A Systematic Analysis of Electricity Markets on Smart Grid Performance

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A Systematic Analysis of Electricity Markets on Smart Grid Performance

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Zusammenfassung

Das heutige Stromversorgungssystem steht vor mehreren Herausforderungen, um die Energiewende zu erreichen und einen vollständig nachhaltigen und sauberen Energiesektor zu gewährleisten. Erneuerbare Energien und Smart Grid-Technologien sind entscheidende Faktoren, die diese Transformation unterstützen. Smart Grid-Technologien beziehen sich auf ein Versorgungsnetz, das digitale Kommunikationstechnologien nutzt, um Informationen über die Verfügbarkeit von Ressourcen bereitzustellen, Steuerbarkeit zu ermöglichen und eine dynamischere Betriebsweise des Stromsystems zu fördern. Derzeit stehen Elektrizitätsmärkte vor der Herausforderung, sich weiterzuentwickeln, da neue Marktprodukte und -dienstleistungen, wie Flexibilitätsdienste, auf den Markt kommen. In liberalisierten Energiesystemen erfordern Veränderungen in den Marktdynamiken jedoch eine gründliche Bewertung, insbesondere wenn das Ziel die Erreichung eines nachhaltigeren Stromsystems ist.

Ziel dieser Forschung ist es, zu untersuchen, wie Smart Grid-Technologien die Leistung des Stromsystems beeinflussen und damit die Nachhaltigkeit des Elektrizitätsmarktes durch die Entwicklung neuer Marktregeln fördern. Um dieses Ziel zu erreichen, verwendet diese Dissertation eine Kombination von Methoden, um verschiedene Strommarktdesigns zu kategorisieren, Lücken für neue Marktregeln zu identifizieren und durch eine systematische Analyse der Literatur relevante Key Performance Indicators (KPIs) auszuwählen. Diese KPIs werden verwendet, um die angestrebten Nachhaltigkeitsziele unter Berücksichtigung der Markteigenschaften des ursprünglichen Designs zu bewerten. Eine bibliometrische Analyse wurde durchgeführt, um ein Set von Leistungsindikatoren für Smart Grid-Märkte zu entwickeln. Diese Indikatoren werden verwendet, um die wirtschaftlichen, sozialen, ökologischen und politischen Dimensionen der Nachhaltigkeit in Stromsystemen zu bewerten. Zur Entwicklung dieses Indikatorsets und zur Visualisierung ihrer Beziehungen zwischen den Dimensionen werden Werkzeuge wie Wissenschafts-Mapping und Co-Word-Analyse eingesetzt. Diese Werkzeuge unterstützen den Aufbau von Beziehungen auf der Basis von Semantikanalysen.

Als Ergebnis wird ein erstes Set von KPIs vorgeschlagen, um Nachhaltigkeitsaspekte basierend auf Veränderungen in den Designs und Regeln des Elektrizitätsmarkts zu

bewerten. Ein Anwendungsfall zur Bewertung der Nachhaltigkeitsimplikationen verschiedener Zahlungsmethoden für Flexibilitätsdienste in Verteilungsnetzen wurde berücksichtigt. Die Auswertung der Beziehungen zwischen den KPIs unterstützte die Visualisierung der Dynamik der Aspekte in Stromsystemen und die Auswirkungen von Änderungen im Marktzahlungsmodell auf verschiedene Dimensionen.

Abschließend wurden Experteninterviews durchgeführt, um den Prozess zu bewerten. Ziel ist es, Wissen zu generieren, indem das Marktverständnis, seine Beziehung zur Nachhaltigkeit und die Bewertungsmethoden, die in verschiedenen Regionen implementiert wurden, erfasst werden. Inhaltsanalyse und Data Mining werden eingesetzt, um Muster in den Expertenmeinungen zu identifizieren und damit die Verbindungen zwischen dem Markt und den Bewertungsmethoden zu unterstützen. Der Prozess ermöglicht die Clusterung und Kartierung marktrelevanter KPIs. Die Beziehungen zwischen den Marktbegriffen verdeutlichen, wie Änderungen im Elektrizitätsmarkt ein nachhaltigeres Energiesystem fördern können.

Dieser Ansatz bietet eine systematische und multidimensionale Analyse der Elektrizitätsmärkte, die es ermöglicht, die Lücke zwischen dem Marktgestaltungsrahmen und seiner praktischen Bewertungsmethode zu überbrücken. Die Dissertation soll eine Grundlage für politische Entscheidungsträger und Branchenakteure bieten und ihnen dabei helfen, den Fortschritt in Richtung nachhaltiger Ziele auf den Elektrizitätsmärkten zu messen.

Abstract

Today's electric power system is facing several challenges to achieve the energy transition and to comply with a fully sustainable and clean power sector. Renewable energies and smart grid technologies are key contributors in supporting this transformation. Smart grid technologies refer to a supply network that uses digital communication technologies to provide information on resource availability, enable controllability, and encourage a more dynamic operation of the power system. Electricity markets nowadays face the challenge of evolving since new market products and services are emerging, such as flexibility services. However, in liberalized energy systems, changes in market dynamics require thorough evaluation, especially if their objective is the achievement of a more sustainable power system.

This research aims to explore how smart grid technologies influence power system performance, thereby promoting sustainability of the electricity market through the development of new market rules. To achieve this goal, this thesis employs a combination of methodologies to categorize different electricity market designs, identify gaps for new market rules, and, through a systematic analysis of the literature, select relevant Key Performance Indicators (KPIs). These KPIs are used to assess intended sustainability goals considering the market characteristics of its original design. A bibliometric analysis was implemented to develop a set of performance indicators for smart grid markets. These indicators are used to evaluate the economic, social, environmental, and policy dimensions of sustainability in power systems. To develop this set of indicators and visualize their relationships among dimensions, tools such as science mapping and co-word analysis are employed. These tools support the construction of relationships based on semantics analysis.

As a result, a first set of KPIs is proposed for the evaluation of sustainability aspects based on changes in electricity market designs and rules. A use case for evaluating the sustainability implications of different payment mechanisms for flexibility services in distribution systems was considered. The evaluation of relationships between the KPIs supported the visualization of the dynamics of the aspects in power systems and the implications of changes in the market payment scheme over different dimensions.

Finally, expert interviews are conducted to evaluate the process. The objective is to generate knowledge through an understanding of the market, its relationship with sustainability, and the assessment methods implemented across different regions. Content analysis and data mining are employed to identify patterns within expert opinions, thereby supporting the connections between the market and evaluation methods. The process enables the clustering and mapping of market-related KPIs. The relationship among market concepts clarifies how changes in the electricity market can promote a more sustainable energy system.

This approach offers a systematic and multidimensional analysis of electricity markets which allows to bridge the gap between the market design framework and its practical evaluation method. The thesis aims to provide a foundation for policymakers and industry stakeholders, assisting them in measuring progress towards sustainable goals in electricity markets.

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Contents

Acronyms

ADS Active demand and supply

API Application Programming Interface

BRP Balance Responsable Party

CAIDI Customer Average Interruption Duration Index

CAIFI Customer Average Interruption Frequency Index

CCA Cross-Consistency Assessment

CPES Cyberphysical Energy Systems

DER Distributed Energy Resource

DSO Distribution System Operator

EM Electricity Market

EOM Energy-Only Market

ERIGRID European Research Infrastructure supporting Smart Grid and Smart Energy Systems

EU European Union

GMA General Morphological Analysis

HHI Herfindahl–Hirschman Index

HTD Holistic Test Description

ICT Information and communications technologyCT][ICTs]Information and communications technologies

KPI Key Performance Indicator

LEM Local Energy Market

MB Morphological BoxB][MBs]Morphological Boxes

NLP Natural Language Processing

PPA Power Purchase Agreement

RE Renewable Energy

SAIDI System Average Interruption Duration Index

SAIFI System Average Interruption Frequency Index

SDG Sustainable Development GoalDG][SDGs]Sustainable Development Goals

TSO Transmission System Operator

Glossary

Electricity market design comprises the definitions for the creation of the electricity market and specifies the properties, rules, and regulations applicable for the trading of the electricity products. Structure the rules to get effective competition, risk aversion and power quality.

Electricity market framework refers to the standardized group of electricity market concepts and organizational relationships that serve as a platform to develop models and tools.

Holistic test description refers to the process and methodology for the evaluation of a function, system or component regarding a given test objective. This concept has been used in ERIGRID Projects.

Market mechanism comprises the actions and decisions to set the price and quantity, based on matching the demand and supply. It is also known as price mechanisms.

Market rule establishes the norms and criteria for market operation. Refers to rules that govern the operation of the market according to [AKZ09].

Power purchase agreement refers to a contract for electricity supply (usually medium to long-term) for a specific energy product, delivery point and/or time interval. It is an agreement between two parties..

SGAM refers to the Smart grid architecture model (SGAM) that enables a higher abstraction level to support interdisciplinary domain-specific concepts regarding smart grid technologies in the power system.

1 Introduction

> *In the future, the expansion of renewable energies is to proceed as much as possible on a market-driven basis.*
>
> — **EEG2021**
> (Renewable Energy Sources Act 2021)

The energy transition has become one of the most important challenges of the 21st century, given that the energy sector is responsible for more than 40% of CO_2 emissions worldwide. Therefore, it is necessary to move towards a sustainable power system to mitigate climate change. Since the Paris agreement, several countries have established policies to support renewable energies (REs). In addition, research has focused on the deployment of new technologies to support the integration of weather-dependent sources into the power grid, such as smart grids.

Stakeholders in the energy sector question how new technologies like *smart grids*, foster the development of new markets in a manner that is cost-efficient, secure, and resilient. They also question whether market-based solutions can effectively address the energy transition. Market-based solutions refer to a range of trading mechanisms that allow all participants to freely offer energy, power, and ancillary services, thereby enabling efficient balancing of consumption demands. Similarly, policymakers and regulators need to analyze how the current Electricity market can adapt to use the advantages that smart grid technologies offer in the interest of a sustainable power system. Furthermore, careful considerations are required when designing and implementing new rules for the electricity market.

Today, due to the digitalization of the power system, information can enhance trading mechanisms. Smart grid technologies support the integration of various components of the power system using an IT infrastructure, enhancing observability and controllability. This, in turn, increases the amount of information for the decision-making process based on resource availability, which could lead to better performance of the power system [Far10]. Customers are taking a prominent role by trading the capabilities of their energy resources through flexibility offers. This flexibility can arise from various sources, ranging from the traditional demand response, active participation in power production, and participation in ancillary services schemes for both active and reactive power. However, the feasibility of implementing certain trading mechanisms varies depending on the market structure and regulations of the specific country or region. While some mechanisms are readily implementable, others may necessitate substantial modifications.

Smart grids are defined as an electrical network capable of ensuring a sustainable power system, enhancing efficiency in operation, and improving the functioning of the market [Eur11]. In addition, smart grid technologies support the "convergence of information technology and communication technology with power system engineering" as mentioned[Far10]. Therefore, enhancing the potential of smart grid technologies can be achieved by introducing new regulations in existing electricity markets or by establishing entirely new markets.

The Renewable Energy Law [Fed20] of the Federal Republic of Germany from 2020 stipulates that "*in the future, the expansion of renewable energy is to proceed as much as possible in a market-driven basis*" This statement implies the necessity of implementing additional trading mechanisms, either changes in the market mechanisms or the creation of new market rules in the system. It is essential to collect information about the regulations, the market characteristics, the actors involved, and their behavior.

Electricity market ontologies are a formal representation of knowledge, developed to depict concepts and relationships for the description of properties, processes, communication capabilities, and information exchange pertaining to specific electricity are employed as a crucial step in the integration of domain knowledge, particularly for simulation purposes [MT09].For example, ontologies such as the one developed for the Hellenic Transmission System Operator [AKZ09], the Nord Pool ontology [San+17b], and a more general ontology for the European Power Exchange (EPEX) [San+17a], among others, have been created to define the conceptual framework of market entities. These ontologies are also employed to assess sustainability in the energy domain, as suggested in [Sch+20]. However, none of these ontologies address other market characteristics or electricity market designs, limiting their capacity to analyze various configurations without modification or extensions for new purposes. Consequently, an ontology or a classification of market characteristics that includes different regions and trading mechanisms is necessary, with particular focus on evaluating sustainability aspects within the power sector.

While existing ontologies, such as those proposed by [San+17a; AKZ09], contribute significantly to elucidating specific market concepts, their limitations underscore the need to advance towards more inclusive frameworks. This involves the development of a market categorization that offers a broad, high-level framework to classify and organize different types of market designs based on shared features [RL78]. Information about regions, trading mechanisms, regulatory frameworks, or other relevant criteria could then be shared and understood more consistently between different systems. A market categorization supports the link between the high-level framework and particular ontologies. For example, each category or type of market design can have its own ontology that defines the specific concepts, relationships, and properties relevant to that design. Therefore, before embarking on the development of ontologies or classification systems, it is imperative to perform market categorization. This process is essential for overcoming localized considerations and facilitating a comprehensive understanding of diverse market designs and their inherent sustainability implications.

Finding a holistic approach to evaluate a new market rule, considering the different market design options available and multiple sustainability aspects, can be complex. Therefore, a common understanding base is needed for evaluation. This can be achieved by using Key Performance Indicators (KPIs) which can link multiple market aspects with sustainability considerations of the power system. Furthermore, smart grid technologies provide a variety of data and information that can be translated into KPIs for evaluation.

The use of KPIs in power systems is not a novel practice. They have been employed for operational functions, ensuring the quality of the power supply through activities such as monitoring power, setting objectives, and demonstrating reliability, and for financial purposes, such as evaluating performance and revenue from various utilities. Regulatory authorities use KPIs to define strategic goals that can be translated into actionable measures. In the Electricity market, it is common to encounter economic evaluations showing market shares, market power, and economic withholding behavior, rather than evaluations that consider the social impacts on customers during the decision-making process. However, the concept of KPIs for the evaluation of smart grids has not been developed to the same extent. Some studies have presented lists of KPIs related to smart grid projects [Con18] or for smart grids in distribution systems [Har17], but the implications of these KPIs for electricity markets have not been thoroughly considered or analyzed. It is necessary to evaluate which KPIs are affected by different market rules and their impact on sustainability aspects.

Consequently, this thesis introduces a methodology for analyzing the impact of new market rules within the framework of the electricity market under evaluation. The goal is to improve the performance of smart grids and concurrently assess the achievement of specific sustainability objectives.

To accomplish this objective, a market categorization was performed to predefine the regulatory framework of the market under scrutiny. Subsequently, a two-layered morphological box is proposed for market categorization and for potential new market rules. This method is used to identify gaps in existing market designs. With the use of bibliometric analysis of open-source papers, potential new markets are examined. Furthermore, KPIs were extracted and meticulously reviewed, considering their influence on the electric market and smart grid performance. Finally, through the application of science mapping and evaluations conducted through interviews, the relationships between these indicators and potential market designs were mapped. Furthermore, the needs expressed by the experts led to the proposal of enhanced KPIs, particularly regarding the participation of customers in several markets to support the evaluation of social aspects. The methodology presented here is replicable for extraction and evaluation of KPIs for other rules of the Electricity market not discussed within the scope of this thesis.

In addition, two case studies were chosen for this assessment, focusing on flexibility markets for distribution networks and the need for KPIs for the evaluation of flexibility offers from neighborhood grids. As a final result, the relationships between the indicators and the sustainability aspects are mapped for different market mechanisms in the study case.

This introductory chapter presents the motivation and state of the art that support this research. In addition, the research questions and scope of this thesis are presented. The sections are organized as follows: Section 1.1 provides a comprehensive motivation to analyze systematically the electricity markets based on smart grid performance. Section 1.2, offers an extensive overview of the current state of the art and identifies the research gap that this thesis seeks to address. Finally, Section 1.4 presents the objectives and research questions of this thesis.

