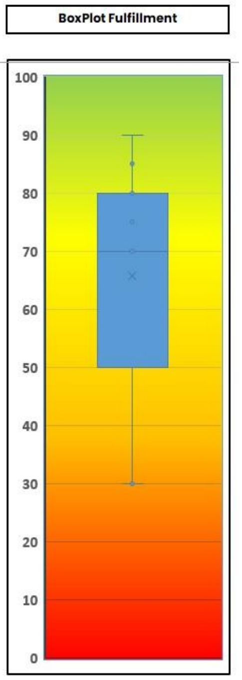


Figure 6.7: Excerpt of a FR1 requirement group example with the boxplot.

The quality of the implementation of the cybersecurity measures can be seen at a glance. As can be seen in Figure 6.7, the FR1 requirements are only partially fulfilled (50% - 80%). The blue coloured area of the interquartile range (IQR) of the box-plot graphic shows (see Figure 6.8). No requirement is fully implemented by 100%. It should also be noted that three requirements are set to "not relevant".

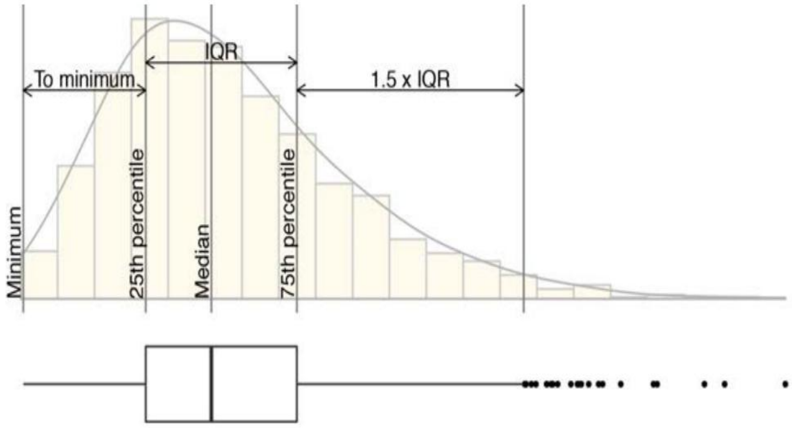


Figure 6.8: Data ranges in a box-plot graphic.
Source: R Graphics Cookbook by Winston Chang / O'Reilly Media

The cybersecurity questionnaire "Expert" provides a compressive graphical overview of all given user inputs and calculated cybersecurity assessments, summarised on an own sheet for printing.

The overview sheet shows a combination of the requirements fulfilment for the seven requirements groups with the individual boxplot diagram and a coverage display for each group as displayed in Figure 6.9 as an example.

