IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 5 April 2024, accepted 23 April 2024, date of publication 25 April 2024, date of current version 3 May 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3393610

RESEARCH ARTICLE

Review of Digital Transformation in the Energy Sector: Assessing Maturity and Adoption Levels of Digital Services and Products via Fuzzy Logic

SALVADOR CARVALHOSA[1], ALEXANDRE LUCAS[1], CAMILLA NEUMANN[2], AND ANDREAS TÜRK[2]

[1]Center for Power and Energy Systems, Institute for Systems and Computer Engineering, Technology and Science (INESC-TEC), 4200-465 Porto, Portugal
[2]Joanneum Research, 8010 Graz, Austria

Corresponding author: Salvador Carvalhosa (salvador.carvalhosa@inesctec.pt)

This work was supported by the European Union through the EU Program HORIZON-CL5-2021-D3-02 under Grant 10175596.

ABSTRACT Digitalization has begun as a transformative force within the energy sector, reforming traditional practices and paving the way for enhanced operational efficiency and sustainability. Enabled by key technologies such as smart meters, digitalization embodies a paradigm shift in energy management. Nonetheless, it is crucial to recognize that these enabling technologies are only the catalysts and not the end goal. This paper presents a comprehensive overview of digital services and products in the energy sector, with a specific focus on emerging technologies like AI and Connected Data Spaces. The objective of this review paper is to assess the maturity and adoption levels of these digital solutions, seeking to draw insights into the factors influencing their varying levels of success. This maturity and adoption assessment was carried out by applying a Fuzzy logic approach which allowed us to compensate for the lack of detailed information in current literature. By analyzing the reasons behind high maturity-low adoption and vice-versa, this study seeks to cast light on the dynamics shaping the digital transformation of the energy sector.

INDEX TERMS Cost-benefit analysis, digitalization, digital products, digital services, energy sector, fuzzy logic.

I. INTRODUCTION

A. THE DIGITAL AGE AND REGULATORY FRAMEWORK.

Since the latter part of 2022, our world has borne witness to an unprecedented surge in the realm of digitalization. Artificial intelligence tools, leveraged by large language models (LLM), have allowed unprecedent interpretative interactive environment creation with the end user and access, processing and data sharing have never been so wide. The Generative AI field alone, has permitted the creation and growth of digital services in most fields of knowledge, impacting our society from several perspectives, job efficiency, knowledge transfer and acquisition, content creation, code development just to mention a few, with wide uptake and social acceptance. The energy domain is no exception. While machine learning, computer vision or deep learning tools have supported many energy-applied models, from Digital twins, generation/demand forecasting, consumer clustering, network planning tools just to mention a few, recent developments on the Data Spaces area, smart metering roll out, IOT and data AI driven tools, have promoted a new generation of services and tools to several target groups in the energy sector. While such developments may entail some risk and concerns, the European Union has taken the lead in regulating the digital era to ensure protection of companies and citizen rights, tackling cybersecurity, privacy, and data sovereignty, clarifying the stage for innovation and businesses. Interoperability has been another area of focus in

The associate editor coordinating the review of this manuscript and approving it for publication was F. R. Islam.

innovation projects, especially promoted under EC Horizon frameworks. Interconnect [1], as an example has expanded several ontologies such as SAREF to incorporate many of the household level new digital services, while it developed the Knowledge Engine tool, to ensure interoperability with a matching and reasoning functionalities, expanding the world of APIs. OneNet [2], Enershare [3] and InterStore [4] are other examples of European projects, defining new features for Energy Data Spaces, for different use cases of services in the energy sector, securing data sovereignty, privacy and interoperability through Data Space Connectors. The foundations for the future data markets are being set today, bringing stakeholders from all corners of society and international coordination such as the International Data Space Association [5] and its Gaia-X [6] initiatives. New roles and actors such as Data Brokers, clearing house or data service providers are becoming everyday concepts in the field. The goal is to promote fair market access, accessibility, awareness, and digital tool uptake will boost the energy transition and help achieve the goals defined under the Green Deal [7] and Fit-for55 [8] towards a carbon neutral European Union by 2050.

In the dynamic world of legislation and regulation, the European Union has introduced a series of forward-thinking measures aimed at shaping the digital landscape and safeguarding the rights of its citizens. To level the playing field and protect consumers, the EU has proposed the Digital Markets Act (DMA) [9] and Digital Services Act (DSA) [10]. This legislation seeks to regulate giant companies by requiring them to share data, preventing self-preferencing, and ensuring interoperability. By doing so, the DMA aims to promote fair competition and discourage potential market abuses. To enforce these rules, hefty fines await those who do not comply.

The DMA is part of the EU's broader mission to maintain fairness in the digital sector while safeguarding the interests of both businesses and consumers. In a data-driven world, information flows across borders at an astonishing rate. Hence, to harness the power of data and foster innovation, the EU introduced the Data Governance Act (DGA) [11]. This legislation establishes a structured framework for the secure sharing of non-personal data. By setting rules and standards, the DGA encourages businesses and public authorities to exchange data safely, promoting innovation and economic growth. The act also created the European Data Innovation Board to guide and support data-driven innovation. In essence, the DGA is a vital part of the EU's strategy to create a unified data market and propel the digital transformation of its economy.

Another milestone document is the E-Privacy Regulation [12]. This regulation steps in to protect citizens' privacy in the digital landscape. It replaces the existing e-Privacy Directive and establishes stringent rules for safeguarding personal data in electronic communications. This regulation ensures that a citizen's online activities, from cookie usage to messaging apps, are handled with care. Like the GDPR [13], it imposes substantial fines for non-compliance. The E-Privacy Regulation is a crucial part of the EU's broader mission to bolster data protection and privacy rights for individuals in the digital age. The European Data Strategy [14] on the other hand is designed to harness the potential of data for the benefit of all.

The European Data Strategy is a framework created by the European Commission to encourage responsible and innovative data use within the EU. It forms a crucial component of the Commission's broader digital strategy, with the goal of unleashing the potential of digital technologies to fuel economic growth and societal advancement. This piece of legislation is complemented by The European Digital Identity [15] (EUid Regulation, eIDAS Revision) envisioning the convenience of using a single, interoperable digital identity to access public services across the EU. The EUid Regulation makes this vision a reality. It streamlines the process of accessing services like healthcare and social security by allowing citizens to use their electronic identification (eID) across borders. Personal data protection is a priority, with stringent security measures and the right to access, rectify, and erase personal information. The EUid Regulation is a key element of the EU's strategy to create a Digital Single Market, enhancing cross-border digital services for its citizens. Finally, and as part of the EU's strategy is the world's first AI act [16]. The AI Act is a legal framework governing the sale and use of artificial intelligence in the EU. Its official purpose is to ensure the proper functioning of the EU single market by setting consistent standards for AI systems across EU member states, it prevents among other things, the use of certain types of data, to track, identify and locate individuals for specific services.

The stage is set for digital tools uptake in the energy domain and the user's response will help guide legislators and businesses manage expectation and demands. While digital services and products are emerging, there is no comprehensive listing of their roles in the energy sector, nor a comparison of their economic performance. Also, an assessment of e the levels of adoption and maturity of many of the existing (or emerging) energy digital services, is absent from the literature. The present aims tom fill these research gaps providing a comprehensive analysis starting by identifying and categorizing those energy digital services, assessing their maturity and adoption level through a Fuzzy logic approach, and showing how Cost Benefit Analysis (CBA), can support the justification of their positioning.

For this reason, the energy sector was one of the pioneering sectors in the embrace of digitalization as a means of self-improvement of its activities. Digital technologies have been adopted since the early 1970s by power utilities, such as Distribution System Operators – DSO – and Transmission System Operators – TSO – to facilitate grid management and operation, and by oil and gas companies to improve decision making for exploration and production assets [17].

However, in current days, digitalization is progressing through the value chain as more services and products are designed and created, not only to assist energy production, transmission, and distribution operators but also energy retailers and consumers. Although the digitalization of the energy system is heavily dependent on technologies such as smart devices and meters that rely on Internet of Things – IoT –, 5G and 6G connectivity, cloud edge computing, digital twins of the energy system, and many other disruptive technologies [18] it is important to not lose focus as these technologies are only the enablers of digitalization, and do not represent the transformation in its whole [18].

B. STRUCTURE

This paper is divided into five main chapters, the first chapter includes the motivation for carrying out this work.

The second chapter consists of a detailed list of existing and emerging digital services and products where we briefly present how they work, what technologies are necessary to enable them, who can supply them and who can benefit from them.

The third chapter presents the methodologies used to assess the maturity level and the adoption levels of each service and product with the goal of being able to generate a scatter plot of maturity versus adoption.

In chapter four we present the classification of the digital services and products introduced in chapter two according to the methodology developed in chapter three.

In the fifth chapter we present a Cost-Benefit Analysis, or CBA, of some of the digital services and products identified in the second chapter. The justification for the chosen digital services and products is presented in chapter four.

Finally, in chapter six, we present our conclusions that, based on the worked carried out, will shed light on the dynamics shaping the digital transformation of the energy sector and the factors influencing their varying levels of success and the reasons behind high maturity-low adoption and vice-versa.

II. DIGITAL SERVICES AND PRODUCTS OVERVIEW

Defining digital services/products is vital in understanding their role in the energy sector. Unlike physical counterparts, these exist in the digital realm, provided by digital service providers – DSPs – and accessed electronically.

Take the smartphone – not a digital product but a facilitator for services like delivery, mobility, online shopping, art, and music.

Beyond the electrical system focus, the energy sector includes major demand and supply sectors, as noted by [19]. Our comprehensive list draws from [IEA, JRC reports] and projects like Eddie, OneNet, DrimPac, Delta, Dr. BoB, EUniversal, InterConnect, Smart4Res, InteGrid, InterStore. While we aim for exhaustion, periodic updates may be needed. We have categorized them into buildings, mobility, and infrastructure/industrial processes, each with a concise list and descriptions covering functionality, implementation requirements, providers, and beneficiaries.

A. BUILDINGS

The digitalization of the energy sector depends heavily on digital services and products that can be provide to and by the buildings sub-sector as this sub-sector contribute significantly to global energy consumption, looking at the European Union the residential sector, was responsible for 28.0% of final energy consumption in 2020 [20].

By optimizing its energy usage, it is possible to reduce the overall energy demand, and by increasing the integration of distributed energy resources – DER – it is possible promote a more sustainable and efficient energy system, this is feasible through the digitalization of the sub-sector, however, the increase in devices must be managed carefully to avoid backfiring, meaning that these technologies can consume more energy than what they offset [21], [22].

Digital services and products play a key role in achieving this optimization by providing real-time information on energy consumption, identifying energy-saving opportunities, and automating building systems to enhance efficiency [23].

Through the implementation of smart sensors, data analytics, and machine learning, these digital solutions transform buildings into intelligent and energy-efficient systems, facilitating the transition to a low-carbon energy system. Apart from the environmental advantages, digital services and products in the buildings sector also offer economic benefits such as decreased energy costs.