1.1 Motivation

The liberalization of electricity markets has transformed the traditional paradigm, shifting from fully vertically integrated, predominantly government-owned systems to decentralized models open to all investors. In decentralized systems, the roles of generation, transmission, and distribution are distinctly separated, yet well coordinated. Traditionally, power plants were mostly based on fossil fuels, nuclear sources, or large hydropower units with reservoirs to compensate for seasonality. Energy was transmitted from generators, located where the resource is easy to find, to load centers in cities. Customers have a passive role, wherein they only consume energy and pay a tariff for it.

Nowadays, wind and solar power plants started to increase their share in the market participation. The modularity of Distributed Energy Resources (DERs) makes the installation easy almost in every location. In addition, customers have begun to participate by producing their own needs based on renewable sources and engaging in demand response programs. Electromobility and storage are gaining prominence. Digitalization of the power sector makes possible the implementation of new market rules and new actors that can support the resolution of physical problems through competition. Smart grid capabilities in terms of distribution automation, communications, data management, and utility applications (intelligent decision processes), support the operation of the system, and open a broad way for trading the new capabilities.

Countries have developed various policies to support the energy transition and diversify energy sources. Feed-in tariffs, tax reductions, and other incentive schemes rely entirely on government support, which is common when emerging technologies are in their early stages. Today, with the implementation of smart grids, the European Union advocates for market-driven mechanisms as a means of expanding clean technologies. If a country lacks the financial capacity to provide funds or create grants for clean energy development, the market can address this need—provided the appropriate regulatory framework is in place. Therefore, achieving a full energy transition requires integrating smart grid technologies with the electricity market.

The markets are continuously evolving to encourage investment, to foster opportunities for diversified participation by all new actors, and to ensure the safety of the system. Furthermore, the new rules for the Electricity market must provide a platform for all new actors to trade electricity and implement the advantages that smart grid technologies bring. To advance the modernization of the electrical grid, it is essential to modify business procedures [Far10]. Any market-based approach must be able to:

- Foster competition and participation by implementing clear rules that allow a diverse amount of stakeholders to trade a variety of products in the system.
- Procure the right signals to ensure long-term power supply and support the conditions for future investments.
- Support the optimization of the resources. The Electricity market has been considered part of a financial instrument for optimizing the resources.
- Support real-time balancing operations, ensuring continuous matching of demand and supply while accounting for the physical constraints of the grid. The amounts traded must be physically produced by generators and delivered to consumers, considering the physical properties of the power systems.

For these reasons, to achieve the energy transition, it is necessary to review the current rules of the Electricity market to establish smart markets that encourage competition. This involves evaluating whether the economic level at which energy is traded can be adjusted for new business models. Furthermore, it is well known that the integration of DER units introduces additional uncertainty due to the weather dependence of these sources. This translates into operational issues within the energy system. Changes in real-time reserves require active control management, allowing the combination of the physical reality of power plants with possible economic transactions. To avoid the need for grid reinforcement, renewable curtailment, redispatch measures, and the use of flexibility services emerge as potential solutions.

The design of the German electricity market is based on the principle of an unbundled power market and power network. Therefore, on the one hand, the physical level matched the demand and supply at each point in time to ensure a reliable system. On the other hand, the economic level supports energy trading by different stakeholders in dedicated markets according to their individual needs. However, to maximize its potential, the physical and economic levels have to be closely integrated [Bee16]. This integration paves the way for the development of smart markets. Smart markets facilitate the link between the behavior of physical components and the possibility of participating in trading mechanisms, thanks to the digitalization of the power system.

The challenge lies in developing an electricity market design that effectively implements specific policies and regulations while accounting for the diversity and complexity of energy systems at regional and national levels. Several scholars have conducted comprehensive literature reviews on the characteristics of the global electricity market, its structural design [Bar+05; MT18; Cra17], modeling methodologies [GMM09; Teu+13], and potential foundational changes, such as clearing mechanisms [Erb16; Cra+22]. These studies provide a basis for understanding the evolution of electricity market structures and the factors influencing their efficiency and adaptability.

In addition, various analytical approaches exist to evaluate electricity market designs. Simulation models, including equilibrium models and game-theoretic methods [ARR22], as well as agent-based simulation models [Mar05], offer valuable insights into market dynamics. However, developing such models requires a deep understanding of the fundamental characteristics of the electricity market, along with the openness and acceptance of potential changes within the system. Consequently, no single simulation or market model is universally applicable across regions. Each country must parameterize and incorporate its specific characteristics to develop a market model aligned with its objectives. Moreover, there is no unified model that enables the evaluation of different market designs, limiting the ability to share knowledge across implementations or compare approaches. As a result, gathering comprehensive information on the regulations and rules of various electricity markets becomes a complex yet essential task. This data is crucial for understanding market intricacies and identifying potential gaps for regulatory adjustments based on international trends.

To evaluate the electricity market design and the development of new market rules, the main characteristics of the current market must be compiled. This information is essential for explaining the behavior and capabilities of the existing trading system and identifying opportunities for the creation of new markets or roles. The characterization of markets serves as the foundation for an electricity market framework and market models that accommodate differences in market design, particularly for simulation purposes. To gather all the characteristics for its design evaluation, to support the basis for the creation of electricity market frameworks, and to analyze the proper configuration of market models, morphological boxes can be used. Morphological boxes are a suitable method for analyzing the combination of different variables for the evaluation of complex models, as it was implemented for smart markets [Fra+17]. Their applicability is further discussed in [ALG22], which forms part of this thesis approach.

The integration of more renewable energy (RE) and the further digitalization of energy systems underscore the pressing need for new market rules to address the challenges. For example, discussions on integrated markets with centralized scheduling and exchange-based mechanisms represent conceptual objectives in this pursuit, for the wholesale market [Ela+18]. Additionally, a significant research stream focuses on the essential role of day-ahead and real-time energy markets in facilitating flexibility services, including the emergence of local flexibility markets, and the provision of ancillary services [Oli+18; Fai+19; AP21]. Regarding this research stream, based on the implementation of information technologies, other trading possibilities open up the provision of active and reactive power from distribution systems [Nie+12] or managing those trading platforms for flexibility [Eid+16; Pra+19a]. As a result, there is a growing discourse on the incorporation of new technologies, such as those exemplified in Germany and other pioneering regions, which underscores the necessity of tailored market designs aligned with the evolving sustainability of the power system.

The implementation of new market rules in the electricity sector presents a multifaceted challenge, contingent upon the unique characteristics of each market. Furthermore, while different sets of rules may aim to achieve similar objectives, discerning their optimal implementation and assessing their respective impacts pose considerable challenges. Ensuring that new market rules align with sustainability goals requires the establishment of KPIs that account for the capabilities of smart grid technologies implemented in those markets. These KPIs serve to link the performance of different market rules with their broader environmental, legal, economical, and social implications.

It is crucial to comprehend the connections between various elements of the new regulation and the system and the impact of external factors such as social behavior and environmental regulations to assess how a new market implementation can enhance the sustainability of the electricity sector, including its effects on energy trading. Impacts on economic aspects, such as price signals, are not sufficient to ensure the objectives in terms of a sustainable power system. Therefore, it becomes crucial to establish the intersection of market and smart grid performance considering the main sustainability dimensions such as economic, social, environmental and legal. In addition, the assessment needs to comply with benchmark use cases and real-life experiences from experts.

1.2 State of the Art

Energy systems require a holistic approach since smart grid technologies involve multiple expertise domains. Testing the behavior of new market rules requires specific models that can address the implications for a variety of stakeholders. [Ste+19] points out the importance of expert collaboration for multi-domain testing and for analyzing market behavior in Cyberphysical Energy Systems (CPES), which integrates the physical system and Information and communications technology (ICT) systems. However, it only indicates the need for market-based tests using multi-agent systems or co-simulation tools to evaluate the impacts on specific grids. Similarly, [Els+20] presents the need for planning the structure of smart grid simulations by implementing a holistic description of the system to be analyzed. In their study, a market questionnaire was developed to extract information on the regulation of the electricity markets that comprise the framework under test. However, the main focus is not to test or evaluate a new market rule, and it does not implement a standardized evaluation method for testing.

When discussing the implementation of smart grid technologies, it is important to mention the EU M/490 Mandate [Eur11], which established the foundation for the Smart Grid Architecture Model (SGAM). SGAM is an architectural model that provides a higher level of abstraction to support domain-specific interdisciplinary concepts related to smart grid technologies in the power system. This framework laid the foundation for an accepted structure in this multidisciplinary domain (i.e., electrical, ICT, and control) and illustrates the interoperability within this framework [Neu+16].

Regarding the methodology for defining use cases in smart grid implementation, the IEC 62559 standards series [Int15] establishes the use case methodology for smart grid requirements as part of the engineering process. In the market-related domain and business cases within smart grid implementation, the IEC 62913-2-2:2019 standard [Int19] is employed. Furthermore, the IEC 62913 standard series does not exclusively address SGAM and the European approach; it also incorporates considerations from the United States National Institute of Standards and Technology (NIST). These two primary models for creating use case templates were considered in the development of methods for testing smart grid implementations [Usl+19].

In practical applications, the testing and evaluation of highly integrated systems based on smart grid technologies are significantly influenced by market dynamics, as the behavior of controllers and component algorithms depends on market participants and the objectives they pursue. Therefore, an appropriate description and evaluation method must be developed to manage this complexity. To bridge the gap between system definition, use case specifications, and evaluation, aHolistic test description (HTD) is proposed by [Heu+19] and implemented in [Heu+20] as a complementary tool for SGAM.

A Holistic Test Description is: "*The process and methodology for evaluation of a concrete function, system, or component within its relevant operational context regarding a given test objective*" [Mee+17]. Holistic Test Description (HTD) is a method that facilitates the conceptualization and replication of experimental tests, widely used in the European Research Infrastructure supporting Smart Grid and Smart Energy Systems (ERIGRID) Project [ERI19]. Structuring a test experiment using the HTD methodology requires defining the system under test, the test function, and the test objective.

This thesis uses and extends the HTD concept to evaluate electricity markets within the smart grid domain. First, a clear definition of the market structure is essential when introducing new or modified market rules as the system under test. For this reason, a harmonized consideration of the market design is required. Second, the function under test refers to the specific rule or modification within that system. Special considerations need to be incorporated for feasible changes. Lastly, the objective under test pertains to the desired outcomes of the rule change. Since market rule changes involve significant qualitative aspects influenced by participant behavior, the evaluation must go beyond purely quantitative metrics. Thus, this thesis proposes a qualitative method incorporating four sustainability dimensions to enable a comprehensive assessment of these objectives.

In the electricity markets domain, a unified definition of the various market characteristics is crucial to ensure consistency and comparability across different studies and experiments, and for the accurate use of models to test new market designs. HTD structuring methodology ensures consistency for the testing process. However, the method relies purely on the researcher's definitions of their own use cases, lacking internal standardization in market domain topics and complicating knowledge extraction. This highlights the need to standardize the classification of power market characteristics, possible combinations, and changes within the smart grid domain.

One method for classifying the characteristics and attributes of multidimensional problems is the use of morphological boxes [Rit02a]. Morphological boxes have been used for the classification of use cases, allowing the typification of smart grid co-simulation tools [Sch+15]. A morphological box, also known as a morphological matrix or Zwicky box, is a multi-dimensional problem-solving and ideation tool used in creative and systematic thinking processes. It consists of a structured grid that lists all possible combinations of parameters or attributes of a complex problem or system along different axes. The morphological box enables the systematic exploration of the total set of possible relationships or configurations in a given complex problem space, facilitating the discovery of novel solutions or concepts. This study highlights the need for highly integrated and interdisciplinary energy system models to support understanding between users (energy stakeholders) and developers (model developers and researchers).

The morphological boxes are the main part of performing a General Morphological Analysis (GMA). They have been used as an assessment tool that supports the decision-making process and also to find solutions to complex problems in different files as in [HSM20], for geodesics solutions. In the energy domain, [Sal+17] implemented a morphological box for energy services to evaluate interdependencies between the Energy Service Company (ESCO) and consumers. Furthermore, [Fra+17] also implemented a morphological box to conceptualize the different characteristics of smart market designs, focusing on four aspects: the coordination principles, the product, the pricing, and the actors. However, so far, this implementation has not been used to evaluate the characteristics of the electricity markets. The first approach to analyze electricity market was presented in [ALG22] which is a partial result of this thesis. Therefore, morphological boxes have been used in power systems to analyze aspects and characteristics of particular topics.

Several market models are already available, each with distinct characteristics. Most of these models are tailored to a specific electricity market framework, based on the conceptualization of the electricity market design and its intended purpose. Consequently, these models are designed for specific cases and may not be suitable for all simulation studies or for evaluating differences between implementations [RKF16].

Additionally, the characteristics of electricity markets vary across regions and countries. Many authors have attempted to compile and analyze differences in market designs. For example, [Bar+05] presented a classification of market characteristics based on questionnaires answered by 23 countries. That global study provides an overview of various electricity markets operating internationally. A comparison between some of the largest markets in the United States and Europe is presented in [IK14]. However, these studies are limited to understanding the behavior of individual electricity markets and do not propose improvements to their design based on new rules. Other researchers analyze specific differences in applied pricing mechanisms [Cra17] or integrate theoretical insights with laboratory experiments to evaluate specific functionalities [Che+21].

Furthermore, several authors have proposed ontologies specifically designed for particular electricity markets, such as EPEX [San+17a] or the Hellenic Transmission System Operator [AKZ09]. These approaches focus on the theory of market mechanisms and their characteristics in each market. However, there is no comprehensive compilation of electricity market characteristics and properties to evaluate differences in market designs or to support the development of general frameworks and models for identifying gaps in their conceptualization.

The analysis of gaps and the proposal of new rules arise from the capabilities that smart grid technologies introduce in the power system. There are several definitions of what a smart grid is. This thesis uses the definition from [Eur11], which states: *"A smart grid is an electricity network that can cost-efficiently integrate the behavior and actions of all users connected to it—generators, consumers, and those that do both—to ensure an economically efficient, sustainable power system with low losses and high levels of quality, security of supply, and safety."* Therefore, smart grids have been implemented to automate and enhance control of the distribution grid, improve power quality, and support better market integration [BS14].

This concept opens the possibility of introducing new rules to the current market or creating a smart market. According to [PH11], *Smart Grids* refer to the internal grid (infrastructure, devices, and communications), while smart markets form the superstructure that encompasses the grid. Therefore, smart grids enable the creation of smart markets.

For the purpose of this thesis, *Smart Markets* are defined as: *markets that are designed based on smart grid infrastructure and information and communications technology (ICT), geared toward the behavior of market players and resources.* In practice, smart markets are integrated into the current electricity market **to a greater or lesser extent**. For example, if regulations allow aggregators to submit offers to the wholesale market based on renewable energy, demand response programs, vehicle-to-grid (V2G) services, etc.

The concept of KPIs for the evaluation of smart grids was briefly presented in [Har17], which develops a catalog listing indicators to measure the degree of smart grid device deployment throughout the grid infrastructure. In that work, the main smart grid functionalities are presented as observability and controllability in transmission grids. Other KPI implementations for evaluating the performance of smart grids based on grid infrastructure can be found in [TB20], which assesses the performance of several scenarios, and in [Bra+22], which focuses on the DSO infrastructure.

Moreover, the utilization of metrics and KPIs in the energy sector has been implemented in several domains, for example:

- **Software Evaluation:** for assessing the efficacy of different market models, as presented in [Ame04]. In this case, the comparison between algorithmic solutions applied to the clearing process is evaluated.

- **Grid Infrastructure Evaluation:** for conducting cost-benefit analysis of projects. For example, evaluating the implementation of a specific pilot project like “Smart City Malaga” [Per+14] or comparing demo projects, as in [BB11], which analyzes 140 smart grid projects.