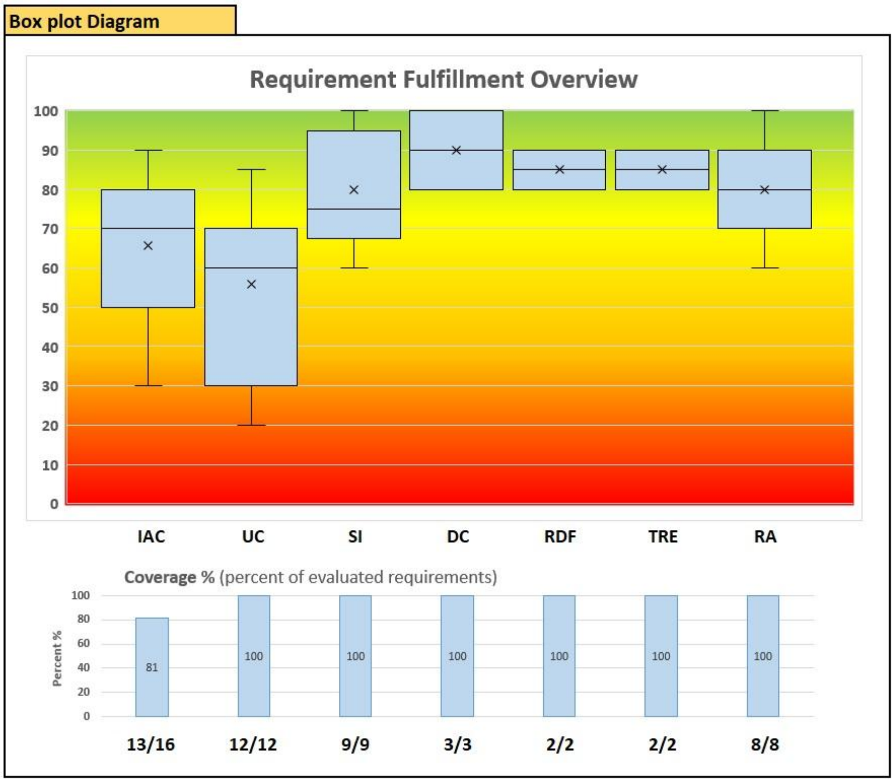


Figure 6.9: The Questionnaire final overview.

This Questionnaire overview provides valuable documentation to illustrate the evaluated status of the cybersecurity implementation in each design phase of the design process. Various dated overviews show the progress in the implementation of cybersecurity measures and can also be used for comparison purposes between different projects.

6.5 Central or Decentral data storage

The section gives a summary of the security advantages and disadvantages of a centralized and a decentralized data storage solution.

This section is the result of a discussion evaluating the differences between centralized and decentralized data storage, including regarding data security and cybersecurity.

Centralized data storage refers to the storage of data in a single location, while decentralized data storage refers to the distributed storage of data across different nodes within a network. As organisations and individuals increasingly rely on data storage solutions, the choice between centralized and decentralized storage has significant cybersecurity implications. Both approaches offer distinct advantages and disadvantages concerning security, resilience, access control, and data integrity. This section provides a comparative analysis of centralized and decentralized data storage in terms of cybersecurity.

6.5.1 Centralized Data Storage

Advantages:

- **Strong Access Control**: Centralized storage allows organisations to enforce strict access controls, ensuring that only authorized users can access sensitive data.
- **Efficient Data Management**: With all data stored in a single location or controlled infrastructure, administrators can efficiently manage, monitor, and update security policies.
- **Simplified Compliance**: Many regulatory frameworks (e.g., GDPR, HIPAA) require stringent data management practices, which are easier to implement and monitor in a centralized system.
- **Robust Security Measures**: Organizations can implement high-end security measures such as firewalls, intrusion detection systems (IDS), and endpoint protection within a controlled environment.

Disadvantages:

- **Single Point of Failure**: Centralized storage systems are vulnerable to single points of failure, making them susceptible to catastrophic data loss in case of cyberattacks or system failures.
- **Higher Risk of Data Breach**: A successful attack on a centralized system can expose vast amounts of sensitive data, making it an attractive target for cybercriminals.
- **Scalability Challenges**: As data volumes grow, scaling centralized storage can become complex and costly, increasing the attack surface.
- **Latency Issues**: Depending on the geographical distribution of users, centralized storage may introduce latency in data access and retrieval. The central data storage must be constantly adapted to the growing load of accesses and data requests. These extensions pose the risk of cybersecurity degradation if they are not implemented carefully and with subsequent integration testing.

6.5.2 Decentralized Data Storage

Advantages:

- **Enhanced Resilience and Redundancy**: Decentralized storage distributes data across multiple nodes, reducing the risk of data loss due to cyberattacks or system failures.
- **Reduced Risk of Mass Data Breach**: Since data is fragmented and stored across different locations, attackers must compromise multiple nodes to access complete datasets.

- **Improved Privacy**: Decentralized storage systems, especially blockchain-based solutions, offer enhanced privacy through encryption and anonymization techniques.
- **Greater Scalability**: In contrast to centralized systems, decentralized storage can scale dynamically without the need for massive infrastructure investments.

Disadvantages:

- **Complex Access Control**: Managing access controls and user authentication in a decentralized environment can be challenging, increasing the risk of unauthorized access.
- **Difficult Compliance Management**: Compliance with data protection regulations can be more complex in decentralized systems, as data governance is distributed across multiple jurisdictions.
- **Higher Computational and Network Overhead**: Decentralized systems often require additional computational resources for encryption, data synchronization, and consensus mechanisms, leading to increased latency.
- **Risk of Data Integrity Issues**: Without a central authority to manage data, ensuring consistency and integrity between nodes can be challenging, especially in peer-to-peer networks.
- **Data Service Provider Review:** Outsourcing data to an external data service provider does not release the data originator from data security responsibility. According to NIS2, the data originator is obligated to periodically review the data service provider's data protection capabilities.