Consequently, the digitalization of the buildings sector is a crucial step towards digitalizing the energy sector, presenting substantial opportunities for energy savings and sustainable practices. Following this logic, we have identified several existing and emerging digital services and products that fall within the sub-sector of Buildings in the process of digitalization of the energy sector.

1) CONSUMPTION COMMUNICATION

Enable the transmission of consumption readings to the DSO via wired or wireless communication. This can be achieved by the roll-out of smart meters coupled with communication devices.

2) LOAD OPTIMIZATION

Optimize load and consumption via the implementation of home and building energy management systems (HEMS/BEMS).

3) CONSUMPTION/GENERATION FORECAST

Utilizing BEMS and HEMS systems plus communication devices to enable the DSO and TSO to forecast the levels of consumption and distributed generation of end consumers and prosumers.

4) CO2/GHG EMISSION ESTIMATION/FORECAST

Using BEMS and HEMS systems so the DSO can provide end consumers with information regarding the generation profile and CO_2/GHG emissions ration associated to each period of the day-ahead.

5) ENERGY TARIFFS COMMUNICATION AND DESIGN
Design custom tariffs for end consumers, enabled by energy retailers, with the implementation of smart meter and communication devices using variables such as GHG emissions, elasticity estimation and flexibility availability.

6) FLEXIBILITY AVAILABILITY ASSESSMENT
HEMS and BEMS systems, as well as communication networks, data storage and processing systems, AI and ML algorithms enable real time information on the availability of flexible resources to be provided to DSOs, TSOs, energy retailers and end consumers.

7) PEAK REDUCTION/SHAVING
Relying on BEMS and HEMS systems and their accessories, the end users can optimize their consumption by reducing or shifting loads to valley periods in accordance with information provided by the DSO.

8) CONSUMER ELASTICITY ESTIMATION
Using shifting tariffs schemes to estimate the end consumer willingness to shift their consumption. This service works in close relation with tariff design and flexibility assessment.

9) FAULT DETECTION AND VOLTAGE/POWER COEFFICIENT
Utilizing algorithms and sensors to detect faults in the distribution system in real time. This can be achieved by voltage coefficient and power coefficient analysis, as well as advanced analytics and monitoring systems.

10) CONTRACTED POWER ESTIMATION SERVICE
Online service for end consumers to calculate or estimate which power level they should contract based on certain variables such as number of appliances, household size, etc.

11) ENERGY HOME DOMOTICS (AUTOMATION SERVICES)
Domotics enables the automation of homes and businesses by implementing a combination of software and hardware that coupled with HEMS and BEMS systems can manage loads such as lighting, heating, and cooling, and ultimately optimize and minimize consumption patterns.

12) BATTERY CHARGE/DISCHARGE ARBITRAGE SYSTEMS
This digital service provides the end user with real time monitorization of the energy prices and determines whether it is advantageous for the batteries to be charged or discharged. Allowing the user to buy energy at off-peak periods and use it at peak periods ultimately reducing the energy cost associated with the household or business.

13) ENERGY ANALYTICS FOR BUILDINGS
This service is enabled by advanced analytics and technologies and provides the end user with valuable insights that can lead to energy consumption optimization, efficiency, and enhanced performance in buildings. This service works closely with energy home domotics, and other optimization-based services.

14) AGGREGATION SERVICES
These services leverage aggregated data from diverse sources, enabling thorough analysis and efficient energy resource management. Market participants, DSOs, TSOs, end users, and other stakeholders stand to gain significant benefits. For instance, aggregating data from public parking lots with EV chargers transforms them into flexible resources. This information equips DSOs to address congestion issues in the grid.

15) ENERGY COMMUNITY MANAGING SERVICES
These services can include previously mentioned services specifically tailored for energy communities. They involve community engagement and participation, energy monitoring and data management, peer-to-peer trading, demand response and flexibility as well as energy community platforms and marketplaces.

The services presented in the previous bullets are those that were identified to have the most significant impact on the digitalization of the energy sector (building sub-sector). As previously mentioned, some of these services are still in the early stages of development while others are already being implemented by DSOs, TSOs, and other stakeholders.

B. MOBILITY
Digitalization of the energy sector relies broadly on digital services and products within the mobility sub-sector. Given that this sub-sector contributes significantly to global energy consumption, with a 28.4% share of the final energy consumption in the EU (excluding aviation and all maritime dutiable petroleum products loaded aboard a vessel for consumption by that vessel) [20], and CO_2 emissions of 7.98 giga tons of CO_2 worldwide [24], optimizing mobility is crucial for reducing energy demand and fostering a more sustainable and efficient energy system.

Digital products and services are fundamental in achieving this optimization, as they offer real-time information on transportation options, enable smart charging and vehicle-to-grid – V2G – services, and contribute to the spread of connected and autonomous vehicles [25], [26].

Through the utilization of data analytics, machine learning, and communication networks, these digital solutions have the capability to transform mobility into an intelligent and energy-efficient sub-sector that supports the transition to a low-carbon energy system [27], [28].

Beyond their environmental advantages, digital services and services in the mobility sub-sector can also grant economic gains, such as reduced energy costs and improved transportation efficacy [29]. Overall, the digitalization of the mobility sector corresponds to a significant opportunity for energy savings and sustainability, constituting a vital step in the broader digitalization of the energy sector.

A survey of existing and emerging digital services and products within the mobility sub-sector allowed us to identify some of the main ones in the following bullets.

1) DELIVERY SERVICES

These types of services rely on online marketplaces, to provide end users with the possibility of purchasing items and having them delivered to a desired location. By coupling these services to the concepts of EVs and V2G technologies these delivery fleets can be charged at optimal times and location to provide flexibility and grid balancing opportunities.

2) MOBILITY SERVICES

Mobility services, akin to delivery services, use digital apps to offer transportation. Introducing features and employing mainly electric fleets enhances flexibility by enabling strategic EV charging. Customized tariffs can incentivize or disincentivize drivers to charge at specific times and locations. The impact is more pronounced with large EV fleets compared to individual users.

3) SCHEDULE CHARGING SERVICES

These services provide real-time information on the availability of charging infrastructure for EVs and can allow users to schedule time slots for recharging in accordance with their needs and the needs of the grid, like other services, this can be achieved by providing customized tariffs to incentivize and disincentivize drivers to charge their vehicles.

4) AUTOMATED DRIVING

These services, when referring to commuting vehicles, can enhance their efficiency and promote a more sustainable use, as automated driving relies on carefully designed software that can optimize fuel consumption, route planning, travel speed, etc., therefore contributing to the energy sector. However, they can also include other means of transportation such as aviation and maritime or even in warehouse management.

5) V2V COMMUNICATION

These services leverage advanced communication technologies to enable vehicles to exchange real-time information, enhancing road safety, optimizing traffic flow, and enabling intelligent transportation systems. By optimizing traffic flow, reducing congestion, and enabling more efficient routing, these services help minimize energy consumption and emissions.

6) V2G POWER TRANSMISSION

Integrated with digital technologies and smart grid infrastructure, this service boosts grid stability, enhances energy efficiency, and optimizes management of renewable sources. In the ongoing energy sector digital transformation, it plays a crucial role in optimizing energy use, reducing peak loads, and supplying valuable data for decision-making and grid management.

7) CONSUMPTION AND EMISSIONS TRACKING

Enable more accurate monitoring and analysis of energy usage and emissions data for various modes of transportation, facilitating the development of more energy-efficient and sustainable transportation solutions, promoting the adoption of alternative fuels and low-carbon technologies, supporting the integration of renewable energy sources into the transportation system, and enabling the development of new business models that can drive innovation and growth in the mobility sector.

8) CHARGER ROLL-OUT PLANNING

Charger roll-out planning enables strategic deployment of charging infrastructure, supporting renewable energy integration, enabling smart charging systems, facilitating EV adoption, improving stakeholder coordination, providing valuable data and analytics, and supporting the development of new business models and revenue streams.

9) CHARGING AND DRIVING PATTERNS (TARIFF DESIGN)

Enabled by data collection, it can be used to design tariffs that incentivize EV owners to charge their vehicles at times when electricity demand is low, reducing the burden on the grid and avoiding the need for expensive infrastructure upgrades. Tariffs can also be designed to incentivize EV owners to drive charge at times when renewable energy generation is high, promoting the integration of renewable energy into the grid.

10) REAL-TIME ASSET TRACKING

This service contributes to the digitalization of the energy sector by providing a platform for monitoring and managing energy consumption and distribution in real-time. By utilizing sensor technology and data analytics, this technology can provide real-time information on the performance, location, and energy usage of vehicles, including electric vehicles and other forms of low-carbon transportation. This can help to optimize energy consumption, reduce waste, and improve overall energy efficiency in the transportation sector.

11) VIRTUAL BATTERY ESTIMATION (FLEXIBILITY MANAGEMENT)

By relying on advanced modelling and forecasting techniques to estimate the capacity of distributed energy resources, such as electric vehicles, to act as a virtual battery, this technology can improve the integration of renewable energy sources, enhance the flexibility and resilience of the grid, reduce the need for expensive infrastructure investments, enable new energy services, and provide consumers with greater control over their energy consumption and costs.

12) INTEGRATED PAYMENTS

This service can help support the digitalization of the energy sector by enabling energy companies to process payments more efficiently, accurately, and securely. Finally, Integrated Payments can help energy companies comply with increasingly complex regulatory requirements. Although listed here, its application is not limited to the mobility sub-sector and can be integrated into services within the other two sub-sectors.

C. INDUSTRIAL INFRASTRUCTURE & PROCESSES

Finally, the digitalization of the energy sector also relies on the availability of digital services and products that are specifically tailored for the industrial sub-sector.

This sub-sector holds a sizable accountability for global energy consumption and emissions, with a total final energy consumption of 26.1% and CO2 emissions of 9.15 giga tons of CO2 by 2022 [20], [24].

The incorporation of data analytics, machine learning, and IoT technologies into these services and products holds potential for transforming industrial processes, and infrastructures, into intelligent, energy-efficient systems. Additionally, digital products and services in the Industrial infrastructures and processes sub-sector offer economic benefits such as reduced energy costs, enhanced performance, and improved competitiveness [30].

Overall, the digitalization of the Industrial infrastructures and processes sub-sector represents a crucial step in the broader digitalization of the energy sector, however, as the authors in [31] stated, few studies analyzed and summarized industrial practices for reducing environmental impact with the support of digitalization throughout manufacturing value chains.

For this work, we gathered a list of existing and emerging digital services and products that can be found within the industrial infrastructures and processes sub-sector that contribute to an overall digitalization of the energy sector, which can be consulted in the following bullets.

1) GROWTH FORECAST

This service can be enabled by data acquisition systems, communication networks, data storage and processing systems, statistical and predictive analytics tools, AI and ML algorithms, and it contributes to the digitalization of the energy sector by providing insights into future energy demand and consumption trends, supporting the planning and design of energy infrastructure and facilities, facilitating the integration of RES, promoting energy efficiency and sustainability.

2) DEMAND SIDE RESPONSE (IMPLICIT)

Demand Side Response (DSR) is a digital service in the energy sector that involves using technology to incentivize customers to adjust their energy consumption in response to changing demand on the grid. By providing real-time information on energy prices and demand, DSR enables customers to shift their energy use to times when it is more cost-effective and helps to balance the grid.