- **Communication Technology Evaluation:** for assessing a particular implementation or ICT functionality, as in [Rad+18], which analyzes the implementation of *Smart Grid Data Management* in the Serbian market, or in [Ken+21], which focuses on Chinese electricity markets (EMs).

Furthermore, instances of KPI implementation in regional projects are evident, as illustrated in the work of Sysflex (2020), derived from the European Union (EU) H2020 initiative [Con18]. This initiative meticulously selects KPIs to highlight the efficacy of pilot projects across various EU member states. Additionally, notable examples showcasing the integration of KPIs with smart grid technologies in distribution systems can be found in [CED+21], which compiles a comprehensive list of customized smart grid KPIs for evaluating distribution grids.

Moreover, recent studies in the field propose distinct sets of KPIs targeting specific functionalities within the smart grid domain. Some authors emphasize the need for a methodology to analyze KPIs in the energy system. For instance, [Far+21; KGG21] propose a methodology focused exclusively on techno-economic factors. Similarly, [Bhu+22] delineates crucial characteristics for evaluation through his proposed set of KPIs. Furthermore, [Vit+21] propose a methodological framework for assessing the degree of integration between transmission and distribution systems, leveraging smart ICT.

Finally, as a partial contribution to this thesis, [Aco+23a] explores the applicability of KPIs designed to measure the demand for flexibility within the retail sector. This final approach supports the usability of KPIs in evaluating different smart market configurations.

The sustainability of the power system encompasses the ability to produce and provide affordable clean energy to all consumers. This concept is often represented by the intersection of three critical dimensions: economic, social, and environmental. However, the role of the electricity market in fostering power system sustainability is frequently overlooked or assessed primarily through an economic lens. Additionally, since electricity markets operate within the framework of specific regulations, legal considerations and energy policies play a crucial role in either facilitating or impeding the progress toward a more sustainable power market.

Key performance indicators (KPIs) can play a crucial role in evaluating the sustainability of specific market designs. A change in market design or regulations affects multiple aspects of the power system, influencing overall progress toward the sector's sustainability. Traditionally, power system sustainability has been evaluated using indicators that focus on specific dimensions. For instance, [Pra+19b; SZ19] emphasize the need for indicators that address complementary aspects of the energy system. A framework limited to the retail market is discussed in [Di +22], while [Far+21] proposes a methodology that considers only economic and environmental aspects.

However, these KPIs are not designed to evaluate electricity market rules that incorporate smart grid capabilities or to assess smart markets or new market implementations with sustainability in mind. Furthermore, no KPIs have been suggested in the literature to evaluate various market designs considering the power grid's economic, social, environmental, and legal aspects [Aco+23a]. This is relevant because the interconnections and impacts among the social, economic, legal, and environmental dimensions of the power sector are not clearly delineated. These dimensions are interrelated, with varying degrees of influence on one another. Understanding these relationships requires expert knowledge and is crucial for designing new markets or implementing changes within existing ones. This thesis proposes a method for evaluating and uncovering the relationships among these four sustainability dimensions, thereby supporting the sustainability of the complex and interrelated power sector.

In alignment with broader global sustainability initiatives, the United Nations ratified the 2030 Agenda for Sustainable Development, which includes 17 Sustainable Development Goals (SDGs). To measure progress, 231 global indicators were implemented. Regarding *SGD 7*, which is *"Affordable and Clean Energy"*, three national targets and two targets for international organizations or specific groups of countries were established. To evaluate these targets, a total of six indicators were proposed: four on the national country perspective and two for international cooperation [Ass15].

Similarly, the European Commission set 100 indicators to measure the progress of European Union countries [Eur17]. It also established similar indicators for each SDG [Com22]. For *SDG 7*, a total of six indicators were implemented. Table 1.1 presents a list and comparison of both sets of indicators. These indicators aim to support the overall energy objective.

Tab. 1.1.: Comparison of United Nations and European Union Sustainability Indicators (SDG 7)

Level	United Nations	ID	European Union (Eurostat)
National Level	7.1.1 Proportion of population with access to electricity	07_10	Primary and final energy consumption
	7.1.2 Proportion of population with primary reliance on clean fuels and technology	07_20	Final energy consumption in households per capita
	7.2.1 Renewable energy share in the total final energy consumption	07_30	Energy productivity
	7.3.1 Energy intensity measured in terms of primary energy and GDP	07_40	Share of renewable energy in gross final energy consumption
		07_50	Energy import dependency
		07_60	Population unable to keep their homes adequately warm
Global Level	7.A.1 International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems		
	7.B.1 Installed renewable energy-generating capacity in developing countries (in watts per capita)		

However, more detailed indicators are needed to assess the electricity sector, particularly in the economic, social, and environmental dimensions that align with the SDGs. Some research has focused on particular aspects of these dimensions. For example, the social impact of green energy [BGG22], energy import dependency, and the security of supply, proposing relevant indicators for its evaluation [MDA18]. Other studies have explored the interdisciplinary nexus between the sharing economy and sustainability [Wan+21]. Yet, a holistic evaluation of the electricity sector's sustainability remains absent.

Few studies have assessed the sustainability of electricity markets or their specific aspects [FRL19]. One of the main challenges is the variation in sustainability considerations across different countries and the necessity of establishing a regulatory framework grounded in sustainability principles. Furthermore, [FRL19] conclude that appropriate indicators and weights are needed to create a composite sustainability indicator. These weights depend on each market's specific characteristics and regulatory framework. This reinforces the influence of market design and regional perspectives on sustainability evaluation.

Additionally, any changes to electricity market rules must be evaluated against their objectives, particularly in the context of achieving the energy transition. It is essential to assess whether these changes also advance sustainability in EMs.

[SSL19] introduced a Sustainability Evaluation Process based on an information model for assessing co-simulation scenarios in the energy sector. This information model, developed using mind maps to identify dependencies and data flows, was not designed to consider electricity market designs or changes. Consequently, it cannot be used to identify gaps in market rules or assess them. Recognizing this limitation, and as a partial contribution of this thesis, an extension of this research was conducted in [Els+20] to incorporate the characteristics of electricity market models and support their selection for specific research experiments.

Table 1.2 presents the most important contributions and research based on the topics discussed in this section, which are considered the foundation of this thesis.

1.3 Problem Statement

The evolution of EMs has undergone a discernible transformation from centralized frameworks to decentralized configurations, featuring more market participants and a notable transition from bulk to distributed energy generation, often integrating weather-dependent sources. Despite this evolution, the regulatory landscape governing these markets has remained relatively static. While some nations have incrementally broadened market engagement through the introduction of feed-in tariffs or technology-centric Power Purchase Agreements (PPAs), the dynamic spot market continues to adhere to uniform regulations, thereby limiting the design of trading mechanisms for emerging technological capabilities.

To implement new market rules or trading schemes, a general assessment must be conducted, particularly considering:

Tab. 1.2.: Overview of existing state of the art of different topics related to the artifacts, - not considered, (✓) partly considered, ✓ considered

Authors	Ontologies and/or morphological boxes	Market categorization	Assessment of new market rules	KPIS assessment	Mapping tool	Validation and evaluation
Barroso and Cornejo, 2005 [Bar+05]	-	✓	-	-	-	-
Bossart and Bean, 2011 [BB11]	-	-	(✓)	(✓)	-	(✓)
Personal et al., 2014 [Per+14]	-	-	✓	✓	-	(✓)
Schloegl et al., 2015 [Sch+15]	✓	-	-	-	-	-
Santos et al., 2017 [San+17a]	✓	(✓)	(✓)	-	-	-
Harder, 2017 [Har17]	-	-	-	✓	-	-
Cramton, 2017 [Cra17]	-	✓	✓	(✓)	-	-
Schwarz et al., 2019 [SSL19]	✓	-	-	-	✓	-
Elshinawy et al., 2020 [Els+20]	✓	✓	-	-	✓	-
Schwarz et al., 2021 [Sch+20]	✓	✓	-	-	✓	-
CEDEC et al., 2021 [CED+21]	-	-	-	✓	-	-

1. The existing implementation or potential feasibility of smart grid technology to facilitate such trading mechanisms. It is essential to assess whether smart grid technologies are already in place or can be effectively implemented to support the envisioned transactions.

2. The repercussions of these changes and their contribution to the sustainability of the power system. This involves special attention to the environmental, economic, and social dimensions to ensure a holistic understanding of the proposed market rule.

Furthermore, the absence of a standardized method for assessing the sustainability of different electricity market designs presents a challenge. International organizations such as SEE4All, the World Bank, and the EU propose ways to measure specific sustainability goals. However, their focus does not extend to the impact of market design on achieving these goals.

Effectively measuring the impact of different market designs necessitates the identification of key performance indicators (KPIs). These KPIs may vary depending on specific market implementations and smart grid capabilities. Researchers have proposed several KPIs based on their particular research needs, making it difficult to compare approaches.

This leads to two main problems. First, there are no standardized KPIs to evaluate market rules based on sustainability aspects considering smart grid implementations. Second, policymakers lack insights into the impact of implementing a new market rule and how it could support the sustainability of the power system.

1.4 Research Questions

The main research question is formulated as follows:

Main Research Question

How can the performance of a Smart Grid System be analyzed and evaluated based on the impacts of different market mechanisms?

From this research question, three sub-questions are derived as follows:

Research Question 1

RQ1: How can electricity markets be categorized for testing new market rules?

To answer RQ1, it is necessary to define:

- What are the characteristics of the electricity market?
- Which new market rules could be implemented?
- What are the objectives to achieve with the new implementation?

These three sub-questions support the definition of the first artifact, which is an electricity market categorization. With this artifact, the system under evaluation (the market framework); the function under investigation (the new intended market rule) and the overall test objective can be defined.

Research Question 2

RQ2: How can relevant KPIs be identified for electricity market rules?

To address RQ2, it is necessary to determine:

- Which KPIs are related to smart grid capabilities, and which are driven by market considerations?
- What is the relationship between the market rules and KPIs?

The answer to this question is given by the Artifact 2. This second artifact proposes a KPI-based assessment methodology for the Electricity market. This methodology begins with a bibliometric analysis, identifying from the open source literature the most relevant smart grid capabilities and their influence on market changes. Similarly, lists of indicators that serve to understand the performance of smart grid were considered. To further explore relationships between market rules and KPIs, pre-defined semantics and co-word analysis are applied. This method facilitates the identification of interconnections between market rules and KPIs, allowing the clustering of KPIs according to specific smart grid capabilities.

To evaluate sustainability in the power system after implementing a market change, the information contained in each indicator was used to create different degrees of relationship among social, economical, environmental, and legal/policy aspects. These relationships allow the creation of a sustainability plane, in which the most relevant indicators per aspect are considered in the new market implementation.

Finally, the evaluation process has to be defined:

Research Question 3

RQ3: How can different market rules be evaluated and compared?

To answer RQ3, it is necessary to define:

- What is the relationship between the market rules and the sustainability of the system?

To address this question, it is first essential to identify the relevant sustainability dimensions to evaluate a more sustainable power system. A sustainability plane is proposed as a framework to map the previously identified KPIs and clusters of smart grid capabilities, offering a visual representation of the interconnections among various system aspects. Artifact 3, the evaluation method, is developed based on knowledge gathered through interviews with international domain experts.

Semi-structured interviews were conducted to assess the relationships between indicators and market mechanisms. This approach enables the extraction of expert knowledge on the most critical market considerations and how they can be effectively evaluated. Furthermore, it reinforces the interconnections among diverse market aspects and their impact on the power system's sustainability, while supporting the practical implementation of this methodology.

By addressing RQ3 through this comprehensive KPI-based evaluation, the process enables an understanding of performance differences when implementing various market mechanisms. This understanding aids in identifying which market rules are better aligned with sustainability objectives and supports the proposal of KPIs.

Figure 1.1 shows the construction of each research question and its artifacts that support this thesis.

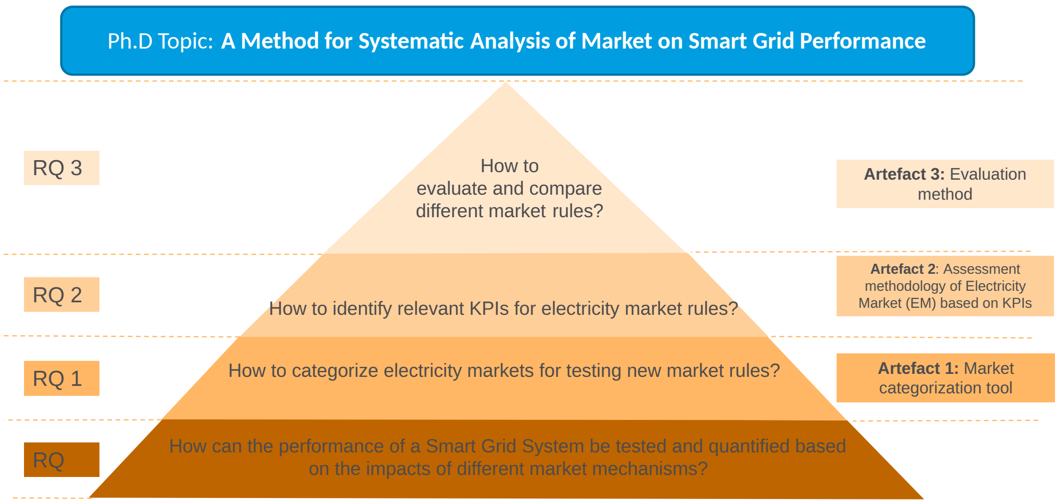


Fig. 1.1.: Research Questions and Artifacts to be Developed

Reference to own preliminary work

Partial results of the research questions have been presented to the scientific community and have already been published, aiming to address specific aspects. For example, in [ALG22], the categorization of EMs was evaluated using morphological boxes as theoretical case studies. The foundation of this categorization supported the market class abstraction presented in [Mau+23].

The process for extracting KPIs and analyzing them using bibliometric tools and co-wording methods was specifically presented for flexibility markets in [Aco+23b]. An additional example of extracting smart KPIs and their application for comparing different optimization methods for the integration of intelligent neighborhood grids was proposed in [Aco+23a].

Other related work includes [Els+20], which supports the holistic selection of market models for simulation purposes, and [Sch+20], which examines the usability of ontologies for sustainability evaluation.

1.4.1 Scope of the Thesis

This thesis develops a systematic methodology for analyzing of electricity markets (EM) in relation to smart grid performance. The primary goal is to establish a framework for defining combinations of electricity market designs, enabling the representation of diverse market structures and identifying potential gaps for smart market creation. These changes in market design or market rules are expected to arise from smart grid implementations targeting specific objectives defined by the researcher (e.g., increasing customers participation, reducing carbon emissions, enhancing market flexibility).

The scope of this research includes the analysis of these market changes using KPIs closely tied to various sustainability dimensions. Specifically, the thesis evaluates the impact of smart grid-driven modifications on electricity market designs in terms of environmental, economic, social, and legal sustainability dimensions. The methodology developed allows for a structured evaluation of these changes by linking smart grid key performance indicators with sustainability aspects.

Moreover, for the evaluation of these market changes the thesis identifies relationships between smart grid concepts, electricity markets and sustainability aspects. Therefore, as a second objective, a visual plane ilustrate the most relevant relationships among concepts based on international experts' experience is constructed. This visual plane supports the selection of the most relevant KPIs that can be used to assess changes in the electricity market based on the objective to achieve.

One limitation of this methodology lies in its non-exhaustive nature. Indeed, it remains conceivable to continually devise new indicators, given that the dynamic nature of the energy landscape may necessitate the continual evolution of additional metrics and market trends. Nevertheless, the primary objective is to provide a comprehensive repository of electricity market indicators for smart grid implementations linked to sustainability aspects for a holistic assessment of the power system.

A second limitation relates to the areas of expertise of the international experts who were selected.These experts primarily worked in Europe and the Americas, excluding other regions. However, based on the extensive international experience of the interviewees, their comments suggest that the methodology proposed in this thesis is valid for evaluating new market rules, as it considers the intended objective from the outset—a key factor in assessing the final outcomes. Taking the final objective into account is essential for evaluating each modification in the power system.