Both centralized and decentralized data storage solutions offer unique cybersecurity benefits and challenges. Centralized storage provides strong access control and regulatory compliance but is vulnerable to single points of failure and large-scale breaches. On the other hand, decentralized storage enhances resilience and privacy but introduces complexities in access control and compliance. The optimal choice depends on the specific cybersecurity needs, regulatory requirements, and operational constraints of an organisation.

6.5.3 External Data Storage

When outsourcing data storage to a data storage service provider, data security responsibilities are generally shared between the customer and the data storage provider. Generally, the data storage service provider will offer support and advice on data security, while implementation and execution will be the responsibility of the customer.

As an example, consider the "Shared Responsibility Model" of Amazon Web Services (AWS) Cloud Data Services. The following section is taken from the AWS.Amazon website.

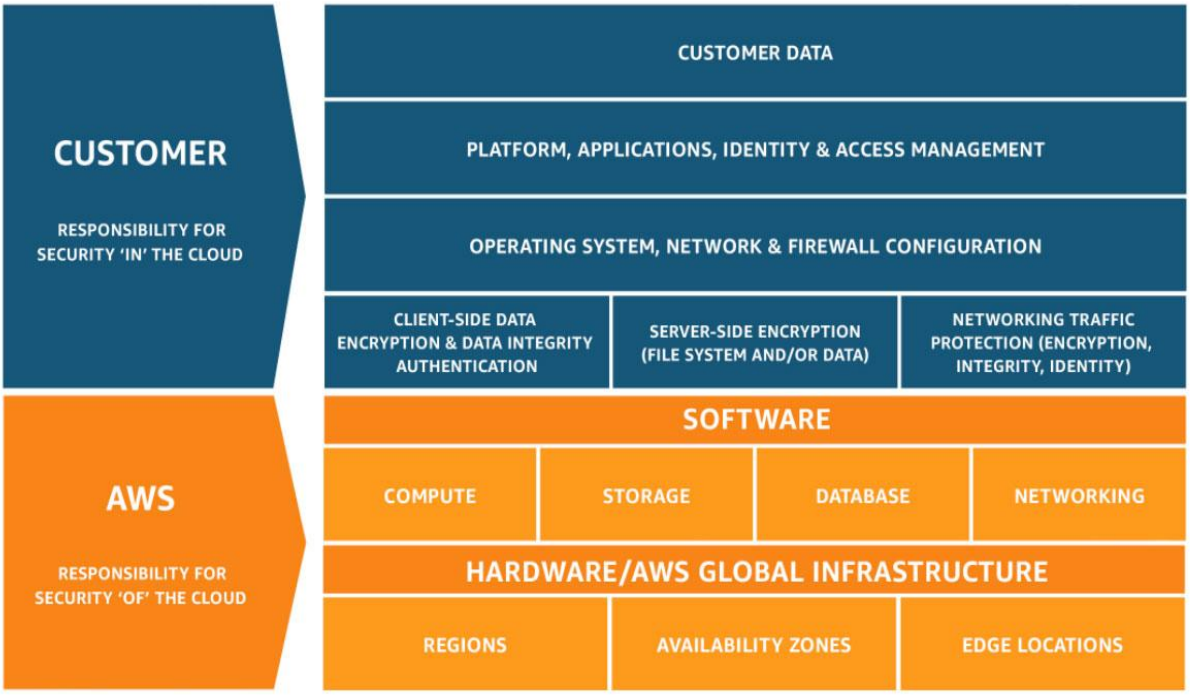


Figure 6.10: Amazon AWS Cloud - Shared Responsibility Model.
Source: https://aws.amazon.com/compliance/shared-responsibility-model/

As shown in Figure 6.10, AWS follows a shared responsibility model, where AWS manages the infrastructure, including the host OS, virtualization, and physical security. Meanwhile, customers are responsible for managing the guest operating system, application software, and security configurations like firewalls. The level of customer responsibility depends on the services used and how they are integrated. This model offers flexibility and control, often described as AWS handling security **"of" the Cloud**, while customers handle security **"in" the Cloud**.