3) PROCESS PERFORMANCE MONITORING

Process Performance Monitoring (PPM) is a digital service in the Industrial Processes sector that involves using sensors, data analytics, and machine learning to monitor and optimize the performance of industrial processes. PPM can contribute to the digitalisation of the energy sector in several ways, including improving energy efficiency, reducing downtime, and optimizing energy supply.

4) REMOTE ASSET MANAGEMENT

Remote asset management can contribute to the digitalization of the energy sector by enabling real-time monitoring, control, and optimization of assets and processes, facilitating predictive maintenance, improving safety and reliability, increasing efficiency and productivity, reducing downtime and costs, and enabling the integration of renewable energy sources and smart grid technologies.

5) IDLE TIME ESTIMATION AND MITIGATION

Estimating and reducing, or even mitigating, idle time in industrial processes and industries can lead to lower energy cost by decreasing the amount of energy required for the same processes. To enable this service, it would require the use of sensors and actuators, communication networks, data storage and processing systems, artificial intelligence and machine learning algorithms, cloud computing platforms, predictive maintenance and condition monitoring software, and visualization and reporting tools.

6) FLEXIBILITY OFFERS (EXPLICIT)

Flexibility Offers is a digital service in the Industrial Processes sector that involves offering flexibility in energy consumption or generation to the energy market, in response to market conditions. By offering flexible energy, industrial processes can help to balance the grid, reducing the need for expensive peaking power generation and improving grid stability.

7) ELECTRICITY MARKET INTEGRATION ANALYSIS

These services use data analytics and modelling to assess the feasibility and benefits of integrating electricity markets. By analyzing market trends, regulatory frameworks, and infrastructure, this service provides insights on the potential benefits and risks of market integration, including increased competition, improved efficiency, and reduced costs. Electricity Market Integration Analysis can be a valuable tool for policymakers and energy companies seeking to optimize their operations and take advantage of new market opportunities.

8) DISTRIBUTED LEDGER TECHNOLOGY FOR THE PURPOSE OF ENERGY AUDITS AND CERTIFICATION OF ORIGIN

This is a digital service that contributes to the digitalization of the energy sector, specifically within the industrial processes and infrastructure sub-sector. This service leverages blockchain technology to enhance security, transparency, and efficiency in energy management. The service utilizes blockchain technology, a distributed ledger technology that ensures secure and decentralized record-keeping.

9) VALORISATION OF DATA FROM CONNECTED DATA SPACES

This service contributes to the digitalization of the energy sector by enabling data-driven decision-making, predictive maintenance, energy efficiency, customer engagement, cybersecurity and data privacy, regulatory compliance, amongst others. This data-driven approach is essential for the energy sector's transformation into a more sustainable and resilient industry.

10) CO2 AND GREEN HOUSE GASES EMISSIONS TRACKING AND DISAGGREGATION

The tracking of CO2 and GHG emissions, and their disaggregation, contributes to the digitalization of the energy sector by enabling more precise monitoring and analysis of energy usage and emissions data, providing insights into energy usage patterns, facilitating the integration of renewable energy sources.

11) LOAD OBSERVABILITY GRID IMPACT

This service is designed to allow the DSO to understand how each consumer under the same grid area impacts one another when their load increases/decreases. Load observability grid impact can be enabled by smart meters data acquisition systems, communication networks, data processing and analysis tools, machine learning algorithms, and visualization and reporting software.

12) GRID PLANNING AND MANAGEMENT SERVICES

These services employ diverse technologies and activities for the reliable and secure operation of electrical grids. They encompass grid planning, renewable integration, asset management, fault detection, load balancing, demand response, and advanced grid control systems. Stakeholders, including grid operators, utilities, regulators, and end-users, benefit from improved grid reliability, efficient renewable integration, and optimized asset management.

13) DIGITAL TWIN ENABLED SERVICES

These services integrate data from sensors, IoT devices, historical data, and external systems, providing a holistic view of asset behavior. Digital twins enable real-time monitoring, capturing data like temperature, pressure, vibration, and energy consumption. Continuously updating, digital replicas identify anomalies, performance deviations, and potential issues, enhancing asset performance, optimizing operations, and improving decision-making.

III. MATURITY AND ADOPTION ASSESSMENT METHODOLOGY

Measuring the adoption and maturity of services and products involves assessing their acceptance and evolution. Key

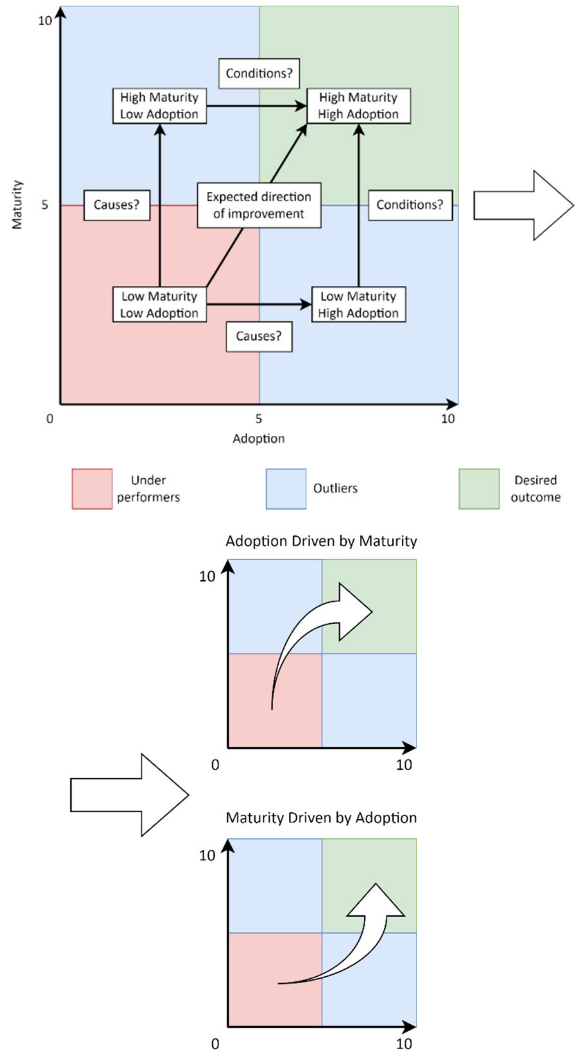

FIGURE 1. Maturity vs. adoption template. This plotting area will serve to provide visual information about digital services and products maturity and adoption, as well as to draw conclusions about maturity and adoption drivers.

indicators for adoption include market share, user base, and customer acquisition rates, reflecting greater acceptance and market penetration. Authors in [32] assessed globalization's impact on digital tech adoption, focusing on metrics like the digital adoption index [33] and adoption rates of digital technologies among EU firms [34]. Reference [35] notes that not actively stimulating customer adoption is a common mistake.

For maturity, factors like product enhancements, feature development, and lifecycle stages matter. Reference [36] conducted a survey on maturity models for digitalization, finding only three define digital maturity. Reference [37] developed an industry 4.0 maturity model, highlighting issues in previous models.

Customer feedback, user satisfaction, and retention rates offer insights into meeting user needs. Tracking adoption and maturity involves quantitative and qualitative assessments.

Comparing digital services in the energy sector requires a methodology balancing qualitative and quantitative assessment due to information nature. Ratings from 1 to 10 for both maturity and adoption allow creating a scatter plot, revealing outliers—digital services relying on mature technology but not benefiting from it in adoption, and those surpassing low-maturity technologies for high adoption. Studying these outliers provides valuable insights for developing high-maturity and high-adoption digital services.

In FIGURE 1 we can see the basis of the scatter plot that will be used to represent the outcome of this work. It is important to notice that the key goals are to identify both the causes for digital services and products to not migrate from the low maturity and low adoption quadrant to the high maturity and high adoption quadrant and, instead, migrate to one of the other quadrants and then identify the conditions that need to be met for those digital product and services to migrate to the high maturity and high adoption quadrant.

As FIGURE 1 demonstrates beyond a linear improvement, where adoption and maturity evolve together, two distinct cases can occur; a first one where adoption is driven by maturity where the digital services and products will have more adoption as the underlying technology evolves; and a second one where maturity is driven by adoption where the digital services and products improve on the underlying technology because of high adoption rates.

In the first case we hypothesized that an adopter would tend to demand a certain high degree of maturity before contracting the digital service or product as the revenue from that digital service or product does not offset the risk associated with contracting an unproven or untested digital service or product.

For the second case we hypothesized that an adopter would tend to contract a digital service or product that presents economic benefits even if the service or product is in its early stage of development and this in turn will cause the developer to invest in maturing the service.

However, two different outcomes are still possible as a digital service or product can face two different dead-ends, one where it is fully matured and that does not translate into an increase of adoption, and another where it has widespread adoption and therefore there are no motivation for increasing maturity levels of the underlying technology.

A. MATURITY

Maturity assessment of digital services relies on the required components and technologies. Services using established technologies lean towards high maturity, while those with emerging technologies tend towards low maturity. We conducted this assessment in two ways.

First, literature reviews and market research determined technology prevalence, supplier diversity, mass production, and stability. This data classified service maturity on a scale of 1 to 10.

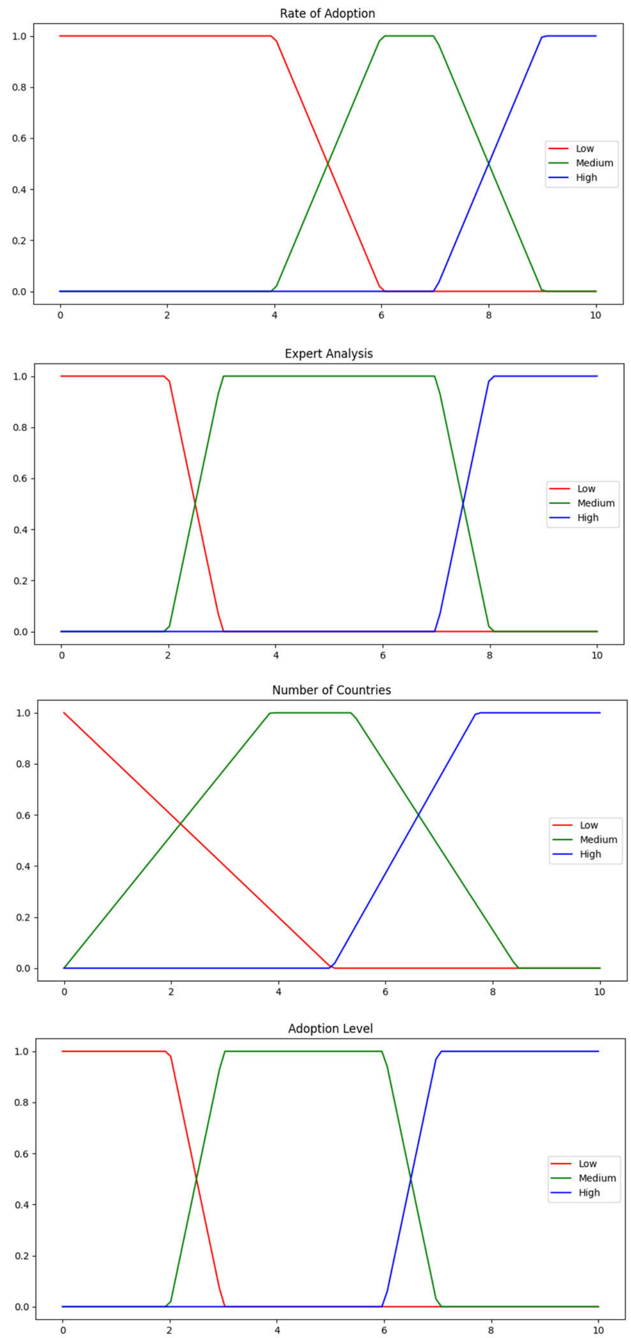

FIGURE 2. Membership functions for adoption assessment. These membership functions were designed to infer, by a fuzzy approach, the perceived adoption of the digital services and products identified in this work.