1.4.2 Methodologies Summary

This thesis implements several well-known methodologies to provide an integrated process for the assessment of EMs gaps. First, a General Morphological Analysis (GMA) identifies the characteristics of electricity markets and analyzes the total set of possible combinations to evaluate both existing and new market frameworks. In addition, GMA, in combination with Cross-Consistency Assessment (CCA), can be applied to reduce the evaluation space and identify gaps for the creation of new market rules. The research results were presented as part of preliminary work in [ALG22].

A *Bibliometric Analysis* is then used to collect and define KPIs and new electricity market considerations based on smart grid aspects, utilizing open-source search engines. The usability of this approach was presented as a preliminary result in [Aco+23b], where results for flexibility services are discussed. Additionally, the use of specific KPIs based on smart grid technologies was also presented in [Aco+23a].

Science mapping is a method used to **support** the visualization of information and identify interactions, connections, and relationships among elements and concepts. Science mapping tools are implemented to discover knowledge by linking the KPIs found through bibliometric analysis with their impact on electricity markets. The use of Natural Language Processing (NLP) and semantics is applied to review the definitions of the KPIs, organize them into smart grid capability clusters, and support their correlation with electricity market KPIs.

Moreover, semantics, NLP, and qualitative assessment are applied to identify direct and indirect relationships, correlating these KPIs with sustainability dimensions. The combination of these techniques supports the proposal of smart electricity market KPIs that can be used to assess changes in market designs or market rules while considering sustainability dimensions such as economic, social, environmental, and legal aspects.

Finally, semi-structured interviews with international experts are conducted to evaluate the process and the relationships identified among smart grid capabilities and their impacts on the electricity market. The most significant KPIs are proposed, along with their relationships to key concepts when assessing a more sustainable electricity market. A detailed explanation of each method is presented in Chapter 2.

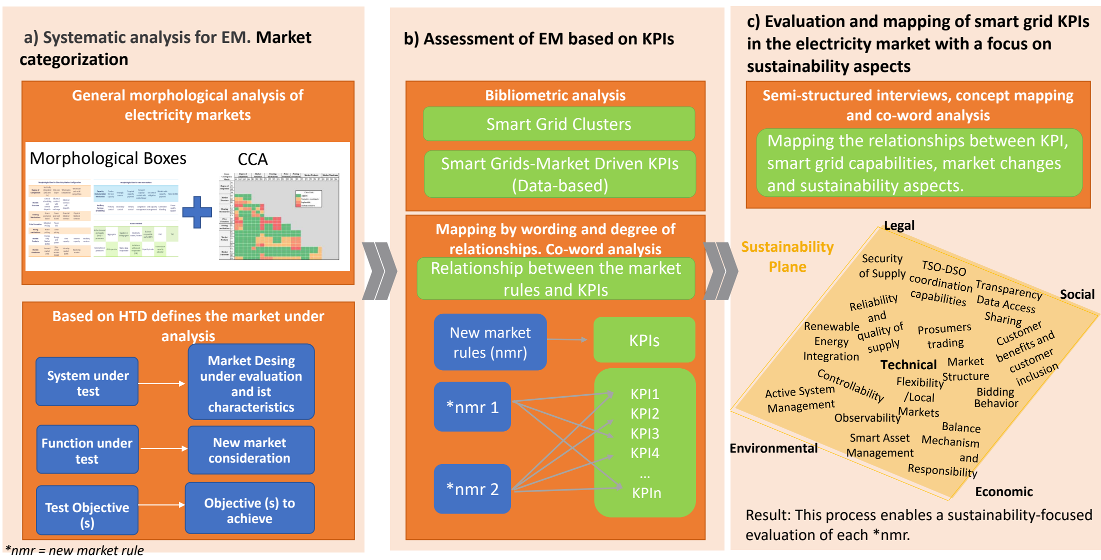


Fig. 1.2.: Research Process and Applied Methods: a) Systematic Analysis of Electricity Markets; b) KPI-Based Assessment Methodology for Electricity Markets; c) Evaluation and Mapping of Smart Grid KPIs in the Electricity Market with a Focus on Sustainability Aspects

Figure 1.2 shows a scheme of all the methods used for the different parts of this research. The left section of the figure (a) depicts the systematic analysis of electricity markets (EM), represented by the market categorization. In this section, the holistic test description is implemented to understand the system under analysis (electricity market design), the new market rule to implement, and the objectives to achieve. The middle section (part b of the figure) represents the assessment methodology and the extraction of KPIs based on bibliometric analysis. The relationship between market rules and KPIs is explored through the use of NLP and semantics. In the right section, marked as (c), the indicators based on a co-word analysis are mapped onto the sustainability plane. The evaluation through expert interviews supports the identification of the most important KPIs in line with new market rule trends. The concepts extracted from the interviews help define relationships among the KPIs that can be used for a sustainability-focused evaluation of a new market rule introduced into the market design.

1.5 Thesis Structure

After this introduction in Chapter 1, the remainder of this thesis is structured as follows:

Chapter 2 provides a comprehensive overview of the methodologies employed throughout the thesis. It explores the intricate details of integrating diverse methodologies to achieve the overarching objective. Section 2.1.1 presents an overview of the implementation of General Morphological Analysis (GMA) and morphological boxes in the literature, highlighting their planned application for the systematic analysis of EMs. Additionally, the chapter elucidates the use of science mapping and bibliometric analysis for extracting key performance indicators (KPIs) and creating clusters of knowledge related to new electricity market rules. Finally, an overview of the evaluation process is provided through semi-structured interviews.

Chapter 3 explores the categorization of EMs using morphological boxes. The application of morphological boxes supports the combination of matrices from different real-case scenarios, offering insights into the similarities and major differences between electricity market rules within those cases. Details are presented on the implementation of the systematic analysis of the EMs, emphasizing their main characteristics. The chapter also evaluates the categories and aspects considered for the morphological boxes, using a case from the literature to assess their functionality.

Chapter 4 implements bibliometric analysis and co-word analysis to extract papers from the past five years on new trends in the electricity market and the methods used to evaluate those trends. Additionally, science mapping methodologies are presented to evaluate the main topics found in the literature. The implementation of bibliometric analysis aids in identifying key performance indicators (KPIs), while science mapping establishes the relationships between KPIs categorized as smart-grid-driven and market-driven. Furthermore, Section 4.3 outlines the degree of relationship between market rules and KPIs using direct and indirect relationships based on the semantics of the indicators. The sustainability plane is introduced and explained in Section 4.2, linking KPIs to various sustainability aspects.

Chapter 5 presents the evaluation methodology employed, focusing on semi-structured interviews with experts. Insights are collected from academia, industry stakeholders, energy policy-makers, and international consultants. The interviewees expressed their opinions on the introduction of changes in the electricity market, as well as the actual methods for evaluating those changes and the main indicators used. The idea was not to evaluate each indicator with an expert; rather, it sought to assess the applicability to the method presented in this thesis and evaluate if it can be applied to their needs. In addition, it seeks to know whether sustainability aspects are considered in the design of new electricity markets rules.

Chapter 6 discusses the approach based on the results obtained from the interview process and the bibliometric analysis. It uses two research projects, developed in collaboration with the OFFIS Institute for Information Technology, as application examples. The first, named VLF, focuses on the selection of components and infrastructure to evaluate scenarios [Els+20], and the second, the Int2Grids project, coordinates the possible optimization of flexibility in usage from neighborhood communities [Aco+23a].

Chapter 7 summarizes the main conclusions drawn from this thesis. It also outlines potential future steps and areas for further research.

Figure 1.3 elucidates the fundamental methodologies and contributions of the thesis, highlighting the research questions addressed and the corresponding answers provided by each artifact, along with the respective chapters of the thesis in which they are discussed.

Thesis Chapter	Research Question	Main Content	
		Fundamentals	Contribution
Chapter 3: Electricity Market Categorization with GMA	RQ 1	• Introduction to HTD and • GMA analysis.	• Electricity market holistic description. • General morphological analysis and morphological boxes for electricity market categorization.
Chapter 4: Bibliometric Analysis and Science Mapping	RQ 2	• Bibliometric analysis and co-wording analysis. • Science mapping. • Semantics.	• Data base of KPI for smart electricity markets. • Degree of relationship between KPIs and market rules.
Chapter 5: Experts Interview Process and Data Mining	RQ 3	• Application of semi structured interviews. • Introduction to NLP and semantic analysis with science mapping.	• Evaluation based on interview concepts mappings. • Results of the final mapping for the relationships between indicators and sustainability aspects of new electricity market rules.
Chapters 6 and 7 Discussion and Concluding Remarks	Main RQ, RQ1, RQ2 and RQ 3		• Discussion of the results • Summary and conclusions • Approaches for future steps and follow-up research topics.

Fig. 1.3.: Structure of the Chapters Addressing the Research Questions Based on the Main Thesis Contributions

2 Methodology

This chapter presents an explanation of the research methodologies used to answer the research questions presented in section 1.4. This dissertation uses a combination of three different methods applied to the development of the thesis artifacts.

First, to analyze different electricity market designs, General Morphological Analysis (GMA) is used. The main characteristics and attributes of the electricity markets are collected and organized in morphological boxes (MBs), focusing on Europe, the United States of America, Panama, and several Latin American market designs. A Cross-Consistency Assessment (CCA) is performed to reduce mutually exclusive market design combinations and highlight whether some new designs could lead to normative constraints based on a predefined market. Consequently, the GMA methodology and the CCA support the definition of the market to be evaluated and the possible changes that can be applied to it when introducing smart grid technologies.

Second, a bibliometric analysis is conducted to observe the potential new market rules proposed to increase the dynamics of electricity markets. Since each researcher proposed their own evaluation method, the need for consistent performance indicators was identified. As a result, a set of Key Performance Indicators (KPIs) was developed, focusing on the context of smart grid implementation in electricity markets for several use cases. To select the KPIs, the bibliometric methodology was employed.

Third, the use of science mapping, in particular concept mapping, is implemented to observe the relationships between the indicators and sustainability aspects of different new rules. Semantic analysis is used to cluster indicators based on their smart grid functionality and their possible impact on the social, economic, environmental, and legal aspects.

Finally, the third section presents the evaluation process based on expert interviews focused on market aspects for assessing the sustainability of the power system. The knowledge extracted from the expert interviews reinforces the relationship between sustainability concepts and electricity market rules. These relationships support the evaluation of the indicators derived from the bibliometric analysis, facilitate the selection of the most relevant indicators, and lead to the creation of new indicators for specific cases, thereby supporting the overall process considered in this thesis.

This approach offers a systematic and multidimensional analysis of electricity markets and allows for bridging the gap between the market design framework and its practical evaluation method. The method also provides an overview of how to evaluate the sustainability of the resulting electricity market after implementing a new rule, based on its original design case and the intended goal. Figure 2.1 depicts the interrelationships between the different methods that are part of the complete methodology proposed and used in this thesis.

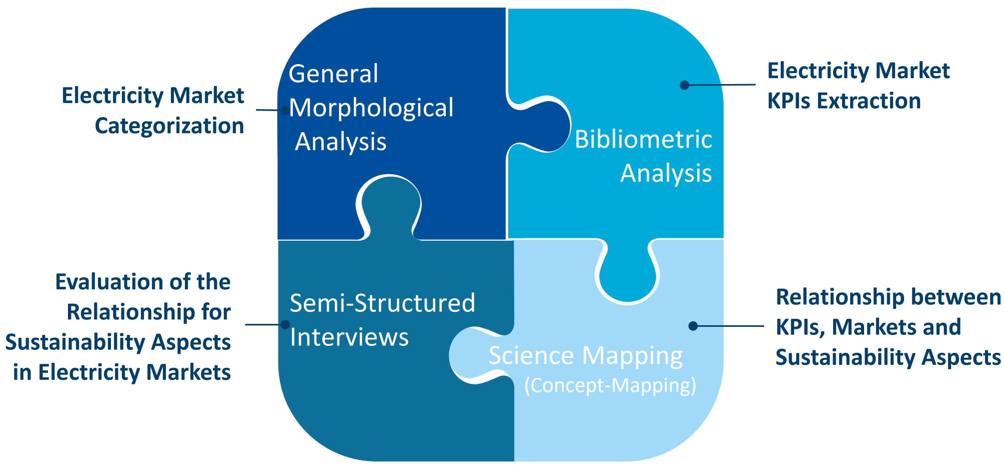


Fig. 2.1.: Methodology Summary

2.1 General Morphologic Analysis

In this section, the importance of categorizing electricity markets is outlined, along with the general principles of GMA and its usability for addressing the first research question (RQ1). This thesis implements a novel two-layer GMA approach to categorize electricity markets and support the definition of the market design, potential new market changes, and objectives to be achieved through these changes. In [ALG22], the author of this thesis demonstrates the applicability of the GMA method for electricity market categorization.

2.1.1 Why categorize electricity markets?

Categorization is necessary because, as "*The perceived world comes as structured information rather than as arbitrary or unpredictable attributes*" [RL78], researchers can use categories to map the perceived structure of the world as closely as possible. This can be achieved by appropriately relating the categories and attributes.

The characteristics of electricity markets vary across regions, countries, and geopolitical contexts. Some markets are more dynamic than others and implement different characteristics in their structure. For example, the degree of competition allowed in different markets varies: while in European markets both wholesale and retail competition take place, in other regions, like Panama, there is only a wholesale market, and in some countries, markets are vertically integrated with almost no competition. In this thesis, the GMA is implemented as a method to collect the most relevant characteristics that allow the definition of a market design.

A morphological matrix, called a morphological box (MB), contains the main attributes and characteristics that support the definition of a complex problem. In this research, MBs were created to represent possible electricity market designs that are subject to evaluation. This opens the possibility to evaluate markets implemented in multiple countries or regions.

Therefore, the creation of MBs followed by a GMA can be applied to categorize electricity markets, organize different market characteristics, and define configuration frameworks to test design gaps for new market rules [ALG22]. Additionally, in the implementation of a GMA, the dependencies of a problem can be identified. GMA evaluates all possible configurations and eliminates mutually exclusive configurations through a CCA [ALG22].

Creating morphological boxes to define market characteristics supports a comprehensive definition of the system. In this thesis, two Morphological Box (MB)s are used. The first one is for electricity market categorization, used to define the market framework under evaluation. The second one is for the selection of new market rules or changes within that framework. Moreover, a list of actors and roles is used to identify gaps within the predefined framework.

These artifacts form the basis for the further creation of market models. [Mau+23] implemented these artifacts in the development of market class abstractions. The information for filling out the MB is presented in Section 3.1.

2.1.2 Overview of the General Morphological Analysis

GMA is considered a scientific modeling method [Rit18] that has been used to identify and investigate the total set of possible relationships in a complex problem using morphological boxes [ÁR15]. The method is recommended for very large and complex problems since it supports structuring and defining relationships between different characteristics [Rit02b]. The complete GMA method was presented by Fritz Zwicky, indicating that "*The method has been conceived and developed to deal with all situations in life more reasonably*" [Zwi67]. Additionally, it is suitable as an assessment tool that supports the decision-making process to analyze policies, develop scenarios, and find innovative solutions in different fields.

For the implementation of a GMA, morphological boxes are used to combine matrices of the characteristics. The morphological box has been used with great success in several fields, as it was presented in astrophysics [Zwi67], construction [HSM20], mechanical design [DJ05], engineering design for policy analysis [ÁR15], and in the policy energy sector [Fra+17]. In this thesis, the GMA is implemented for the categorization of electricity markets.