- AWS responsibility "Security of the Cloud": AWS is responsible for securing the infrastructure, including hardware, software, networking, and facilities that supports all AWS Cloud services.
- Customer responsibility "Security in the Cloud": Customer security responsibilities in AWS depend on the specific services they use. For Infrastructure as a Service (IaaS) like Amazon EC2, customers must handle tasks such as OS updates, application management, and firewall configuration. In contrast, for abstracted services like Amazon S3 and DynamoDB, AWS manages the infrastructure, while customers are responsible for managing their data, applying encryption, classifying assets, and setting permissions using Identity & Access Management (IAM) tools.

6.6 Conclusion

For data-driven processes in the energy sector, cybersecurity has become a cornerstone for ensuring operational reliability, regulatory compliance, and public trust. With the digitalization of energy systems, which integrate extensive networks of connected devices, real-time data exchange, and intelligent automation, their vulnerability to cyber threats increases. The implementation of the Network and Information Systems Directive (NIS2) provides a robust legal framework that obligates energy companies to strengthen their cyber defences, promote risk management practices, and ensure the rapid reporting and resolution of incidents. By aligning with NIS2 requirements, energy sector stakeholders can establish a harmonized approach to cybersecurity, strengthening national and cross-border resilience within the European energy ecosystem.

A practical method for continuously improving cybersecurity is the use of a cybersecurity questionnaire to assess the company's current security status. This structured, repeatable assessment process enables energy companies to identify vulnerabilities, measure compliance with industry standards, and prioritize investments in areas of highest risk. The questionnaire approach also fosters awareness and accountability across all departments, transforming cybersecurity from a purely technical issue into a shared corporate responsibility. Cybersecurity questionnaires that conduct an assessment analysis based on existing industry standards are particularly valuable, as they enable a statement of compliance.

Furthermore, decisions regarding the use of centralized versus decentralized data storage play a crucial role in the security architecture of data management in the energy sector. Centralized data storage systems enable consistent policy enforcement and simpler monitoring but can also represent single points of failure. Decentralized data storage models, on the other hand, distribute risks and increase resilience against targeted attacks, but require more complex coordination and data management mechanisms. A balance between these approaches, supported by secure cloud technologies, encryption, and access management can significantly improve data integrity and availability.

Ultimately, the convergence of regulatory compliance according to NIS2, structured security assessment using questionnaires, and strategic data management will determine the maturity level of cybersecurity in the energy sector. By integrating various cybersecurity measures into the operational and strategic process structures of energy companies, the sector can not only protect its digital assets but also create a secure foundation for innovation, sustainability, and the reliable energy systems of the future.

7 CONCLUSION

The work developed in EDDIE's WP7 and presented in this deliverable evidence that a decentralised, interoperable, and secure European energy data space is achievable and can play a central role in Europe's green and digital transitions. By integrating perspectives from economics, behavioural science, law, regulation, and cybersecurity, WP7 has produced a comprehensive understanding of how energy data can generate value while safeguarding citizens' rights and system integrity.

- From an economic point of view, interoperability and transparent cost-allocation mechanisms enable new market entrants, support innovation, and reduce integration costs across Member States.
- In behavioural terms, user-experience studies demonstrate that accessible, well-designed interfaces and feedback mechanisms can empower consumers, fostering engagement and energy efficiency while illustrating how individual interaction patterns connect to wider systemic transitions toward data-driven and sustainable energy practices.
- Ambiguities arising from the interplay between different legal frameworks, namely data and electricity law, and the incomplete systematic integration between them create legal uncertainty, risking fragmented implementation and confusion for consumers and service providers. Clarification on the scope and applicability of different EU legislative acts regarding electricity metering and consumption data sharing with eligible parties is needed to support a smooth rollout of data-driven energy services across the EU.
- In regulatory terms, governance models should balance central coordination with local autonomy, ensuring trust and accountability within distributed infrastructures.
- From a cybersecurity standpoint, compliance with the NIS2 Directive and "security-by-design" principles is a prerequisite for resilience and trust in data-driven energy services.

In summary, these findings demonstrate that the work conducted in the EDDIE project can become a cornerstone of the CEEDS, promoting innovation, competition, and sustainability while maintaining high standards of privacy and security. As previously mentioned, the insights gathered here will guide the policy recommendations and exploitation strategies developed in WP8, helping the European Union to realise a truly interoperable and citizen-centred digital energy ecosystem.

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