Second, an expert survey among peers and large language models (LLMs) like ChatGPT [38] and Gemini [39] enriched the assessment. Respondents and LLMs attributed maturity scores based on service explanations. Perceived maturity, though not directly translating to actual maturity, impacts adoption. We computed an overall value by assigning weights

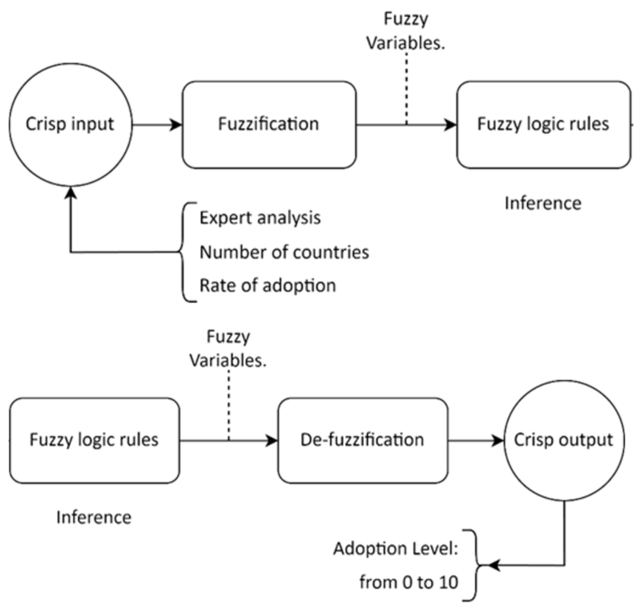

FIGURE 3. **Fuzzy logic model workflow. By defining a set of inputs like "Expert analysis", "Number of Countries" and "Rate of Adoption" the model can use the membership functions and rules to output the "Adoption Level" or perceived adoption level.**

(0.1 to 0.9) to three components, ensuring a cumulative sum of 1.

B. ADOPTION

In contrast to maturity assessment, adoption evaluation for digital services/products must consider the specific sub-sector they target. Services/products designed for entities like a TSO have a smaller potential adoption pool compared to those targeting the public. This relativization is crucial for representing maturity vs. adoption levels in a single scatter plot.

Directly assessing adoption through literature review faces challenges due to factors like service novelty, lack of studies, and varied nomenclature among EU countries. To infer perceived adoption, a fuzzy logic approach was employed, suitable for the energy sector's inherent complexities and uncertainties. Fuzzy logic accommodates imprecise and vague information, aligning with the subjective nature of adoption perception.

In the energy sector, adoption is influenced by factors exhibiting degrees of fuzziness and ambiguity. Fuzzy logic captures and models these uncertainties, facilitating nuanced analysis and decision-making. It handles incomplete and uncertain data, offering a more accurate understanding of perceived adoption.

Three parameters contribute to input information: Expert Analysis, Number of Countries, and Rate of Adoption. Expert Analysis involves assessments by project developers, research institution surveys, and large language models like ChatGPT and Bard, each weighted differently. Number of Countries is presented as an interval due to variations in service/product names and functionalities. Rate of Adoption, on a scale of 0 to 10, depicts the speed at which a service/product is integrated into the energy sector, based on expert opinions and literature reviews.

Membership functions for each input guide their impact on the output, as seen in FIGURE 2.

To obtain the adoption level value a set of fuzzy rules was created that specify how each input impacts the output. These rules are as follows:

- Rule 1 - If expert analysis or number of countries low and rate of adoption medium then adoption level is low.
- Rule 2 - If expert analysis or number of countries medium and rate of adoption low then adoption level is medium.
- Rule 3 - If expert analysis medium or number of countries high and rate of adoption medium then adoption level is high.

With all the pre-conditions established it is possible to calculate the Fuzzy Adoption levels for each service and product by following the steps presented in FIGURE 3.

Based on this, in the following chapter we present the input and output values for each identified digital service and product within the energy sector, dividing them according to their sub-sector.

IV. DIGITAL SERVICES AND PRODUCTS MATURITY AND ADOPTION CLASSIFICATION

By applying the methodology presented in the previous section, and based on the values of the input variables, we were able to reach a set of results that translate to the perceived maturity and adoption of the previously catalogued digital services and products. The next table, Table 1, presents the findings regarding the buildings sub-sector.

As we can see in Table 1, and as previously mentioned, three inputs were considered for the measurement of digital products and services adoption which in turn, by a fuzzy logic approach produce an output that we named "Fuzzy adoption" also previously referred to as perceived adoption.

As one of the inputs – Number of countries – is an interval, it can happen that the fuzzy adoption output is also an interval, this is because the output was calculated for each possible combination of inputs. For example, in service ID 1, if we consider [Expert analysis; Number of Countries; Rate of Adoption] we can have the following input combinations:

- [6.2; x; 4.4] where x = 8; 9; 10; 11; 12.

Each one of these inputs can produce a different output, and in that case, we present the fuzzy adoption as an interval between the minimum and maximum values calculated. However, it can also happen that different values for the "number of countries" input do not produce a different output, this is due to how the membership functions and the rules are created as well as the other inputs values, an example of this is service ID 3.

TABLE 1. Digital services and products adoption, within the building's subsector.

Service Name	EA	NoC	RoA	Fuzzy Adoption		ID
Remote Consumption Communication	6.2	8 to 12	4.4	4.17	4.22	1
Load optimization	4.0	12 to 15	7.2	7.29	7.61	2
Consumption/Generation forecasting	3.4	15 to 18	7.0	7.67		3
Consumption and Emissions Tracking (B)	5.3	20 to 22	5.6	6.63		4
Energy Tariffs Communication	6.1	10 to 14	5.8	6.67	7.11	5
Load Dis-aggregation and Flexibility Availability Monitoring	1.9	10 to 14	7.2	1.29	2.83	6
Peak Reduction	3.3	12 to 15	7.0	7.37	7.67	7
Consumer Elasticity Communication	2.2	8 to 12	4.2	3.85	3.87	8
Fault Detection and Voltage/Power Coefficient	4.6	12 to 15	6.8	7.37	7.67	9
Contracted Power Estimation	6.0	10 to 14	5.8	6.67	7.11	10
Energy Home Domotics	5.4	6 to 10	4.8	4.74	4.87	11
Battery Charge/Discharge Arbitrage System	1.7	10 to 14	7.4	1.31	2.96	12
Energy Analytics for Infrastructures and Buildings	5.5	15 to 23	7.6	7.49	7.49	13
Aggregation Services	7.5	10 to 15	5.6	5.85	6.07	14
Energy Communities Managing Services	7.2	6 to 10	5.4	5.47	6.06	15

EA – Expert Analysis
NoC – Number of Countries
RoA – Rate of Adoption.

The same holds true for the other adoption assessments regarding the remaining two sub-sectors, mobility, in Table 5, and industrial processes and infrastructures in Table 2.

To provide easier service and product identification their IDs do not reset for each sub-sector, so the building sub-sector goes from service ID 1 to service ID 15, the mobility sub-sector encompasses services ID 16 to 26, and the industrial processes and infrastructure sub-sector goes from service ID 27 to service ID 39.

So, although it is not immediately clear once analyzing the previous tables, the inputs and output can vary within the following intervals: Expert analysis and Rate of Adoption, as well as Fuzzy adoption vary from 0 to 10; Number of countries varies between 0 and 27 which is the pool of adoption when considering the European Union member states.

Regarding the maturity assessment of the digital services and products follows the same presentation methodology,

TABLE 2. Digital services and products adoption, within the mobility subsector.

Service Name	EA	NoC	RoA	Fuzzy Adoption		ID
Delivery Services	6.7	8 to 12	2.2	3.50		16
Mobility Services	7.1	12 to 15	4.6	4.57	4.61	17
Scheduled Charging Services	5.4	10 to 14	5.2	5.64	5.77	18
Automated Driving	1.7	12 to 15	3.2	3.50		19
V2V Communication	1.6	8 to 12	3.6	3.50		20
Consumption and Emissions Tracking (M)	6.3	15 to 18	6.8	7.67		21
EV Charger Roll Out Planning	4.4	12 to 15	5.8	7.10	7.11	22
Charging and Driving Patterns (Tariff Regulation)	3.9	10 to 14	6.6	6.87	7.67	23
Real Time Asset Tracking	6.6	12 to 15	7.4	7.21	7.55	24
Virtual Battery Estimation	3.9	10 to 14	6.4	6.87	7.67	25
Integrated Payments	7.7	12 to 15	6.2	6.60	7.24	26

EA – Expert Analysis
NoC – Number of Countries
RoA – Rate of Adoption.

services are grouped by their respective sub-sector and are presented with the input values and output value for "fuzzy maturity" or "perceived maturity".

Unlike the adoption assessment, the maturity assessment only focuses on two inputs. The first input is technology readiness level – TRL – and the second one is compliance. However, the TRL does not refer to the service but to the main technological enablers or, in other words, the main technologies required to implement the digital service or product.

In this case, the TRL values can vary between 1 and 9 and the compliance is classified as low, medium, and high, according to the following specifications:

- Low – service or product complies with legal frameworks however issues may arise linked to data protection, data ownership and cybersecurity, no industry standards.
- Medium – service or product complies with legal frameworks however issues may arise linked to data protection or data ownership or cybersecurity, some industry standards.
- High – service or product complies with legal frameworks and industry standards and no issues are foreseen.

The following tables, Table 4, Table 5, Table 6, present our findings regarding the maturity assessment of the digital services and products within the buildings, mobility, and industrial processes and infrastructure sub-sectors, respectively.

As we can see by observing the previous table, Table 4, the input components, or assessments are not additive in a

TABLE 3. Digital services and products adoption, within the industrial processes and infrastructure subsector.