In each morphological box the main categories for the definition of the problem must be defined. Each category can have different amounts of characteristics. The method allows the inclusion of as many categories as needed. A careful selection of the number of categories and characteristics is necessary to determine the size of the problem. The size of the problem is measured by the amount of possible combinations represented as the *total amount of simple configurations* T_{SC} considering that n is the number of categories in a morphological field, and v_i the number of characteristics for each category i. It must be considered that the T_{SC} increases geometrically based on the amount of categories and characteristics. This is calculated by multiplying all possible options in each category:

$$T_{SC} = \prod_{i=1}^{n} v_i \tag{2.1}$$

Nevertheless, not all the combinations are feasible. For this reason, a Cross Consistency Assessment (CCA) can be implemented to eliminate mutually exclusive configurations [RR11]. The CCA supports the reduction of the size of the problem to a more manageable solution by examining each resulting pair coming from the MB. This step is necessary to avoid unfeasible solutions, based on contradictory concepts. To perform a CCA, first the amount of *Parameter Blocks* PB_ij is defined by the category pairs in the matrix field, where: N is the number of categories, v_i and v_j are the number of characteristics per category of each pair of PB_ij. Then, the number of configurations in the cross-consistency matrix is defined as the $NCCM$ and calculated as follows:

$$PB_ij = \frac{1}{2}N(N-1) \tag{2.2}$$

$$NCCM = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} v_i * v_j \tag{2.3}$$

These equations determine the primary formal properties of a morphological model [Rit02b; RR11; Rit18]. The limitation of the GMA is that for the combinations formulated, only one characteristic selection per category is allowed for every design to model. However, the model is flexible, allowing i modification, as presented in [PS15; Pan+18], where a two-stage modified morphological analysis method was used, in which every object of the second stage considered the alternatives of the first stage [PHS21]. Similarly, [HSM20] implemented a modified morphological analysis method, concluding that the modified morphological analysis method supports combining different alternatives of its parameters or characteristics.

2.1.3 A Novel approach: Using a two-layer morphological box

Morphological boxes are a method for investigating and structuring the interrelationships of complex problems in different fields [RR11]. The method begins with the identification of the most important considerations of the problem (categories) and a definition of their corresponding characteristics. However, since MB only allows the selection of one characteristic at a time, other researchers have proposed modifications to the method. One such modification is the two-stage morphological box, in which the first part of the problem is defined in one MB, and later, a second morphological box is constructed. The second MB is used based on the possible implications resulting from the first part. This modified morphological box approach has been implemented in the construction field [PHS21]. In this thesis, a novel approach applicable to electricity markets is formulated, building on the research of [Zwi67; Rit98; Pan+18]. Consequently, this thesis proposes a two-layer morphological box approach to achieve a comprehensive electricity market categorization.

The first layer of the two-layer morphological box implementation focuses on the capability to examine the *current* market design. This means defining the system under evaluation. This first layer, termed the *Electricity Market Categorization Morphological Box*, establishes a baseline of the existing market structure.

The second-layer morphological box incorporates potential changes to enhance the advantages of smart grid implementations. This second layer provides a broad scope for identifying gaps, differences, and possible adjustments in the existing market design, as defined by the first layer.

Additionally, a list of actors and roles for all power system participants is incorporated to assess gaps between the current system and the proposed changes. This list, referred to as the Actor's Plane, defines the existing roles of each market participant and identifies missing roles essential for implementing the new market rules or changes. Clearly defining certain roles in the current system is essential to enable the transformations suggested in the second layer. The Actor's Plane exists outside the first and second layers of the MB because multiple actors must be selected for both the existing market design and the proposed changes. Since MB allows only one selection at a time, the Actor's Plane functions independently and is not itself an MB, but is complementary to the two layer proposal.

Therefore, the first morphological box defines the current electricity market design, while the second box explores potential new market mechanisms within this system. To complement these layers, a separate Actor's Plane is incorporated to identify any missing roles necessary for implementing market changes, as it supports the assessment of the roles within and beyond the current system.

Electricity markets are complex, diverse, and shaped by their unique design and regulatory frameworks. To address this complexity, a review of several market designs implemented worldwide identified the most relevant categories and characteristics needed to represent these structures accurately. However, the selection of many categories increases the size of the problem and may limit its usability for stakeholders. Therefore, the characteristics of the electricity market's structure (first layer) were grouped into seven categories with the use of MB, as presented in [ALG22]. Nonetheless, the method is versatile and allows the addition of more characteristics, which is useful when proposing new rules or changes.

The definitions and selections of the categories and characteristics for both layers are discussed in Chapter 3.

2.1.4 The Integration of HTD Concepts within GMA for Electricity Markets

One of the main characteristics of applying GMA is that only one characteristic from each category of the MB can be chosen at a time. To address this, the Holistic Test Description method is proposed for the structured definition and utilization of the MBs, since HTD aids in streamlining the process and ensure consistency in defining a test.

Within the HTD methodology, the researcher is supported by defining the *System under test*, *the function or component under test*, within its relevant operational context regarding a given goal or objective, and the *test objective* itself. By considering these three main definitions, the implementation of GMA can be better structured as follows:

1. Define the electricity market framework or market design to be evaluated. This step is necessary to define the market under study and the main market characteristics of the system being evaluated. In this case, the first morphological box is used. With the use of the first MB, the market is categorized, and the "*System under Test*" is defined.

2. Define the new market rule using the second morphological box (the new market rules MB). This MB defines the new market implementation to be considered, similar to the called "*Function under Test*" in the HTD method. This information is complemented with a list of actors and roles, already in place under the system under test (the market to be evaluated). The information about the actors is presented in an actor plane, which is used to evaluate whether the roles and functions required to implement a new market rule are already established in the system, or if any roles are absent due to gaps in market regulation.

3. Define the objective to be achieved and the goals driving the market change. These goals are equivalent to the "*Test Objective*" in the HTD method, and it is critical for the subsequent evaluation supporting the final decision process. A set of potential sustainability objectives is proposed to guide the assessment. Additionally, this thesis proposes evaluating any market change by considering how the test objective

is achieved across the four specified sustainability dimensions: economic, social, environmental, and legal.

Therefore, implementing the HTD concepts within the structured GMA and the morphological boxes encourages the establishment of a common framework, which underpins the refinement of the process.

2.2 Sustainability Aspect and KPIs

An electricity market is understood to provide sufficient, clean, secure, reliable, and affordable amounts of electricity to satisfy energy needs. Our main objective is to provide a selection of appropriate KPIs for a sustainability assessment of the electricity market, supporting its holistic evaluation. Furthermore, the implications of different policies on KPIs can be determined based on studies of their variables.

Moreover, the main benefit of smart grid technology is its ability to dynamically influence several sustainability dimensions such as the *economic*, *social*, *environmental*, and *legal* ones [Okw+22; Nou18; Bhu+22]. These dimensions must be considered when conducting a sustainability assessment. However, as mentioned in the Section 1.1, when it comes to evaluations of the electricity market, such a holistic approach is usually neglected or tends to focus on a single dimension. Therefore, it is essential to identify the appropriate KPIs to support the assessment of smart grid performance, accounting for differences in market designs and rules, and focusing on the four mentioned dimensions. Furthermore, a common sustainability comparison framework is needed to reveal differences arising from market changes.

Therefore, it is necessary to elucidate the intricate relationships between KPIs and the multifaceted aspects of sustainability. Given the potential direct or indirect influence of each indicator on one or more sustainability dimensions, a dimensional plane emerges as a crucial analytical framework. This dimensional plane facilitates the systematic mapping of KPIs and their subsequent interplay with the overarching sustainability aspects.

This thesis introduces a sustainability plane to facilitate these comparisons by evaluating the four identified sustainability dimensions. The sustainability plane links the smart grid capabilities with the sustainability dimensions, further highlighting their relationship and variations relative to market characteristics and supporting the assessment of changes in its design, as outlined in Section 2.4. To operationalize this framework and illustrate the interrelations between KPI clusters and sustainability dimensions, bibliometric analysis and science mapping methodologies are deployed, as described in Section 2.3

The definition and concepts encompassing each sustainability dimension are:

(i.) **Social dimension** aims to represent the social aspects and social externalities related to electricity markets. The KPIs that would be strongly linked to this dimension are those that demonstrate benefits for the customers and their possible inclusion and participation in the power system. As mentioned in [Com+19], it represents more than just social well-being; it also needs to consider social welfare and inequity aversion, such as the support of fair tariffs and high-quality energy services for customers. The potential creation of neighborhood grids, mini-grids, and energy communities are also considered within this dimension, regardless of the possibility of direct market participation. In addition, it includes the customer's ability to engage with the energy system through, e.g., building flexibility [Air+21], demand-response mechanisms [Dom+22], becoming a prosumer, or even having the capability to actively participate in markets. The social dimension aims to provide insights into system behavior from the customer's perspective with a high incidence on social aspects. Participatory mechanisms and transparency in customer data are also related to this dimension.

(ii.) **Environmental dimension** aims to promote the use of clean energy products and the general reduction of greenhouse gas (GHG) emissions through the use of regional renewable resources, clean technology and unrestricted access to renewable energies. Additionally, it includes not only the generation of electricity, but also the consumption. Therefore, the deployment of strategies to enhance energy efficiency and energy-saving techniques influences this dimension.

(iii.) **Economic dimension** aims to achieve production savings, reduce operational and maintenance costs, and improve efficiency in price formation and clearing processes. Additionally, it includes the potential to use market mechanisms to defer or avoid grid expansion investments and minimize costs. The effects of economic withholding and market power, as presented in [Sun+22; HA11] also belong to this aspect. This considers the incorporation of technical elements and new components with a detailed cost-benefit analysis from the planning process.

(iv.) **Policy/Legal dimension** ensures adequacy in the institutional framework and the establishment of regulations and norms to promote transparency within the power system. It also fosters the creation of incentives and markets. Furthermore, the political dimension addresses specific objectives (goals) in the power system, such as ensuring the security of supply through the deployment of renewable energy resources, managing interconnection dependency, and implementing carbon neutrality regulations.

The sustainability plane is constructed by representing each of the aforementioned dimensions at the plane's corners. The technological aspects are positioned at the center of the plane, intersecting all dimensions. This is because the technical features of the smart grid infrastructure are inherent in the KPIs for each of the four dimensions.

2.3 Bibliometric Analysis of Smart Grid Key Performance Indicators Considering Electricity Market Aspects

A bibliometric analysis is conducted to collect recent information about scientific studies on electricity markets that have originated due to smart grid technologies. Bibliometric analysis, in contrast to other traditional literature review approaches, enables examination of the knowledge structure of a research topic and includes a large number of works for a broader scope [Aco+23a; Don+21]. In contrast, a literature review is a method for collecting and synthesizing previous research but tends to be less systematic [Sny19]. Therefore, [TDS03] implements a stricter strategy for article selection, improving the quality and reproducibility of the results known as systematic literature review. Nevertheless, the approaches are less suitable for more general subjects or interdisciplinary approaches, particularly when the systematic literature reviews aim to synthesize viewpoints and develop novel theoretical models [Sny19]. To complement the review, [KM21] suggests systematic mappings with bibliometric analysis. This uses bibliographic mapping techniques to display data and draw conclusions through the systematic literature review.

Bibliometric analysis is employed for multiple purposes, including identifying new trends in the performance of articles and journals, examining collaboration patterns and research components, and investigating the intellectual framework of a particular field within the body of existing literature. [Don+21]. Bibliometric analysis can also support the detection of topics that exist within the analyzed field and visualize the findings with the support of a systematic mapping study [KM21]. It supports the definition of terms and the construction of bibliometric maps based on co-occurrence data as it was proposed by [Van+10].An example of bibliometric analysis implemented in the energy field, particularly for the retail market, can be found in [Di +22].

The implementation of bibliometric mapping strength, based on co-occurrence data, provides a graphical representation of topics while reflecting the relationship between those items [Van+10]. There are several software programs that can be employed to conduct bibliometric analysis, like *Bibexcel, VOSviewer, CiteSpace, Biblioshiny*, among others [Mor+20]. In this thesis, VOSviewer was selected. VOSviewer is an open-source software that supports distance-based maps and density and cluster definitions. VOSviewer uses an *association strength* measure that calculates the proportional ratio between the observed number of occurrences of two items i and j, and the expected number of co-occurrences of those items (i and j), assuming that they are statistically independent, as presented in [Van+10]. Therefore, this selected tool enables observing via bibliometric mapping the relationship between concepts, supporting clustering them for specific analysis.

Bibliometric Analysis for KPI extractions This thesis proposes the utilization of bibliometric analysis as a methodology to facilitate the identification and clustering of key performance indicators (KPIs) relevant to smart electricity markets, considering prevailing research trends and sustainability aspects. As elucidated in Section 1.2, the adoption of smart grid systems underscores the necessity for novel market paradigms. Researchers often tend to selectively employ indicators that align with their immediate study objectives, occasionally overlooking broader ramifications or repercussions. Furthermore, despite efforts to devise indicators and metrics for smart grid evaluation like the ones presented by [Ang+19], the comparability of disparate concepts remains elusive, as outlined in Section 1.2, This discrepancy is primarily attributable to differences in project scope and evaluation methodologies [Pra+19b].

This difficulty highlights the need for a wide range of KPIs that can capture the complexities of the electrical markets, especially those related to new market rules or regulatory changes, like capacity compensation mechanisms and flexibility trading, among other developments. Moreover, these KPIs must accurately reflect the changes in behavior induced by smart markets and the innovative regulatory frameworks enabled by smart grid technology. Additionally, since the main goal of implementing the smart electricity market is to promote sustainability in the power system, the social, environmental, policy, and economic aspects must be considered for a holistic evaluation assessment.

To perform this analysis, bibliography databases such as *MDPI* and *SCOPUS* are used to extract the data list of scientific studies based on queries that seek for specific keywords, such as '*electricity markets*', '*indicators*', and '*performance*'. The search did not limit the year of publication. This first query was constructed to extract all documents that relate to those terms. This means that the researcher implemented or studied the electricity market and used a specific metric to measure its performance. Journals, open-access conference papers, white papers, and reports were analyzed.

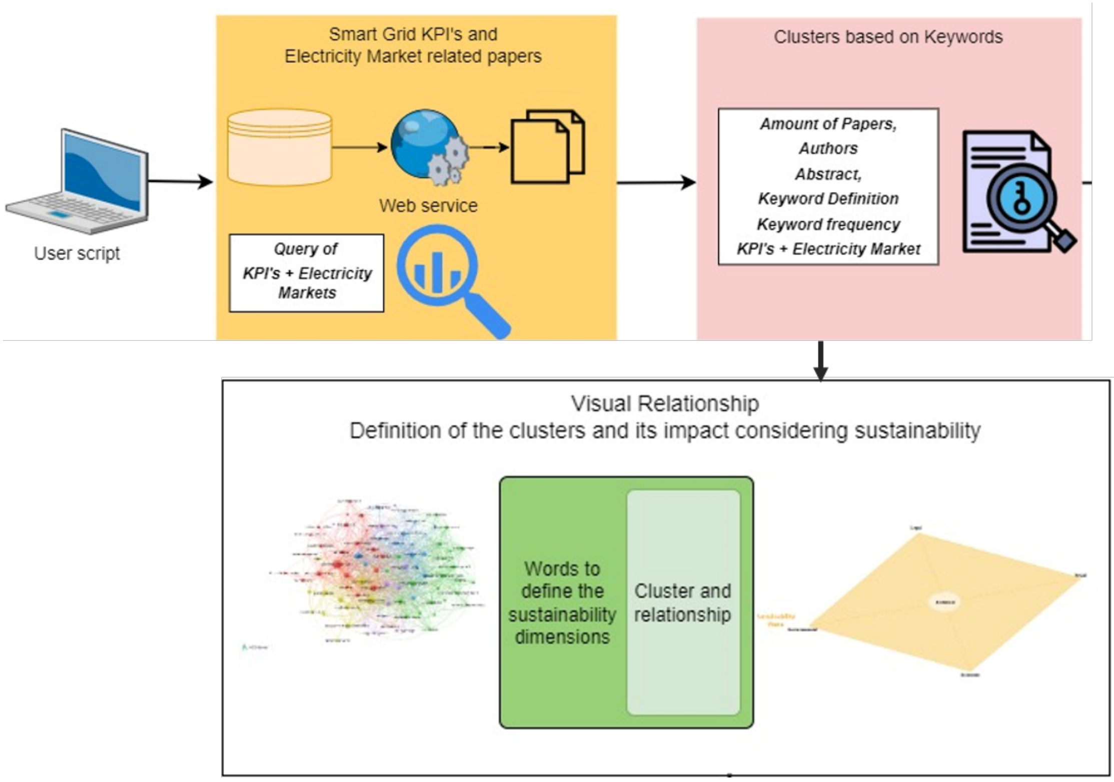


Fig. 2.2.: Bibiliometric Analysis for KPI Extractions

Similarly, the same process was used to extract documents that were published in the last six years on the predefined *new market rule*. Table A.3 in Appendix A.3 shows examples of the queries used for extracting the data. Duplicated papers were eliminated in the process.

The resulting papers were processed using the open-source software *VOSviewer 1.6.19*. This software tool is used for constructing and visualizing bibliometric networks, facilitating the identification of patterns and tendencies in the words used between those papers. In addition, a co-word analysis is carried out to examine the content of the papers. This supports the creation of maps that can show the relationships between important terms in the field [Van+10]. In this case, it supports the creation of smart grid clusters.

The visual relationship created with the bibliometric mapping and the frequency of words were used to define clusters. These clusters are saved for further queries. The clusters are located in a sustainability plane in which the economic, social, environmental, and policy aspects were defined. The sustainability plane and aspects are introduced in section 2.2

For the smart grid and market-driven KPIs extraction, only papers that used or proposed KPIs were reviewed in detail and extracted into a database. Based on the wording that defines those KPIs and their equations, a main cluster classification was selected for that KPI. Since one KPI could belong to several clusters, a qualitative assessment of those KPIs was elaborated based on the semantics of the KPIs. The main cluster classification for that KPI remains. However, the KPI was also marked in additional clusters with an indirect relationship. NLP techniques were additionally used to support the correlation between the clusters and the KPI definition, since NLP techniques support the classification of text into categories [Cho20].

This KPI extraction process was designed to define *which KPIs are Smart Grid related and which of them is market-driven*. Some of the proposed KPIs in scientific papers were not directly related to market implementation due to smart grids. In those cases, the KPIs were organized as *system indicators*, as explained in Section 4.1

A use case demonstrating the applicability of this process was developed and published in [Aco+23a], presenting the extraction of the KPIs for flexibility market mechanisms. Figure 2.2 illustrates the process for cluster creation, KPI extraction, and cluster definition. Therefore, the primary clusters based on smart grid technologies and electricity markets are defined.

Additionally, a sustainability plane is presented to identify and analyze the relationship between the clusters and sustainability aspects as explained in Section 2.2. The clusters are mapped on the sustainability plane. However, at this stage of the methodology, the location and relationships of the clusters within the sustainability plane need to be further defined.

Furthermore, the same query process is applied to each specific new market rule to extract the KPIs and organize them into the predefined smart grid clusters. The main difference is that the query is refined with the intended new market rule, e.g., *for flexibility market mechanisms in distribution grids*. The extracted KPIs are then stored in a database. To relate KPIs to each particular cluster and to consider its impacts on sustainability aspects, science mapping is employed. Figure: 2.3, illustrates the complete KPI extraction process and the relationships with them and each cluster.

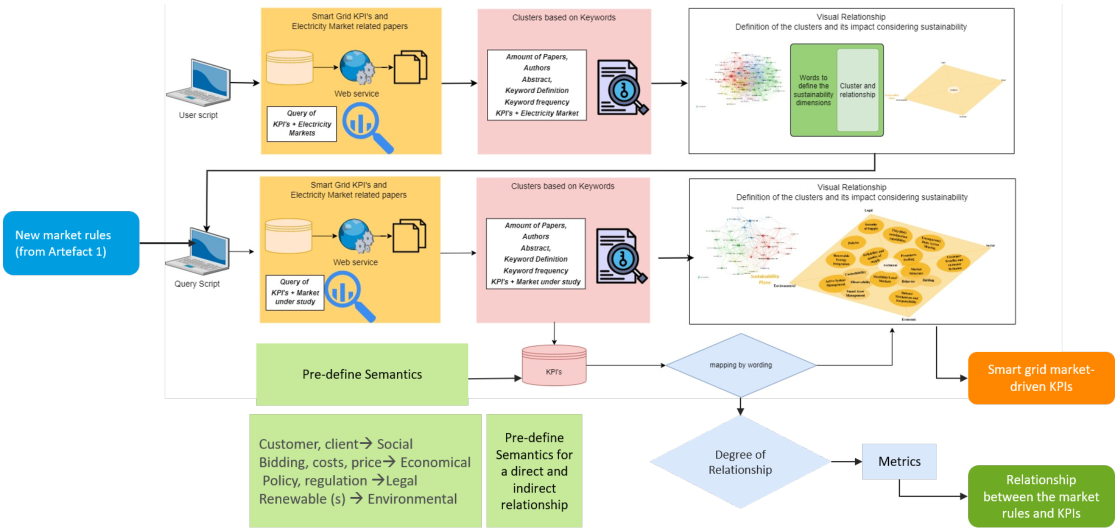


Fig. 2.3.: Development Process of Artifact 2: Bibliometric Analysis, Co-Word Analysis, and Predefined Semantics to Link Market-Driven KPIs and Rules

2.4 Science Mapping, Co-Word Analysis, and Concept Mapping as Tools for Relating Knowledge

To answer *what is the relationship between the market rules and KPIs*, science mapping is implemented as a complement to the bibliometric analysis. The objective of *science mapping* is to identify the structure, interactions, and connections for a topic in the scientific domain. It focuses on acquiring scientific knowledge through information visualization. According to [Don+21], it "*examines the relationships between research constituents and analyzes the connections among different elements of research*". Science mapping supports the visualization of information to discover knowledge. It has been used primarily as part of scientometrics to investigate the links between scientific research and articles and to find connections between words. The methods employed in science mapping encompass citation analysis, co-citation analysis, bibliographic coupling, co-word analysis, and coauthorship analysis [CDS15]. While many methods concentrate on assessing publications and the associations among authors, co-word analysis stands out as a technique that delves into the specific content of a publication. In addition, science mapping is used in different research areas to support conceptualization, codification, and tool construction [Che17]. Nevertheless, science mapping not only organizes knowledge into clusters or groups of related topics but also reveals how certain concepts are correlated and evolve over time. These techniques enable the visualization of key connections between terms and relevant concepts emerging in the scientific literature.

Since science mapping highlights and identifies emerging patterns across various fields, it is an effective method for revealing the relationships between market changes arising from smart grid technologies and the potential for enhancing power system sustainability. In this thesis, science mapping provides a framework for exploring the complex interactions needed to achieve a more sustainable power system by modifying the current state of the electricity market. For example, within the context of sustainability in the power system, this thesis uses science mapping to show how concepts such as 'electricity market,' 'smart grid technologies,' and 'sustainability' are interrelated across various studies. This approach facilitates the identification of central and emerging concepts that, collectively, outline the areas of knowledge driving transformations toward more sustainable power systems.

As part of the science mapping approach, co-word analysis was employed to extract and analyze interdependencies within the collected documentation. This technique allowed for the identification of elements that researchers consider as improvements to the power system and their possible connection to enhanced sustainability. In this context, however, the sustainability assessment in the power system is defined by the confluence of four key dimensions: economic, social, environmental, and legal.

Concept mapping is an additional graphical tool to gain knowledge, support conceptual thinking, and conduct research [CSY17]. It was originally used to accelerate meaningful learning as a strategy to organize ideas [NG84]. It has also been applied to encourage learning [ZO12]. Nowadays, researchers also use concept mapping to support interpretation, illustrate connections between topics, present findings, and study interrelationships, among others. This method, according to [CSY17], has three main approaches: relational, cluster, and word frequency.

Concept mapping, on the other hand, is employed to represent and clarify specific concepts or ideas, particularly when examining the qualitative aspects of market rules and sustainability goals. This method allows for a structured exploration of relationships between distinct concepts that arise either from the market domain or from each of the four sustainability dimensions. Extracted text from either open source papers or from the interviews with experts enables a visual representation of key interdependencies when evaluating changes in the market.

In this thesis, concept maps are applied to evaluate the primary statements of each interviewee, offering a focused, stakeholder-driven approach for refining and integrating practical knowledge into theoretical constructs. Moreover, the relationships found support connections between KPIs and the sustainability aspects, as evaluated in the bibliometric analysis. This visual approach aids in evaluating potential changes in market dynamics and their relation to other non-domain specific topics that influence markets and the sustainability of the power system. One example is revealing the nexus between market size and renewable energy promotion.

Therefore, this thesis applies science mapping and concept mapping as visualization techniques to represent the relationship between the differences in the electricity markets and correlate KPIs used for their evaluation with four dimensions of sustainability accordingly. Since queries are tailored to the *new market rule* to implement, the main topics discussed in each paper support the definition of the main structures of the electricity market, and therefore, the implementation of its KPIs contributes to the generation of knowledge. However, as mentioned in Chapter 1, researchers may have differences in the implementation of the testing procedure for the electricity market and their subsequent evaluation process. Differences may also arise from regulatory schemes and market designs. Thus, applying concept mapping to relate clusters and KPIs avoids direct comparison of results.

Figure 2.4 shows an example of the co-word analysis for a query that relates electricity markets and performance indicators. The search engine SCOPUS brought up 1357 different papers that relate those concepts. A co-word analysis was proposed using "author keywords", “article titles”, "abstracts", and "full texts" for the analysis [Don+21; Che17]. Using VOSviewer, the size of the node indicates the number of times that the keyword occurs, the lines between the nodes represent the co-occurrence of keywords, and the thickness of the linking nodes represents the frequency of co-occurrences between keywords. The thematic clusters are represented by colors.

Moreover, even though co-word analysis supports elaborating on the content of each thematic cluster, reading and reviewing the publications becomes necessary to under-

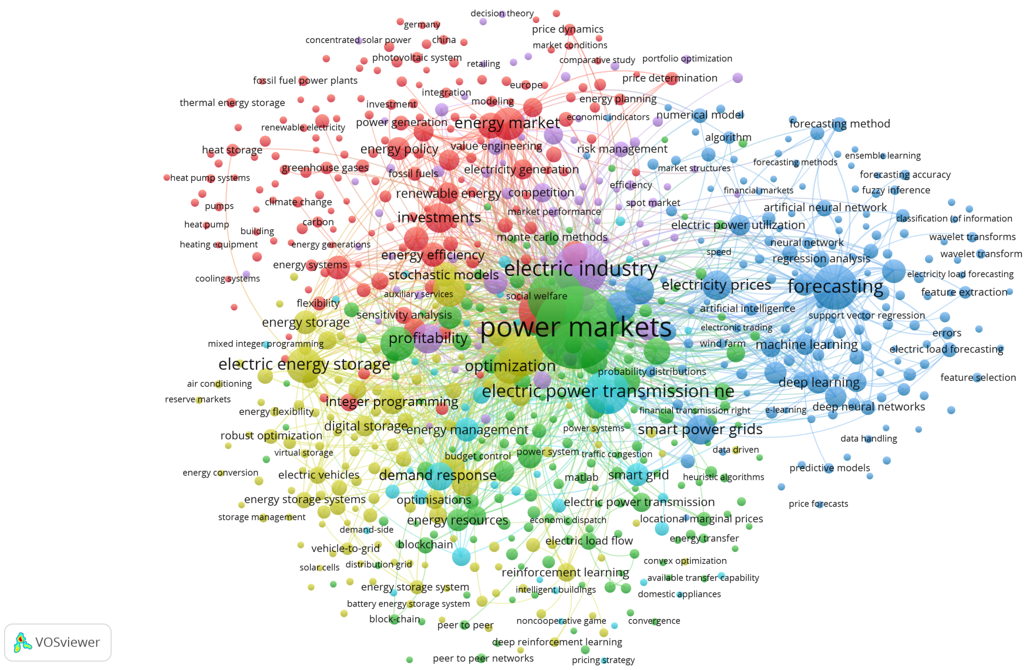


Fig. 2.4.: Five-Time Co-Occurrence of Keywords on a Map from a Scopus Search of 1,357 Sources

stand the additional meaning of the relationships between words. To support this task, term identification techniques are implemented to relate KPIs to different sustainability dimensions based on their semantics, as supported by the implementation of science mapping [Van+10; KM21; Che17; Che+16; CDS15; RSH22].

Furthermore, NLP techniques were employed to support the definition of terms for particular clusters and the dimensions of sustainability. For example: KPIs that include the words "*customer, customer, client, big client, consumers, consumer, energy users, user, amount of customers, big customer, big customers*" were considered strongly associated with social aspects. This association stems from the meaning of these terms within the context of electricity markets. Generally, 'customer' refers to the end user or consumer of electricity, even though, internally among stakeholders, generators are also considered customers of the transmission grid. A similar approach was taken when analyzing interview responses. A comprehensive list of words and phrases, along with their corresponding association with sustainability aspects, is provided in Table A.4 and explained in detail in Chapter 4, Section 4.1.

2.5 Evaluation Process Using Semi-Structured Interviews

This section provides an overview of semi-structured interviews as a method for understanding the know-how regarding the assessment of changes in electricity markets and the evaluation of sustainability in the power system. In addition, it explains the process that links the results of the interview with the evaluation of this thesis methods and results.

2.5.1 Overview of Semi-Structured Interviews

According to [DL18], the interviewer has a greater chance of "*actively contribute as a participant who generates knowledge in the process*", rather than simply following a pre-established interview guide. For this reason, semi-structured interviews are defined as an "interview with the purpose of obtaining descriptions of the real- world and interpreting the meaning of the described phenomena" [Bri14]. For this thesis, the definition of a semi-structured interview is:

> A semi-structured interview is a qualitative research method designed to obtain detailed descriptions of reality, allowing the interviewer to explore the interviewee's perspectives and experiences and to identify emerging themes and implicit meanings related to the phenomenon under study. Its flexible approach facilitates the generation of knowledge.

Interview-based knowledge extraction is a difficult endeavor because humans' implicit information is both valuable and difficult to apprehend. Knowledge consists of information that is practical, pertinent, and grounded in part in personal experience. Most of the knowledge is tacit in the interviewee's mind. Thus, capturing the "know-how" of experts can be challenging, as there is often little incentive to make this knowledge explicit. Moreover, certain insights may remain tacit, with connections between domains understood by the expert but not easily observable to others.

Performing semi-structured interviews requires a flexible design in which the interviewer starts with a general idea and uses a guide to develop topics and questions. The goal is to allow the interviewee to speak freely about perspectives, experiences, and ideas without predetermining responses. Unlike questionnaires, semi-structured interviews are not provided in advance and do not follow a rigid sequence of questions. This approach provides freedom to discuss a topic openly. Such interviews go beyond the verbal expression of preconceived notions and therefore serve as a way of generating knowledge.

This thesis utilizes semi-structured interviews with experts to access knowledge across domains, including the relationships among indicators, sustainability aspects, and electricity market assessment. Experienced domain experts can articulate the implicit connections among these topics, drawing on their perspectives in assessing market changes from multiple angles.

2.5.2 Evaluation through interviews

After conducting the interviews, the text is transcribed and coded. Coding the interviews is a process of organizing and interpreting the content by assigning labels to specific segments. It involves segmenting the text based on relevant topics and using a certain hierarchy among them. Coding facilitates the identification of relationships between different concepts.