Service Name	EA	NoC	RoA	Fuzzy Adoption		ID
Demand Growth Forecast	6.4	12 to 15	7.6	7.12	7.49	27
Demand Response Potential	4.9	12 to 15	7.4	7.21	7.55	28
Process Performance Monitoring	7.7	10 to 14	7	5.61	7.23	29
Remote Asset Management	7.8	12 to 15	8	6.16	7.21	30
Idle Time Estimation	7.5	8 to 12	6	5.72	6.94	31
Flexibility Offers	2.8	10 to14	7	6.64	6.70	32
Electricity Market Information Analysis	4.1	12 to 15	7.6	7.12	7.49	33
Load Observability Grid Impact	5.3	10 to 14	6.6	6.87	7.67	34
Blockchain for optimized security and energy management	1.9	10 to 14	5.8	1.83	2.86	35
Consumption and Emissions Tracking (IPI)	6.2	15 to 18	7.4	7.55		36
State Estimation Services	5.4	10 to 18	6.6	6.87	7.67	37
Grid Planning & Management Services e.g., D-Plan	7.1	13 to 20	7	7.60	7.67	38
Digital Twin Enabled Services	4.7	10 to 10	7	6.87		39

EA – Expert Analysis
NoC – Number of Countries
RoA – Rate of Adoption.

direct way therefore cases occur where two distinct digital services or products have the same TRL level and the same compliance level but do not have the same maturity level. This is because the compliance input is a qualitative assessment so there can be different degrees of low, medium, and high.

As previously mentioned, the column containing the main technological enablers, as stated, only contains some of the required technological components required, in this case, we have decided to include, for each digital service or product, technological enablers that are related to the digital component of the service, for example, services ID 16 and 17 require vehicles to be implemented, such as cars or motorbikes, however they are not listed as there were other enablers that more closely relate to the digital component of the services.

In the following FIGURE 4 we can observe the plot of the different digital services and products according to the previous results.

V. DIGITAL SERVICES AND PRODUCTS COST-BENEFIT ANALYSIS

As previously demonstrated some digital services and products fall under the category of either low maturity and high adoption – LMHA – or high maturity and low adoption –

TABLE 4. Digital services and products maturity, within the building's sub-sector.

Service Name & MTE	TRL	C	M	ID
Remote Consumption Communication. Smart meters, Data Analytics, Communication Protocols.	9	High	7.9	1
Load Optimization. Data Analytics, Energy Monitoring Sensors, Actuators.	8	Medium	5.0	2
Consumption/Generation Forecasting. Machine Learning, Data Analytics, Statistical Models.	8	Medium	6.2	3
Consumption and Emissions Tracking (B). Smart Meters, Communication Protocols, Data Analytics.	6	Medium	4.8	4
Energy Tariffs Communication. Communication Protocols, Data Management, Billing Systems.	6	Medium	7.1	5
Load Dis-aggregation and Flexibility Availability Monitoring. Energy Monitoring Sensors, Data Analytics, Machine Learning.	6	Medium	5.1	6
Peak Reduction. Demand Response Systems, Data Analytics, Communication Networks.	6	Low	5.2	7
Consumer Elasticity Communication. Smart Grid Infrastructure, Communication Protocols, Data Analytics.	5	Medium	2.8	8
Fault Detection and Voltage/Power Coefficient. Sensor Technology, Data Analytics, Machine Learning.	9	High	7.3	9
Contracted Power Estimation. Load Profiling Algorithms, Data Analytics, Predictive Models.	7	Medium	7.9	10
Energy Home Domotics. Home Automation Systems, Energy Monitoring Sensors, Actuators.	8	High	7.7	11
Battery Charge/Discharge Arbitrage System. Energy Storage Systems, Energy Monitoring Sensors, Market Analysis.	7	Medium	5.4	12
Energy Analytics for Infrastructures and Buildings. Building Management Systems, Data Analytics, Energy Monitoring Sensors Networks.	7	Medium	5.1	13
Aggregation Services. Data Integration Platforms, Communication Protocols, Analytics.	6	Low	5.3	14
Energy Communities Managing Services. Peer-to-Peer Energy Trading Platforms, Smart Contracts, Blockchain.	6	Low	6.2	15

MTE – Main Technological Enablers.
TRL – Technology Readiness Level.
C – Compliance.
M – Maturity.

TABLE 5. Digital services and products maturity, within the mobility sub-sector.

Service Name & MTE	TRL	C	M	ID
Delivery Services. Global Positioning System (GPS), Mobile Applications, Data Analytics.	9	Medium	7.3	16
Mobility Services. Connected Vehicles, Mobile Applications, Cloud Computing.	9	Medium	7.3	17
Scheduled Charging Services. Electric Vehicle (EV) Charging Infrastructure, Smart Grid Integration, Communication Protocols.	8	Medium	7.8	18
Automated Driving (all means). Artificial Intelligence (AI), Computer Vision, Sensor Technology.	6	Medium	5.2	19
V2V Communication. Wireless Networking, Data Security, Protocol Standards.	5	Low	2.0	20
Consumption and Emissions Tracking (M). Smart Meters, Data Analytics, IoT	6	Medium	5.9	21
EV Charger Roll Out Planning. Geographical Information Systems (GIS), Load Forecasting, Energy Demand Analysis.	6	Medium	5.5	22
Charging and Driving Patterns (Tariff Regulation). Smart Charging Infrastructure, Data Analytics, Tariff Regulations.	6	Medium	4.4	23
Real Time Asset Tracking. IoT, GPS, Asset Monitoring Sensors.	8	Medium	7.0	24
Virtual Battery Estimation. Battery Management Systems, Machine Learning, Data Analytics.	6	Medium	3.8	25
Integrated Payments. Payment Gateways, Financial Systems Integration, Data Security.	9	High	8.0	26

MTE – Main Technological Enablers.
TRL – Technology Readiness Level.
C – Compliance.
M – Maturity.

HMLA. In both these cases we can be looking at a transitional phase where it may happen that the service or product under analysis was in the process of achieving high adoption and

TABLE 6. Digital services and products maturity, within the industrial processes and infrastructure sub-sector.

Service Name & MTE	TRL	C	M	ID
Demand Growth Forecast. Data Analytics, Machine Learning, Statistical Models.	7	High	6.1	27
Demand Response Potential. Smart Grid Technology, Communication Protocols, Data Analytics.	7	Medium	6.0	28
Process Performance Monitoring. Industrial Internet of Things (IoT), Sensors, Data Analytics.	8	High	7.5	29
Remote Asset Management. Internet of Things (IoT), Connectivity, Data Analytics.	8	Medium	7.1	30
Idle Time Estimation. Machine Learning, Data Analytics, Real-time Monitoring.	8	High	7.5	31
Flexibility Offers. Smart Grid Infrastructure, Communication Protocols, Data Analytics.	5	Low	3.3	32
Electricity Market Information Analysis. Big Data Analytics, Machine Learning, Market Data Integration.	8	Medium	7.1	33
Load Observability Grid Impact. Advanced Metering Infrastructure (AMI), Grid Sensors, Data Analytics.	7	Medium	6.1	34
Blockchain for optimized security and energy management. Blockchain Technology, Data Encryption, Smart Contracts.	4	Low	3.2	35
Consumption and Emissions Tracking (IPI). IoT Sensors, Data Analytics, Emissions Monitoring Systems.	7	High	5.9	36
State Estimation Services. Power System Models, Sensor Data Fusion, Estimation Algorithms.	8	High	6.6	37
Grid Planning & Management Services e.g., D-Plan. Grid Simulation Tools, Optimization Algorithms, Data Integration.	9	High	6.9	38
Digital Twin Enabled Services. Digital Twin Technology, IoT Connectivity, Data Analytics.	6	Medium	5.0	39

MTE – Main Technological Enablers.
TRL – Technology Readiness Level.
C – Compliance.
M – Maturity.

TABLE 7. Digital services and products classified according to their assessment.

High Maturity & Low Adoption (HMLA)	Low Maturity & High Adoption (LMHA)
01 - Remote consumption communication.	04 - Consumption and emission tracking (buildings sector).
06 - Loads dis-aggregation and flexibility availability monitoring.	23 - Charging and driving patterns (for tariff design).
11 - Energy home domotics (Home Automation).	25 - Virtual battery estimation.
12 - Battery charge and discharge arbitrage systems.	32 - Flexibility offers (explicit).
16 - Delivery services.	
17 - Mobility services.	
19 - Automated driving (all sectors, e.g., aviation, maritime, railway, etc.).	

high maturity as there can be a time interval between a service or product reaching maturity and being highly adopted. However, there can be cases where a digital product or service can be in these situations for other reasons. One of these reasons could be the financial feasibility of the specific service. To assess this, literature research as well as data collection for the specific services were conducted. Where data availability allowed a cost-benefit calculation was performed following the methodology presented in [40]. Especially for immature services, literature was quite scarce a not a lot of data was available. Also, the economic feasibility of many services is very case-dependent – therefore the following assessment does not follow a systematic approach but features general insights into the economic feasibility of the services.

The following services, in Table 7, were assessed:

The literature scanning highlighted the following characteristics regarding the financial feasibility of the proposed services:

The previous tables, Table 8, Table 9, Table 10, give indications of the economic feasibility of the services. For example, energy arbitrage does currently not provide a business case. Loads dis-aggregation and flexibility availability monitoring are very case-dependent but become a viable option, especially in future scenarios. Regarding mobility services, several companies have established themselves over the last couple of years, however, the regulatory framework and the availability of public transport significantly impact the economics of this service. Automated driving is likely to become valuable in the future, however significant capital expenditures must be undertaken. Regarding the LMHA services, economic feasibility can be given for cases of flexibility offers and virtual battery estimation. Charging and driving patterns also seem to entail some relevant benefits. Consumption and emission tracking heavily depend on achieved savings. The following FIGURE 5 gives a screenshot of IRRs

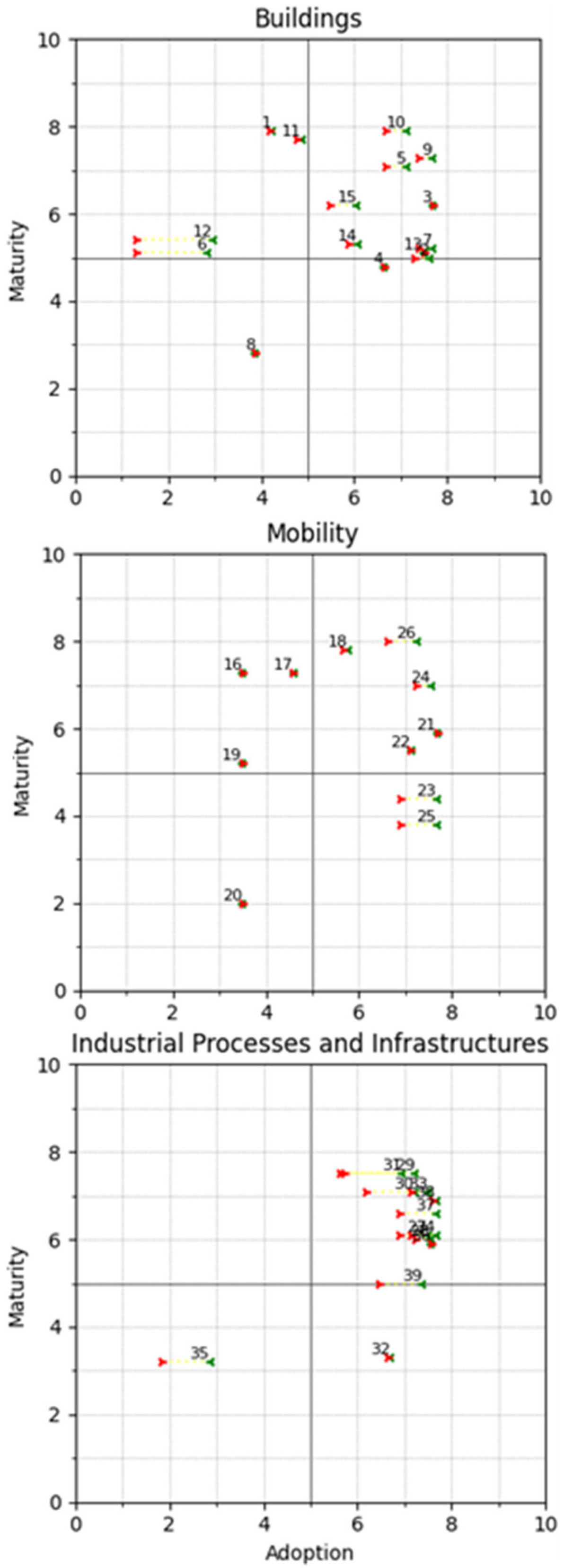

FIGURE 4. Digital services and products adoption vs. maturity plots for the three subsectors. Henceforward the quadrant from (0,5) to (5,10) is the high-maturity low-adoption (HMLA) quadrant and the one from (5,0) to (10,5) is the low-maturity high-adoption (LMHA) quadrant.

TABLE 8. Economic feasibility of HMLA/LMHA services, buildings sub-sector.

Service	Financial feasibility	IRR	Source
01) Remote consumption communication	Gas smart meter boiler: Significant reduction in costs, financial savings achieved by the energy supplier using the legal measure on energy savings are sufficient to cover the investment and operating costs of the entire investment.		[41]
04) Consumption and emission tracking	CBA calculation based on the insights of literature and expert consultation.	-20%, +8%	[42] [43]
06) Loads dis--aggregation and flexibility availability monitoring	The flexibility option can be preferable to grid reinforcement.	0%	[44]
	Large benefit for the DSO if it contributes to postponing investment in network upgrade. Current grid: negative Net Present Value – NPV – but becomes positive in the future.		[45]
	All flexibility options may be preferable alternatives to traditional grid expansion from an economic point of view: savings can be up to 85% of grid reinforcement costs.		[46]
11) Energy home domotics (Home Automation)	Smart home energy management solutions in Algeria and Germany /modest automation.	50%, 481%	[47]
	Energy consumption of devices must drop significantly to become economically viable.		[48] [49]
	Potential economic advantages.		[50]
12) Battery charge and discharge arbitrage systems	Life cycle net present value of all case buildings was positive under the assumption that an intelligent system can save 6% of the building's energy consumption / improper operation might lead to a negative NPV.		[51]
	Economically feasible operation through arbitrage is not possible due to small price differences in the market and limitations due to battery aging and efficiency.		[52]
	Grid-scale battery energy storage system arbitrage.	-28%, -29%	[53]
	Battery used for arbitrage and self-consumption.	-18%	[54]
	Viability of the electricity arbitrage business for different European countries.	-10%, -3%	[15]
	Implement Energy Time Shift during peak hours for commercial consumers with BESS instead of diesel generator, not economically attractive, with reduced CAPEX BESS costs it could however become interesting.		

TABLE 9. Economic feasibility of HMLA/LMHA services, mobility subsector.

Service	Financial feasibility	IRR	Source
16) Delivery services	In presence of wind power, V2G beneficial from charge/discharge power cost point of view.		[56]
	Electric truck fleet: Lifetime revenues between $ 10 000 to $ 60 000.		[57]
	V2G in the UK could provide a significant source of income, NPV of £8 400 per vehicle.		[58]
17) Mobility services	Uber generated $ 31.8 billion in revenue in 2022, an 82% increase on the previous year. It made $ 14 billion in revenue from ride-hailing, and $ 10.9 billion from mobility. The rest came from freight services. Loss of $ 9.1 billion in 2022. Limited adaptation due to competitive landscape (other similar services) in certain countries /regulatory barriers /availability of public transportation.		[59]
	Lyft ride hailing app: • Annual revenue is $ 2.36 billion, • Generated $ 4 billion revenue in 2022, a 27.8% percent increase year-on-year and a record for the company. • Had 20.3 million active riders in 2022, an 8.5% increase on the previous year.		[60]
	Maas Global (WHIM): • Estimated annual revenue is currently $9M per year.		[61]
19) Automated driving (all sectors, e.g., aviation, maritime, railway, etc.)	Significant capital outlays will be necessary before autonomous-vehicle businesses are profitable. Per-mile cost of autonomous shared mobility will be highly competitive with private vehicles and more cost-effective than car-sharing services, car rentals, ride-hailing, or solo taxis.		[62]
	By 2035, autonomous driving could create $300 billion to $400 billion in revenue. Total value of advanced driver assistance systems market could reach $55 billion to $80 billion by 2030.		[63]
	The results show that the greatest benefits are saved driver costs for trucks and decreased travel time costs for car drivers. In the example calculations, capital costs may increase by 22 percent for cars and 36 percent for trucks for benefits to exceed costs in 2025.		[64]
23) Charging and driving	Reduction of 32%-34% of the costs due to optimized charging and a prolonged stay time.		[65]

TABLE 9. ***(Continued.)*** **Economic feasibility of HMLA/LMHA services, mobility subsector.**

patterns (for tariff design).	Reduction of charging costs of 11%.		[66]
	Non-residential EV charging stations: All modeled scenarios generate a negative NPV, study from 2012.		[67]
	Economics of EV charging depends on the level of the charger, higher level chargers (fast charging) have higher costs than lower-level ones unless utilization is very high.		[68]
25) Virtual battery estimation	Virtual power plant.	IRR: 321% IRR: 76%	[69]

TABLE 10. **Economic feasibility of HMLA/LMHA services, industrial processes, and infrastructure.**

Service	Financial feasibility	IRR	Source
32) Flexibility offers (explicit)	Dependent on different technology set-ups (Battery in Bulgaria, Battery in Slovenia – high investment costs, Battery in Slovenia – low investment costs, Electrode boiler in Slovenia).	-9%, 13%, 56%, 19%	[70]

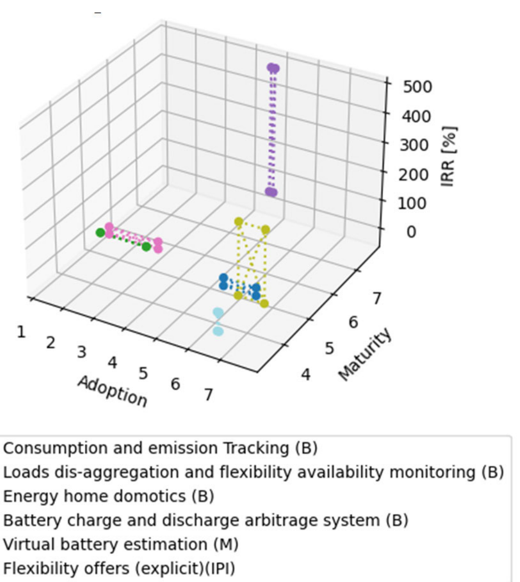

FIGURE 5. **3D overview of the internal rate of return of the different services, plotted against their maturity and adoption.**

for the different services, plotted against their maturity and adoption classifications.

In general, the collected information supports the theory that low adoption can be contextualized with a lower economic feasibility than services with high adoption. We point out that several other factors such as the existing regulatory framework (regulatory frameworks not ready for small scale flexibilities) or customer preferences limit the market potential. Moreover, many of the services are very specific and therefore make the economic feasibility very case dependent.

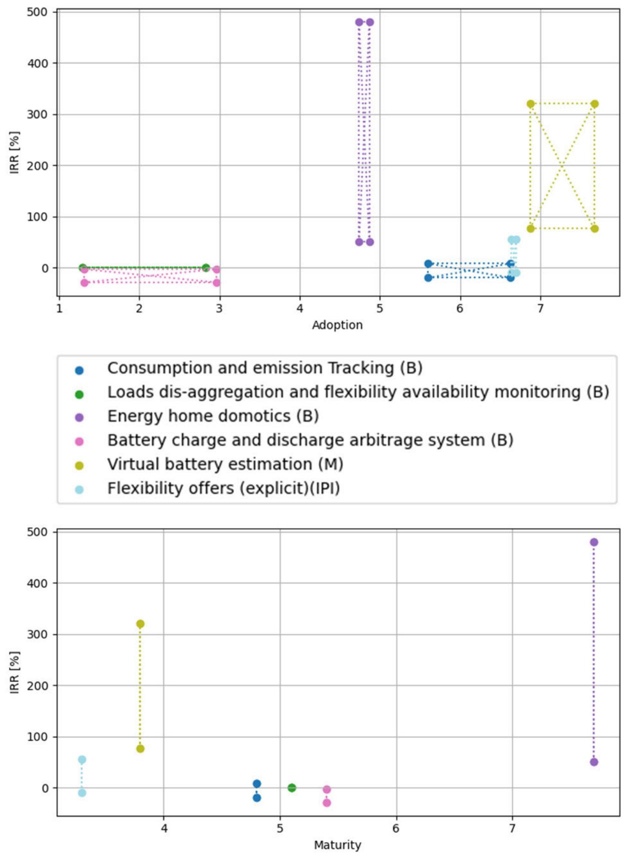

FIGURE 6. **2D subplots: (TOP) adoption versus internal rate of return; (BOTTOM) maturity versus internal rate of return.**

To better analyze FIGURE 5 we also present FIGURE 6 where the reader can see two 2D subplots extracted from the previous 3D plot.

So, by analyzing the data from FIGURE 5 and FIGURE 6 we see what the expected internal rate of return for each digital service and product compares against the previously estimated values of adoption and maturity.

Because of the nature of the results, in intervals, we now know that each digital service can create a 2D plain in the 3D plot. However, due to the small number of digital services and products it is not recommended to extract any conclusion from this scatter plot alone.

VI. CONCLUSION

In this study we created a comprehensive and extensive list of existing digital services and products that, directly or indirectly, play or will play a role in the digitalization of the energy sector and its sub-sectors. Based on a literature review we dived deeper into these digital services and products by assessing their adoption and maturity and presenting the reader with our findings in an accessible and comprehensive manner. To tackle this problem, we have employed a fuzzy logic methodology designed based on our experience as well as tried and tested methods coupled with emerging technologies such as AI powered Large Language Models. To back our findings, we conducted a Cost-Benefit analysis aimed at outlying digital services and products that demonstrated to have unexpected results in their adoption and maturity assessments.

However, like any other study, we have found ourselves confronted with limitations and external factors that are common to occur in this type of literature driven study. Two main limitations could be identified.

The first one resides in the uncertainty of interpretation, as some of these services and products are still in the early stages of development, it is easy to have varying opinions. This became evident as we were confronted with different understandings and interpretations of the services by each expert.