To process the interviews, various methods and tools can be utilized, ranging from manual coding to automated coding. For this thesis, the selected open-source qualitative data analysis tools for coding the interviews are: *Voyant Server 2.6.10*, a web-based processing tool, *Qualcoder 3.4*, and *Taguette vs 1.4.1* [BTP23; RR21]. They were chosen for their capability to automate the coding of specific terms while enabling manual identification of additional codes within the corpus.

These tools are suitable for identifying patterns in topics, analyzing metrics such as term frequency within the text corpus, finding correlations, and creating collocate graphics. Collocate graphics illustrate keywords and terms that frequently occur in close proximity, thereby supporting the analysis of conceptually related terms. Collocate graphics represent keywords and terms that frequently occur in close proximity, supporting related concepts. Moreover, *QualCoder 3.4* offers the possibility to use the same code structure among all interviews, facilitating the evaluation of topics among interviewees. The open-source tool *Voyant Server 2.6.10* is utilized to calculate and correlate the metrics of the interview.

Additionally, Natural Language Processing (NLP) libraries and artificial intelligence (AI) methods, as outlined in [RM21], assist with data summarization and other aspects of data processing essential for developing mind maps that relate the concepts coded in each interview. According to [SH09], text mining serves as an information extraction technique suitable for uncovering knowledge within textual data and includes text clustering algorithms. These techniques are applied to cluster terms and construct mind maps that linked concepts expressed by each interviewee, facilitating the identification of relationships across multiple interviews.

Since the semi-structured interviews did not follow a specific questionnaire, three main topics are carefully introduced during the discussions to allow participants to share their expertise. The primary focus of the discussions centered on the assessment of:

- Emerging electricity market trends and potential changes driven by smart grid technologies.
- Capabilities of smart grid technologies and the anticipated key performance indicators (KPIs) for their deployment.
- Sustainability in the power system and current evaluations for integrating new technologies.

The mind maps, constructed based on expert knowledge, allow for a comparison of relationships between key performance indicators (KPIs) in electricity markets and sustainability aspects identified through bibliometric analysis. Each topic —electricity market trends, smart grid capabilities, and sustainability— was revisited multiple times during the interviews, as evidenced by the frequency and timing of specific terms. This pattern enables the extraction of insights into factors and influences that underpin these assessments, contributing to the analytical framework presented in this thesis.

The mind maps developed through expert input provide valuable insights into the interconnections between KPIs across electricity markets and sustainability, while also supporting the evaluation of smart grid clusters and emerging market mechanisms. In parallel, coded data were processed with the aid of Natural Language Processing (NLP) libraries in Python, further enhancing the analysis.

Figure 2.5 illustrates the process, which includes interview analysis, coding, and the development of mind maps. The entire process is systematically integrated and evaluated through the application of use cases, providing a structured framework for assessing the methodology's effectiveness. In Chapter 6, a use case is presented to demonstrate how the KPIs derived from the bibliometric analysis are utilized to assess the concepts articulated by interviewees.

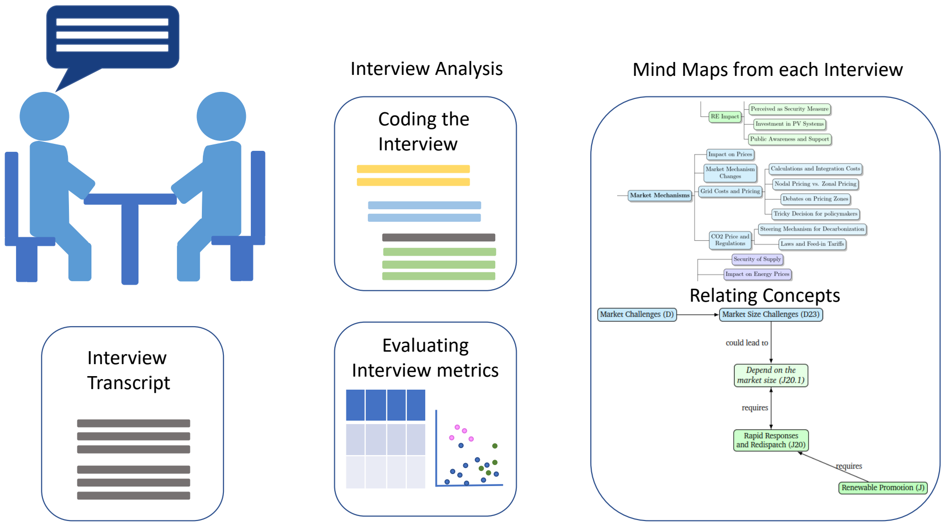


Fig. 2.5.: Process for the Evaluation of the Interviews

2.6 Conclusion

The presented approaches support the complete method outlined in this thesis. The evaluator is the individual who will apply this tool for further assessments or research studies.

- The methodology provides a structured guide for evaluators to define and assess electricity market designs and frameworks, adaptable even for hypothetical or experimental market scenarios. This proposal provides a clear structure for defining the system under evaluation, outlining the possible intended changes, and establishing the *a priori* definition of the intended objective to be achieved when implementing changes in the market, which are crucial for the final evaluation among market rules.
- The market categorization enables the evaluator to establish new rules or changes within the electricity market design, as demonstrated with the two-layer mor-

phological box. The use of this novel morphological box approach facilitates the identification of potential regulatory gaps and assists in systematically exploring combinations of market changes. It also supports the precise clarification of roles and actors relevant to the specified framework and seeks missing gaps in the defined system. This structured approach enhances comprehension and fosters effective implementation of the new rule.

- The proposed bibliometric analysis, combined with semantic analysis, supports the extraction and evaluation of KPIs for smart grid electricity markets. The versatility of this process enables the continuous updating of the created indicators data based for any intended market changes to evaluate. The process of relating the indicators using the semantic analysis ensures that they remain consistently aligned with sustainability aspects.

- The relationships between smart grid capabilities and sustainability dimensions provide an overview of the influence of topics and the implications of one measure over the others in achieving sustainability in the power system. Moreover, the creation of concept maps resulting from the weighted relationships among KPIs offers a comprehensive approach for uncovering market externalities.

- The concept maps and the process implemented for assessing changes in the market were reviewed by experts revealing the importance of the holistic approach implemented in this dissertation. Additionally, through expert evaluations, the relationships between the indicators and the market design are mapped, reflecting potential impacts on clusters beyond the primary analysis.

3 Electricity Market Categorization Implemented with a General Morphological Analysis (GMA)

This chapter elucidates the implementation of the initial artifact in response to Research Question 1 (RQ1): *'How can electricity markets be categorized for testing new market rules?'*. To answer this question, a combination of the concepts delineated in Section 2.1, pertaining to the utilization of the Holistic Test Description HTD and the General Morphological Analysis (GMA), are implemented.

Two morphological boxes are created: the first groups the main characteristics of the electricity market that support the investigated system or market framework. The second groups possible new market rules aimed at promoting changes in the electricity markets due to smart grid technologies.

These two morphological boxes, together with an extraction of the current actors, contribute to:

- The representation of possible and actual markets and the differentiation between market designs.
- The representation of opportunities for new market rules.
- The clear observation of gaps in the current framework.

3.1 Electricity Market Categorization

The morphological boxes are fundamental components of the electricity market categorization. As explained in Section 2, it can be used to provide a structured framework for identifying key components and relationships within complex systems. In this approach, to elaborate on a complete market categorization and use it as the framework for defining new gaps, it is necessary to determine the answers to the following sub-questions:

1. **What are the characteristics of the electricity market?** A morphological box is implemented to support the definition of the market design under analysis. This box contains the main market characteristics of the different possible market designs. Therefore, by selecting a feature from each category, the overall framework under evaluation will be enclosed.

2. **Which new market rules could be implemented?** A second morphological box is elaborated with possible new mechanisms to be implemented that might be different from the business as usual of that particular market framework. It will focus on the creation of ancillary services and capacity markets. It does not imply that the system to be evaluated has not implemented one of those mechanisms: for example, capacity payments may already be in place. The separation was performed since several options are possible at the same time and most of the latest research has been focused on potentiating flexibility services to support renewable energies and in the intentions to change Energy-Only Market (EOM) to capacity markets.

3. **What are the objectives to achieve with the new implementation?** Every change in the current system needs to follow a specific objective. Regulators and stakeholders do not change market rules indistinctly without the intention to achieve a particular overall goal. Therefore, defining the overall goal is crucial for the final evaluation, as it represents the primary intent behind any market modification. Furthermore, some changes may lead to similar outcomes across different dimensions of sustainability. Thus, the intended goal will play a decisive role in guiding the final assessment.

3.1.1 A Novel Approach: Implementing a Two-Layer Morphological Box for Electricity Markets

As mentioned in Chapter 2, when assessing a problem by using morphological boxes, all the possible combinations of the selected categories and characteristics are considered. This is only possible if only one characteristic is selected per characteristic at the time. Thus, applying a two-layer morphological box enables the identification of different market frameworks and designs, allowing for a structured approach to define potential changes within each framework. The objective of the second layer is to strengthen the definition of gaps for new market rules and to support the intended implementation of market rules based on smart grid capabilities. The new market definition that results from the second layer is evaluated based on the result of the first layer, which defines the market design.

This approach, published in [ALG22], separates the solution space to reduce the total amount of possible combinations. Table: 3.1 presents the main variables of a general morphological analysis, as explained in section 2.1. Analyzing the entire problem without distinguishing new market rules from the initial market categorization dramatically expands the solution space. In contrast, the two-layer analysis reduces the solution space for each part of the assessment. Specifically, the complete problem involves more than 2 million combinations, whereas the layered approach segments and reduces the solution space, as shown in the table with the number of simple configurations.

Table 3.1 presents the main property metrics of the GMA across the entire problem scope, specifically for the case in which a two-layer morphological box is not employed, and presents a comparison of these metrics with each specific component of the two-layer morphological box proposed in this thesis. The categorization option pertains to metrics associated with the first-layer morphological box, while New Markets represents the second-layer morphological box. The actor plane is defined by 13 distinct roles. Additionally, the column titled *Number of dyadic relationship between parameter blocks* shows the amount of the interactions between each category pair, or parameter block PB_{ij}, necessary for constructing a CCA, as described in Section 2.1. Notably, the actor plane does not contain parameter blocks. It serves to observe existing actors, identify role gaps, and assess the potential need for additional roles.

These numbers assume only 13 final actor combinations. However, when considering all possible actor combinations, the number of simple configurations resulting solely from the permutations of actors is *13!*, yielding $6,227,020,800$ combinations. Consequently, the total number of possible market design configurations, accounting for all simple configurations, is $2.36E + 11$.

Therefore, the ability to decompose the problem into two distinct layers and incorporate actors as an additional dimension facilitates the redefinition of the problem space and enables a clearer observation of the system under evaluation.

Options	Number of parameters	Number of dyadic relationships between parameters blocks	Number of CCM cells	Number of simple configurations
	N	$\frac{1}{2}N \cdot (N-1)$	$\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} v_i * vj$	$\prod_{i=1}^{n} v_i$
Entire Problem	10	45	1122	2446080
Categorization	7	21	243	3840
New Markets	2	1	49	49
Actors Plane	1	0	13	13

Tab. 3.1.: Comparison of Morphological Box Properties. The Entire Problem refers to the case in which a two-layer morphological box is not used. Categorization presents the metrics for the first-layer morphological box, while New Markets represents the second-layer morphological box. The Actor Plane is defined with 13 roles

3.1.2 Electricity Market Categorization: First-Layer MB

In order to complete the morphological box proposed for the categorization of electricity markets, a comprehensive literature review of the market designs in Europe, North America and Latin American countries is conducted. The goal of this literature review is to observe different real market designs and research improvements when smart grid technologies are employed.

Furthermore, scientific publications about potential enhancements in various market domains are consulted to assess and formulate the morphological framework for new market rules. Innovations in both transmission and distribution power systems were explored to ascertain the requisite information for elaborating a second morphological box.

From the literature review, seven main categories were selected. Each category can have distinct amounts of characteristics. The characteristics were coded using an alphanumeric combination as depicted in Figure 3.1. The following subsections explain the contents of every characteristic for each of the seven categories.

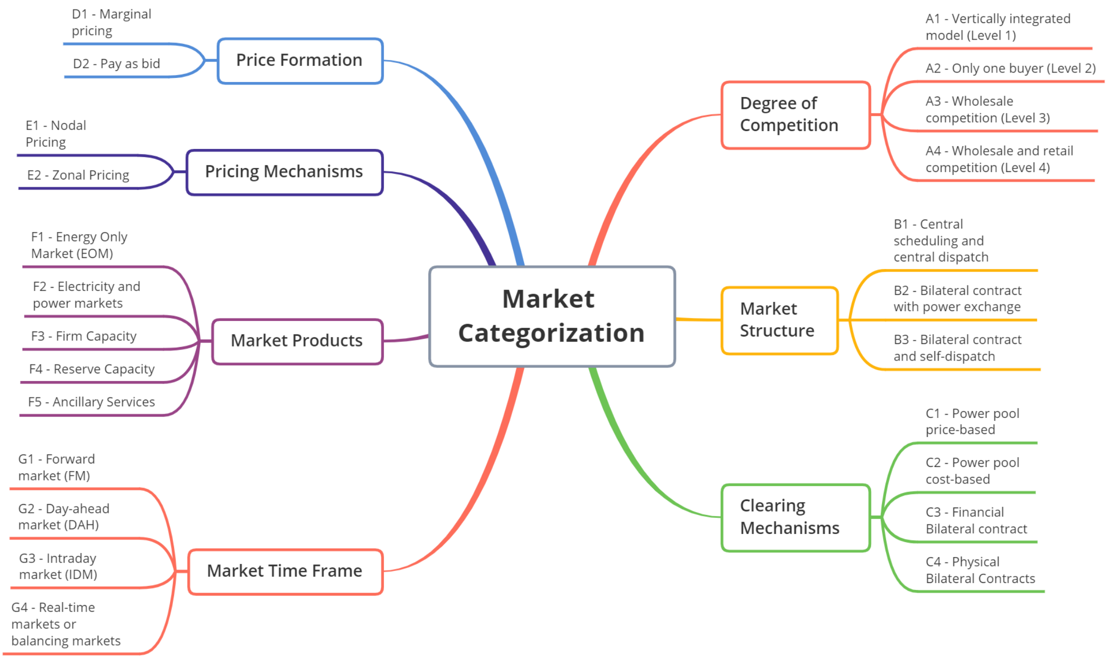


Fig. 3.1.: Electricity Markets Categorization

A. Degree of Competition:

The power system can be structured into generation, transmission, and distribution. Depending on the region or country, different levels of competition have been implemented for each part of the power system. This is a result of the deregulation of the sector to restructure the market and prevent monopolies. Although most regions followed the deregulation process, some chose to implement competition only for generation, while others opted for no competition at all.

Based on these considerations, four levels of competition are defined, ranging from *Level 1*, which involves minimal competition, to *Level 4*, which incorporates competition across all sectors. The descriptions and definitions used are as follows:

A1- **Vertically Integrated System (Level 1):** This represents a design mechanism in which a single company is responsible for generation, transmission, distribution, and commercialization, with no competition. At this level of competition, neither generation companies nor retailers sell or purchase products.

A2- **Single Buyer Model (Level 2):** Competition is allowed in only one sector, usually generation, though it may also be restricted to only new energy sources. In this design, a single entity is typically responsible for purchasing energy from all generators and generally retains control over the rest of the system.

A3- **Wholesale Competition (Level 3):** This degree of competition opens the market for trading between generators and distribution companies but restricts competition to wholesale transactions only. The key distinction is that it does not permit retail competition. This type of market can be used as a complementary mechanism for deviation trading and is commonly applied in most emerging economies.

A4- **Wholesale and Retail Competition (Level 4):** In this case, both producers and consumers are authorized to participate actively in the market. This level of competition allows customers to choose among energy suppliers. Consequently, retail companies can actively engage in the market to offer their customers attractive services, such as competitive pricing or fully renewable energy supply. This level of competition remains unaffected by whether retailers own the utility infrastructure or operate solely as energy providers.