The second limitation is linked to data availability, this was more evident when assessing services and products that are not yet established in the market, as companies will withhold information for newly developed products and services.

Regarding the fuzzy logic methodology assessment, this is an expert driven analysis that can be easily manipulated to cater to the intended narrative. However, by implementing surveys and external inputs we have strived to design an unbiased and clear set of rules that ultimately can provide close to real-world results.

For the Cost-Benefit Analysis, we emphasize its exposure to a handful of impactful external factors such as: electricity costs, that are difficult to estimate for future scenarios; technology costs, which present a learning curve for new services and products; the uncertainty of economic value, in case of flexibility services; the lifetime of these services and products, especially regarding software as improvements are expected for low-maturity services and products; and finally the utilization factor, if energy services and products are not widely adopted it potentiates same costs but lower revenues.

Importantly, we have identified other factors that impact the uptake of digital services and products in the energy sector.

Technology degradation, which affects efficiency and reliability, can negatively impact consumer trust and adoption. For example, solar photovoltaic panels or batteries lose their efficiency over the years, and still present high replacement costs.

Regulatory limitations and heavy bureaucracy, such as government policies, regulations, and standards can either encourage or hinder the adoption of digital energy services and products. Complex or stringent regulatory frameworks might impede the development and implementation of these digital technologies. Also, people's current habits and comfort levels significantly impact the adoption of energy services. Factors like the charging time of electric vehicles or the time required for travel play a pivotal role. If a service disrupts established habits or is significantly less convenient, it might face resistance. So, we can conclude that social factors and usage patterns also play an important role in the uptake of these digital services and products.

Other factors such as the utilization rate also demonstrate to be un-negligible in this analysis. The frequency and efficiency of digital services and products usage impact its appeal. For instance, if a service is only usable under specific conditions or has limited availability, it might deter potential users.

The perceived or actual environmental advantages associated with an energy digital service or product, whether direct (like reduced emissions) or indirect (such as supporting clean energy production), significantly impact its acceptance.

Moreover, the competitive landscape and the investment costs, when significant, also have their impact in the adoption of a digital service or product and their path to maturity. The presence and quality of alternative options, such as the availability and reliability of public transport, influence the uptake of energy services. If existing solutions are more convenient or cost-effective, it can hinder the adoption of new services. Initial investment costs for establishing energy services can be a barrier. High upfront expenses or long payback periods might deter both consumers and businesses from adopting new energy solutions, especially if the benefits aren't immediately evident.

These factors collectively shape the landscape in which energy services are embraced and addressing them effectively is crucial for widespread adoption and integration into the energy sector.

Finally, considering the digital services and products we have identified, and to give answer to our previously posed question we see a trend that implies that adoption will be driven by maturity as seven digital services and products were in the HMLA quadrant versus the four digital services and products located in the LMHA quadrant. Nonetheless, further analysis would be required to cement these observations and conclusions.

As we move towards the future, and as new material and information is made available, the outcomes of this study can also evolve and mutate in either direction, what was once perceived as a mature or highly adopted service can prove to have degraded over time so, with our findings, we present the reader with a methodology to assess the perceived adoption and maturity of digital services and products, based on literatures reviews and expert opinions, that can be used to either extract bench mark practices to achieve the high levels of adoption/maturity or to compare results with real-world outcomes.

To finalize, we present an itemized and emphasized list of the outcomes of our assessments:

1. Comprehensive Listing:
    - Created an extensive list of digital services and products in the energy sector, capturing both direct and indirect influences on digitalization.

2. Literature Review and Assessment:
   - Conducted a thorough literature review to delve into the adoption and maturity levels of identified digital services and products.
   - Employed a fuzzy logic methodology supplemented by emerging technologies like AI-powered Large Language Models for assessment.
3. Cost-Benefit Analysis:
   - Conducted a Cost-Benefit analysis to highlight unexpected outcomes in the adoption and maturity assessments of digital services and products.
4. Identified Limitations:
   - Acknowledged limitations including uncertainty in interpretation due to early-stage development of some services/products and data availability issues, especially for nascent market offerings.
5. Methodological Transparency and Vigilance:
   - Emphasized efforts to mitigate biases in the fuzzy logic methodology through surveys and external inputs.
6. External Factors Affecting Digitalization:
   - Highlighted external factors such as technology degradation, regulatory limitations, consumer habits, and competitive landscape impacting the uptake of digital energy services and products.
7. Social and Environmental Considerations:
   - Emphasized the role of social factors, environmental benefits, and perceived advantages in driving adoption.
8. Economic and Competitive Dynamics:
   - Addressed the significance of investment costs, competitive landscape, and alternative options influencing adoption and maturity pathways.
9. Trend Analysis and Future Outlook:
   - Observed a trend where adoption is driven by maturity, indicating potential future trajectories of digital services and products in the energy sector.
10. Continuous Evolution of Findings:
    - Recognized the dynamic nature of the study outcomes, highlighting the need for ongoing assessment and adaptation to evolving circumstances.
11. Methodological Contribution:
    - Presented a methodology for assessing adoption and maturity based on literature reviews and expert opinions, offering benchmarks for achieving high levels of adoption/maturity and facilitating comparison with real-world outcomes.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

ACKNOWLEDGMENT

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor CINEA can be held responsible for them.

REFERENCES

[1] *Interconnect*. Accessed: Oct. 31, 2023. [Online]. Available: https://interconnectproject.eu/
[2] *OneNet*. Accessed: Oct. 31, 2023. [Online]. Available: https://onenet-project.eu/
[3] *The Energy Data Space for Europe*. Accessed: Oct. 31, 2023. [Online]. Available: https://enershare.eu/
[4] *InterStore*. Accessed: Oct. 31, 2023. [Online]. Available: https://cordis.europa.eu/project/id/101096511
[5] *International Data Spaces Association*. Accessed: Oct. 31, 2023. [Online]. Available: https://internationaldataspaces.org/
[6] *Gaia-X*. Accessed: Oct. 31, 2023. [Online]. Available: https://gaia-x.eu/
[7] European Comission. (Dec. 11, 2019). *Communication From the Comission—The Europena Green Deal*. Accessed: Oct. 31, 2023. [Online]. Available: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0008.02/DOC_1&format=PDF
[8] *On the Path to Climate Neutrality*. Accessed: Oct. 31, 2023. [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal/fit-55-delivering-proposals_en
[9] (Sep. 14, 2022). *Document 32022R1925*. Accessed: Oct. 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022R1925
[10] (Oct. 19, 2022). *Document 32022R2065*. Accessed: Oct. 31, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32022R2065
[11] (May 30, 2022). *Document 32022R0868*. Accessed: Oct. 31, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32022R0868
[12] (Jan. 17, 2017). *The EPrivacy Regulation*. Accessed: Oct. 31, 2023. [Online]. Available: https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vkayfua65ols
[13] (Apr. 27, 2016). *Document 32016R0679*. Accessed: Oct. 31, 2023. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2016/679/oj
[14] (Feb. 19, 2020). *Document 52020DC0066*. Accessed: Oct. 31, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0066
[15] (Jun. 3, 2021). *Document 52021PC0281*. Accessed: Oct. 31, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0281
[16] (Apr. 21, 2021). *Document 52021PC0206*. Accessed: Oct. 31, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52021PC0206
[17] (2017). *IEA, Digitalisation and Energy, IEA, Paris*. [Online]. Available: https://www.iea.org/reports/digitalisation-and-energy.
[18] *Digitalising the Energy System EU Action Plan*, European Comission, Brussels, Belgium, 2022.
[19] J. Sathaye and A. H. Sanstad, "Bottom-up energy modeling," in *Encyclopedia Energy*. Boston, MA, USA: Elsevier Science, 2004, pp. 251–264.
[20] Eurostat. (2022). *Energy Statistics—An Overview*. European Comission, Strasbourg. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview
[21] IEA. (2019). *Energy Efficiency and Digitalisation*. IEA, Paris, France. [Online]. Available: https://iea.blob.core.windows.net/assets/8441ab46-9d86-47eb-b1fc-cb36fc3e7143/Energy_Efficiency_2019.pdf
[22] M. E. Mondejar, R. Avtar, H. L. B. Diaz, R. K. Dubey, J. Esteban, A. Gómez-Morales, B. Hallam, N. T. Mbungu, C. C. Okolo, K. A. Prasad, Q. She, and S. Garcia-Segura, "Digitalization to achieve sustainable development goals: Steps towards a smart green planet," *Sci. Total Environ.*, vol. 794, Nov. 2021, Art. no. 148539.
[23] P. Borowski, "Digitization, digital twins, blockchain, and Industry 4.0 as elements of management process in enterprises in the energy sector," *Energies*, vol. 14, no. 7, p. 1885, Mar. 2021.
[24] (2022). *IEA, CO_2 Emissions in 2022, IEA, Paris*. [Online]. Available: https://www.iea.org/reports/co2-emissions-in-2022.
[25] A. Mangipinto, F. Lombardi, F. D. Sanvito, M. Pavičević, S. Quoilin, and E. Colombo, "Impact of mass-scale deployment of electric vehicles and benefits of smart charging across all European countries," *Appl. Energy*, vol. 312, Apr. 2022, Art. no. 118676.

[26] M. Yilmaz and P. T. Krein, "Review of benefits and challenges of vehicle-to-grid technology," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Raleigh, NC, USA, Sep. 2012, pp. 3082–3089.

[27] A. Pernestal, A. Engholm, M. Bemler, and G. Gidofalvi, "How will digitalization change road freight transport? Scenarios tested in Sweden," *Sustainability*, vol. 13, no. 1, p. 304, Dec. 2020.

[28] H. Virkkunen. (Dec. 10, 2021). *Reduce CO_2 Emissions on Transport by New Services Provides By Digitalization*. Accessed: May 5, 2023. [Online]. Available: https://www.europeanfiles.eu/climate/reduce-co2-emissions-on-transport-by-new-services-provides-by-digitalization

[29] D. H. Bardakci, "Benefits of Digitalization in International Logistics Sector," *Int. J. Social Sci. Econ. Res.*, vol. 5, no. 6, pp. 1476–1489, Jun. 2020.

[30] Y. Shi, Y. Gao, Y. Luo, and J. Hu, "Fusions of industrialisation and digitalisation (FID) in the digital economy: Industrial system digitalisation, digital technology industrialisation, and beyond," *J. Digit. Economy*, vol. 1, no. 1, pp. 73–88, Jun. 2022.

[31] X. Chen, M. Despeisse, and B. Johansson, "Environmental sustainability of digitalization in manufacturing: A review," *Sustainability*, vol. 12, no. 24, p. 10298, Dec. 2020.

[32] M. Skare and D. R. Soriano, "How globalization is changing digital technology adoption: An international perspective," *J. Innov. Knowl.*, vol. 6, no. 4, pp. 222–233, (Oct. 2021.

[33] The World Bank. (2016). *Digital Adoption Index*. World Bank. Accessed: Nov. 2, 2023. [Online]. Available: https://www.worldbank.org/en/publication/wdr2016/Digital-Adoption-Index

[34] OECD, "Digitalisation and productivity: A story of complementarities," in *OECD Economic Outlook*, vol. 2019, no. 1. Paris, France, OECD Publishing, 2019, pp. 55–83.

[35] McKinsey & Company. (May 2017). *Mastering the Digital Advantage in Transforming Customer Experience*. Accessed: Oct. 31, 2023. [Online]. Available: https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Operations/Our%20Insights/Mastering%20the%20digital%20advantage%20in%20transforming%20customer%20experience/Mastering-the-digital-advantage-in-transforming-customer-experience.pdf

[36] T. Thordsen, M. Murawski, and M. Bick, "How to measure digitalization? A critical evaluation of digital maturity models," in *Responsible Design, Implementation and Use of Information and Communication Technology, Skukuza*. Cham, Switzerland: Springer, 2020.

[37] R. G. G. Caiado, L. F. Scavarda, L. O. Gavião, P. Ivson, D. L. D. M. Nascimento, and J. A. Garza-Reyes, "A fuzzy rule-based Industry 4.0 maturity model for operations and supply chain management," *Int. J. Prod. Econ.*, vol. 231, Jan. 2021, Art. no. 107883.

[38] OpenAI. *ChatGPT*. Accessed: May 10, 2023. [Online]. Available: https://chat.openai.com/

[39] Google. *Gemini*. Accessed: Aug. 10, 2023. [Online]. Available: https://gamini.google.com/app

[40] Joint Researc Center. (2012). *Guidelines for Conductiing a Cost-Benefit Analysis of Smart Grid Projects*. Accessed: Nov. 2, 2023. [Online]. Available: https://ses.jrc.ec.europa.eu/sites/default/files/publications/guidelines_for_conducting_a_cost-benefit_analysis_of_smart_grid_projects.pdf

[41] I. Smajla, D. K. Sedlar, L. Jukić, and N. Vištica, "Cost-effectiveness of installing modules for remote reading of natural gas consumption based on a pilot project," *Energy Rep.*, vol. 8, pp. 5631–5639, Nov. 2022.

[42] O. Husiev, A. Campos-Celador, M. Álvarez-Sanz, and J. Terés-Zubiaga, "Why district renovation is not leading the race? Critical assessment of building renovation potential under different intervention levels," *Energy Buildings*, vol. 295, Sep. 2023, Art. no. 113288.

[43] Global Alliance for Buildings and Construction. (2019). *2019 Global Status Report for Buildings and Constructions*. [Online]. Available: https://iea.blob.core.windows.net/assets/3da9daf9-ef75-4a37-b3da-a09224e299dc/2019_Global_Status_Report_for_Buildings_and_Construction.pdf

[44] Anm4L. (2021). *D4.1 Value of Flexibility for Utilities*. [Online]. Available: https://anm4l.eu/wp-content/uploads/2021/03/D4.1-Value-of-Flexibility-for-Utilities-Ver1.0-approved.pdf

[45] I. Verdelho, R. Prata, D. Koraki, and K. Strunz. (2016). *Demand Flexibility Benefits From the DSO Perspective—A SuSTAINABLE CaseStudy*. [Online]. Available: http://www.cired.net/publications/workshop2016/pdfs/CIRED2016_0104_final.pdf

[46] M. Resch, J. Bühler, B. Schachler, and A. Sumper, "Techno-economic assessment of flexibility options versus grid expansion in distribution grids," *IEEE Trans. Power Syst.*, vol. 36, no. 5, pp. 3830–3839, Sep. 2021.

[47] M. Ringel, R. Laidi, and D. Djenouri, "Multiple benefits through smart home energy management solutions—A simulation-based case study of a single-family-house in Algeria and Germany," *Energies*, vol. 12, no. 8, p. 1537, Apr. 2019.

[48] J.-N. Louis and E. Pongrácz, "Life cycle impact assessment of home energy management systems (HEMS) using dynamic emissions factors for electricity in Finland," *Environ. Impact Assessment Rev.*, vol. 67, pp. 109–116, Nov. 2017.

[49] S. S. van Dam, C. A. Bakker, and J. C. Buiter, "Do home energy management systems make sense? Assessing their overall lifecycle impact," *Energy Policy*, vol. 63, pp. 398–407, Dec. 2013.

[50] J. Lemos-Vinasco, A. Schledorn, A. Pourmousavi and D. Guericke. (2022). *Economic Evaluation of Stochastic Home Energy Managment Systems in a Realistic Rolling Horizon Setting*. [Online]. Available: https://www.researchgate.net/publication/359277913_Economic_evaluation_of_stochastic_home_energy_management_systems_in_a_realistic_rolling_horizon_setting

[51] Z. Chen, F. Wang, and Q. Feng, "Cost-benefit evaluation for building intelligent systems with special consideration on intangible benefits and energy consumption," *Energy Buildings*, vol. 128, pp. 484–490, Sep. 2016.

[52] F. Braeuer. (2023). *Techno-economic Evaluation of Battery Storage Systems in Industry*. [Online]. Available: https://publikationen.bibliothek.kit.edu/1000157261

[53] S. Yamujala, A. Jain, R. Bhakar, and J. Mathur, "Multi-service based economic valuation of grid-connected battery energy storage systems," *J. Energy Storage*, vol. 52, Aug. 2022, Art. no. 104657.

[54] STORY. (2020). *Deliverable 7.5 Evaluation of Simulation Results: Comparing Large Scale Storage Simulation Results With the STORY Demonstration Sites*. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d6b1f718&appId=PPGMS

[55] F. Núñez, D. Canca, and Á. Arcos-Vargas, "An assessment of European electricity arbitrage using storage systems," *Energy*, vol. 242, Mar. 2022, Art. no. 122916.

[56] A. Ahmadian, M. Sedghi, B. Mohammadi-Ivatloo, A. Elkamel, M. A. Golkar, and M. Fowler, "Cost-benefit analysis of V2G implementation in distribution networks considering PEVs battery degradation," *IEEE Trans. Sustain. Energy*, vol. 9, no. 2, pp. 961–970, Apr. 2018.

[57] Z. Liao, M. Taiebat, and M. Xu, "Shared autonomous electric vehicle fleets with vehicle-to-grid capability: Economic viability and environmental co-benefits," *Appl. Energy*, vol. 302, Nov. 2021, Art. no. 117500.

[58] R. Gough, C. Dickerson, P. Rowley, and C. Walsh, "Vehicle-to-grid feasibility: A techno-economic analysis of EV-based energy storage," *Appl. Energy*, vol. 192, pp. 12–23, Apr. 2017.

[59] Business of Apps. (2023). *Uber Revenue and Usage Statistics (2023)*. Accessed: 2023. [Online]. Available: https://www.businessofapps.com/data/uber-statistics/

[60] Business of Apps. (2023). *Lyft Revenue and Usage Statistics (2023)*. Accessed: Jul. 18, 2023. [Online]. Available: https://www.businessofapps.com/data/lyft-statistics/

[61] Growjo. *Maas Global Revenue and Competitors*. Accessed: 2023. [Online]. Available: https://growjo.com/company/MaaS_Global

[62] McKinsey&Company. (2023). *Where Does Shared Autonomous Mobility Go Next*. Accessed: 2023. [Online]. Available: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/where-does-shared-autonomous-mobility-go-next

[63] *Autonomous Driving's Future: Convenient and Connected*, McKinsey&Company, New York, NY, USA, 2023.

[64] P. Andersson and P. Ivehammar, "Benefits and costs of autonomous trucks and cars," *J. Transp. Technol.*, vol. 9, no. 2, pp. 121–145, 2019.

[65] *D2.2 Stakeholder Perspective and Business Models*, Car2Flex, Green Energy Lab, Vienna, Austria, 2021.

[66] S. TIan, X. Du, Y. Liang, X. Yang, J. Yin, M. Ji, Y. Chen and T. Gong. (2021). *Multi-Objective Optimized Charging Strategy for Electric Vehicles Based on Demand Response*. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9713319

[67] D. Chang, D. Erstad, A. Rice, C. Goh, A. Tsao and J. Snyder. (2012). *Financial Viability of Non-Residential Electric Vehicle Charging Stations*. [Online]. Available: https://innovation.luskin.ucla.edu/wp-content/uploads/2019/03/Financial_Viability_of_Non-Residential_EV_Charging_Stations.pdf

[68] Pwc. (2023). *Electric Vehicles and the Charging Infrastructure: A New Mindset*. Accessed: 2023. [Online]. Available: https://www.pwc.com/us/en/industries/industrial-products/library/electric-vehicles-charging-infrastructure.html

[69] hybrid-VPP4DSO. (2017). *Economic Appraisal of VPP Use Cases*. [Online]. Available: https://www.grazer-ea.at/hybridvpp4dso/images/hybrid-vpp4dso_workshop_economicevaluation.pdf

[70] *D8.2 Economic Impact Assessment and Business Model's Analysis Report*, X-FLEX, Austin, TX, USA, 2023.

[71] Drectorate-General for Energy. *Digitalisation of the Energy System*. Accessed: May 18, 2023. [Online]. Available: https://energy.ec.europa.eu/topics/energy-systems-integration/digitalisation-energy-system_en

[72] Eurostat. (2013). *Glossary: Bunkers*. Eurostat. Accessed: May 23, 2023. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Bunkers

SALVADOR CARVALHOSA received the B.Sc. and M.Sc. degrees in electrical and computer engineering from FEUP, where he is currently pursuing the Ph.D. degree in sustainable energy systems. He is an Associate Researcher with INESC TEC and a Guest Lecturer with the Engineering Faculty, University of Porto. He teaches subjects, such as circuit theory, energy grids, and power systems. Reference projects include the Green-Est, Asprela+Sustentável and Every1 projects, and PROT Norte 2023, which is the regional plan for territorial development of the northern region of Portugal. His research interests include sustainable energy systems, energy policy, and electric mobility.

ALEXANDRE LUCAS received the Electrical Engineering degree from ISEL, in 2007, the master's degree in business and industrial strategy from ISEG, in 2009, and the Ph.D. degree in sustainable energy systems from IST, in 2013. He developed research at MIT, from 2011 to 2012, and complementary training at the Harvard on Energy Management. With nine years of experience in power substations, he joined the European Commission, in 2014, working for the JRC, until 2020. Then, he joined INESC TEC, dedicated to research projects. Reference projects are Electra, Delta, Drimpac, Interconnect, OneNet, MagPie, InterStore, and Every1. His research interests include energy digitalization, energy management, demand response, forecast, and LCA.

CAMILLA NEUMANN received the joint international master's (M.Sc.) degree in energy and materials from the University of Graz and Utrecht University. She specializes in assessing renewables from an economic, societal, and regulatory viewpoint. She joined Joanneum Research, in 2018, as a Junior Scientist. Currently, she works on business models for flexibility solutions and energy communities.

ANDREAS TÜRK received the M.B.A. degree. He has been with Joanneum Research for ten years. He was involved in many EU projects and projects funded by Australian Government. His research interests include international and national energy and climate policy and in particular smart grids, smart cities, and the design of electricity markets energy efficiency policies related to economic evaluation and policy design and investigating innovation mechanisms and regulatory frameworks for deploying low carbon technologies. He is an expert with the International Energy Climate Policy.