Based on the degree of competition, the regulation establishes specific rules for energy trading. For example, a vertically integrated system tends to match demand and supply based on the optimization of its resource availability. As a result, the energy company assumes the risks associated with the power generation plants. It is also expected that less competitive structures will require significant regulatory changes if the goal is to transition to a more dynamic market structure. However, when the degree of competition is higher, power production companies as well as retailers are responsible for offering, purchasing, and assuming market risks. This opens the possibility for increased investment in technologies to mitigate forecasting deviations and to make more informed business decisions.

B. Market Structure:

Worldwide markets can be categorized into centralized and decentralized structures. Centralized markets operate as power pools, while bilateral contract models typify decentralized market structures. However, it's noteworthy that within centralized markets, bilateral contracts can coexist alongside a power exchange mechanism.

Therefore, to better represent the differences, the definition proposed by [Bar+05] is implemented and extended as follows:

B1- **Central Scheduling and Central Dispatch:** Also known as central management, this refers to a power pool in which unit commitment is centrally scheduled.

B2- **Bilateral Contract with Power Exchange:** This refers to a bilateral contract model that implements central dispatch. These contracts may be financial or physical. It is also known as self-scheduling with central dispatch.

B3- **Bilateral Contract and Self-Dispatch:** This represents a physical bilateral contract and is also known as self-scheduling and self-dispatch.

C. Clearing Mechanisms

Clearing mechanisms refer to the process by which financial trades are settled. In electricity markets, these mechanisms can take the form of either a power pool or a contract. For this thesis, the clearing mechanisms are defined as follows:

C1- **Power Pool Price-Based:** A type of power pool in which generators submit offers specifying both price and quantity for each time frame of the pool.

C2- **Power Pool Cost-Based:** This mechanism follows a typical merit order in which the price is determined by the marginal cost of the last generation unit called upon to meet demand. The key difference between this and the power pool price-based mechanism lies in cost-based mechanisms, where generators do not submit price offers but instead report their variable costs. This type of mechanism is commonly implemented in emerging economies or small markets.

C3- **Financial Bilateral Contract:** A contract traded between power producers or between power producers and distribution companies or eligible consumers, in which the price is settled but not the actual physical delivery.

C4- **Physical Bilateral Contract:** Similar to financial contracts but with mandatory physical delivery from the power producers involved in the contract.

D. Price Formation

When a market has central dispatch or implements a power pool (exchange), price formation and pricing mechanisms (Section E) become relevant. Otherwise, the price is settled within the contract.

D1- **Marginal Pricing:** The supply and demand curves intersect, and the resulting price corresponds to the system's marginal cost for that time frame. The merit order is used to calculate the system marginal price (SMP). Under this mechanism, each generation offer receives the market-clearing price.

D2- **Pay-as-Bid:** Each generator is paid according to its bid price.

E. Pricing Mechanisms

Pricing mechanisms refer to the methods used to calculate prices within the system.

E1- **Nodal Pricing:** Each node of the power grid is assigned a price that considers the power grid topology (transmission grid). This method is useful for representing grid congestion. Nodal prices are derived from the locational marginal price (LMP) [IRE19; Lop18].

E2- **Zonal Pricing:** The power exchange calculates a single price for an entire area or zone, assuming unrestricted transmission capacity. The price is uniform across the region and does not account for delivery or withdrawal points. Uniform pricing also falls under this category.

F. Market Products

This section categorizes the primary products traded within electricity markets. In a power system, market design typically involves a combination of multiple products rather than a single market product. However, this section aims to identify the primary product traded in the market, which is also the focus of our interest for introducing modifications in market rules. These market products vary in their approach to trading energy, capacity, and power generation, supporting both short-term operations and long-term investment strategies.

This methodology is designed to focus on a single primary market product, which may appear to be a limitation of the tool, as it does not aim to observe interactions between multiple markets. Instead, the approach emphasizes defining and highlighting indicators that support the assessment of the selected product. Therefore, only the main option to be analyzed should be selected. If interactions between multiple markets are to be examined, separate scenarios must be developed, with each scenario focusing on a different primary product of interest.

F1- **Energy-Only Market (EOM):** Refers to an electricity-only market. Electricity generation (MWh) is the commodity. There is no direct compensation for power or capacity.

F2- **Electricity and Power Markets:** Power production (generation) and power capacity are traded.

F3- **Firm Capacity:** A power capacity market designed to ensure long-term investment.

F4- **Reserve Capacity:** Usually represented as a percentage of peak demand and can be considered part of a capacity remuneration mechanism.

F5- **Ancillary Services:** A market for primary, secondary, and tertiary reserves for balancing markets and real-time operations. It also includes services to ensure the quality of supply.

G. Market Time Frame

For this category, the time horizon is considered as follows:

G1- **Forward Market (FM):** This is also a financial instrument with a delivery time that can range from days to years. Typically, this time frame is not applicable to Day-Ahead (DAH) markets. In some markets, there are also divisions into futures markets for a yearly time frame and forward markets for weekly planning, but their differences lie in standardization [Lop18].

G2- **Day-Ahead Market (DAH):** This market allows for trading one day in advance.

G3- **Intraday Market (IDM):** Following the closure of the DAH market, intraday trading takes place, allowing participants to make adjustments within the trading day to respond to real-time conditions. The IDM time frame can range from hours to minutes, depending on the market.

G4- **Real-Time Markets or Balancing Markets:** These markets are used to balance real-time operations due to differences between production and consumption, usually within ancillary service markets.

3.1.3 New Market Implementations: Second-Layer MB

Different sets of new market rules, based on literature research, were investigated, collected, and categorized in a second MB. For this purpose, only research on new market rules in Europe was considered. This includes EU Regulations 2019/943, 2015/1222, 2016/1719, and 2017/2195 [Com19; Com15; Uni16; Com17], as well as research papers on the creation of ancillary service markets and smart market design [Fra+17]. From these, two main focuses were selected for the support and development of markets: the analysis of capacity remuneration mechanisms and the creation of ancillary service markets.

Therefore, a group of market characteristics for these two categories was considered as follows:

Capacity Remuneration Mechanism

The extreme fluctuations in the price signal and the zero marginal cost of renewable energies in the wholesale market are current challenges for tstimulating of long-term investment.

Theoretically, in a perfectly competitive market, the price rises quickly, supporting an efficient solution for peak conditions. In reality, there are several problems associated with the systems that are linked to the specific characteristics of the EM. These problems range from physical barriers to the intermittency of RE, investors' uncertainty, and the regulatory intentions to avoid high electricity prices. Therefore, there is an ongoing debate regarding the necessity of capacity remuneration mechanisms as a means to secure and ensure sufficient generation capacity to meet future demand.

[Bub+19] describes several types of possible capacity payment designs. Its proposed organization of capacity payments is considered as an option for evaluation within the market design. The definitions and explanations of the different capacity options are as follows:

- **Tenders for new capacity:** Refers to the procedure by which electricity market regulators or operators open bids from suppliers to deliver new capacity to the market. These tenders are frequently used to purchase capacity from specific sources and the resulting contract are known as Power Purchase Agreement Power Purchase Agreement [COS13].

- **Strategic reserves:** Refers to additional generation capacity or demand-side resources that can be activated during periods of high demand or supply shortages to maintain grid stability. This reserve is contracted and maintained outside of the EOM and is used under specific conditions. Usually, the regulator establishes the quantity that must be reserved [HCS16].

- **A target capacity payment:** In this mechanism, a central buyer establishes a fixed price to be paid to eligible capacity. This payment may apply to specific technology, such as batteries, or for exclusively to new fast response generators, among others. This mechanisms has been implemented in Spain and Portugal [Bub+19].

- **A forward capacity market:** Involves procuring capacity in advance of the delivery period. In this model, a central buyer procures capacity through auctions or bilateral contracts, e.g., *the attribution of long-term cross-zonal capacity through an auction before the day-ahead time frame* [Uni16].

- **A market-wide capacity payment:** Similar to a pool, the capacity need is estimated and a capacity price is determined centrally, which is paid to all capacity providers in the market.

- **Implement de-centralized obligation:** involves imposing obligations on market participants, such as generators or consumers, to ensure the availability of a certain level of capacity.

- **None of them:** Typically energy-only markets do not require implementing any capacity remuneration mechanism. This option is contemplated in case the analysis focuses on other new market mechanisms unrelated to capacity.

Ancillary Service or Flexibility Service Market

Ancillary services can be traded in some markets. These services refer to the possibility of trading not only the primary, secondary, and tertiary control but also to establish a formal market mechanism for flexibility trading like:

- **Grid capacity management market:** Also known as congestion management market. These types of markets are activated if line congestion is foreseen after the optimization of the resources or during operation. To implement this mechanism, a careful cost-benefit approach in the region must be evaluated, considering curtailment costs and the assignment of costs to other externalities.

- **Power quality support market:** Possible creation of active and reactive power markets.

- **Controlled islanding:** Future consideration of intentional islanding, particularly to improve customer-impact indicators during a blackout. This approach enables the creation of islands or mini-grids to prevent service interruptions from affecting other customers.

3.1.4 Actors and Roles for the Power System

This section discusses the parties that have specific functions within the power system. These functions depend on the market organizational model, which is determined by the level of competition. Some actors are already integrated into the system, while others need to be developed to align with the new market rules. For example, developing an ancillary service market will require the involvement of active demand and supply parties, aggregators, and balance-responsible parties, among others. To identify gaps in the roles and functions of actors, a list of actors and key features has been developed, based on the current harmonized electricity market role model in Europe and the USEF Framework [ENT20; Con+05; DLA21].

- **Active demand and supply (ADS) or prosumers:** This party can both consume and produce electricity. There are no size constraints for being considered an ADS, but they do not act purely as power producers or generators.

- **Aggregators:** The role responsible for collecting ADS and prosumers for market purposes. This role is key when assessing a flexibility service market.

- **Supplier or billing agent:** Responsible for procuring electricity for customers and handling commercialization (invoicing). In some markets, the distribution company also performs this role.

- **Electricity trader:** A broker who sells or buys bulk energy. Even though ADS can sell electricity, it is not considered a trader.
- **Balance responsible party:** Responsible for balancing zones and managing the imbalance in the system caused by demand and supply within an area. According to Regulation (EU) 2019/943 [Com19], all market participants are responsible for the imbalances; therefore, they will contract a BRP through their supplier.
- **Distribution system operator (DSO):** Owns and operates the distribution grid.
- **Transmission system operator (TSO):** Owns and operates the transmission system grid.
- **Generators or power producers:** Owners of licenses to generate and participate in the electricity market.
- **Grid operator:** Responsible for the operation of the system. Owns the grid model, calculates prices, and manages line congestion events. It can also be the actor responsible for granting grid access for new projects and can be a third-party agent.
- **Meter data responsible:** Responsible for the metering system. In some markets, grid operators take on this function. They may own and be in charge of the commercial metering system. In some places, this is not an additional actor. However, it is important to distinguish the actor in charge of the meters for smart grid implementations due to the volume of information and sensitive data.
- **Imbalance settlement responsible (ISR):** The actor that establishes quantities of energy products for the Balance Responsible Parties.
- **Capacity trader:** The actor who can participate in the Capacity Market.
- **Transmission capacity allocator:** The actor responsible for allocating and offering transmission capacity to the market. In some cases, the TSO also takes on this role.

Table A.2 shows this information as developed for the artifact. The actors will not constitute an additional category of the morphological box for categorizing electricity markets. This is because a key property of the morphological box MB is that only one selection is possible at a time. As the electricity market involves multiple actors, the intention is for all relevant actors within a given framework to be included. Consequently, the actors and roles were organized in an "actors' plane" to facilitate the identification of any missing actors or roles. In addition, purely passive customers are not listed, as they lack the ability to participate in the market directly. Typically, another actor, such as an electricity trader or aggregator, represents them in the market to provide necessary services, depending on the regulatory framework.

After identifying the actors participating in a particular market framework, the actors' plane is developed. The actors' plane examines whether the selected actors enable the framework to implement the new rule subject to examination. Additional actors, such as the regulatory authority or the governmental entities, that are not listed can significantly influence the market. However, their omission from the initial actors' plane is deliberate, as their effects and impacts could only be perceived following the implementation of a new market mechanism or legal policy.

Finally, for the elaboration of a cross-consistency analysis, the missing actors or roles are discussed to evaluate whether the new market rule can be implemented or if a significant modification is needed.

3.1.5 Objective

The process of modifying the electricity market typically begins with a specific goal, making it imperative to define the objective that drives the market change. This is a key aspect for performing evaluations. Furthermore, any change to the current market intends to support the energy transition towards more sustainable power systems.

For this reason, the objectives are evaluated based on economic, social, and environmental sustainability aspects at the end of the entire process. Additionally, the legal aspects are incorporated to gauge the regulatory frameworks influencing the power system and their alignment with specific objectives.

The objective definition is established by the evaluator of the new market rule. No extension of the morphological box is created for this goal. However, some examples are provided for clarity. For instance, an objective could be the creation of local markets and flexibility markets in the distribution grid to increase the share of renewables in a designated area, without requiring additional reserve capacity.

3.2 Cross Consistency Assessment

The goal of conducting a Cross Consistency Assessment CCA is to assess all the possible configurations of electricity market designs that can be created with the morphological analysis, particularly the *Morphological Box for Electricity Market categorization* proposed in this thesis. A CCA consists of evaluating each characteristic found in every category of the MB against the rest.

Within the field of smart grids, predominant research and implementation efforts have focused on delineating two principal thematic areas or key topics identified within the morphological box for new market rules: capacity remuneration mechanisms and ancillary services, including their use in the flexibility market. These two topics introduce significant changes impacting the current electricity system. Since the primary objective of the proposed GMA is to systematically assess different market designs based on these changes, only the Morphological Box for Electricity Market categorization is considered for a CCA, excluding the morphological box for new market rules.

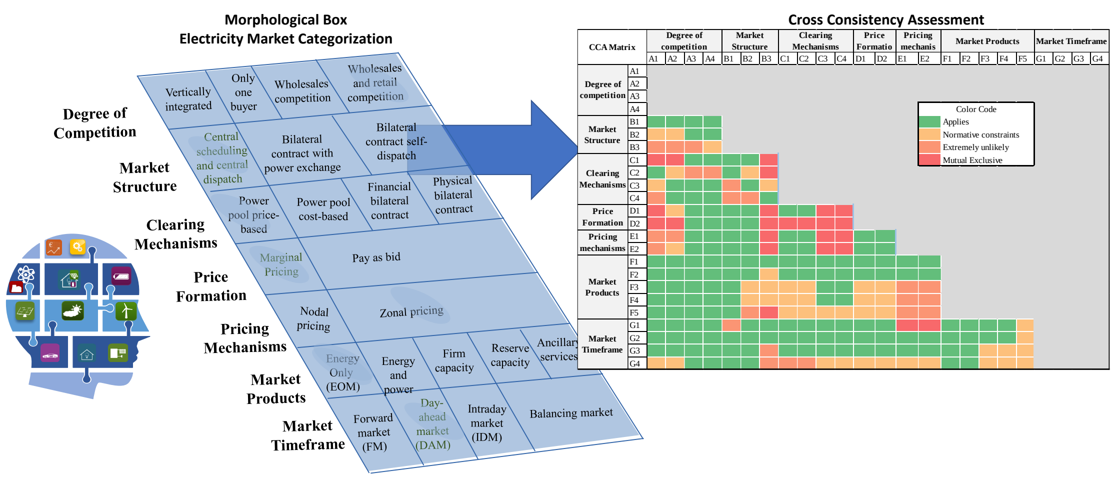


Fig. 3.2.: Morphological Box for the Categorization of Electricity Markets and its Corresponding Cross-Consistency Assessment"

Figure 3.2 depicts how the process is conducted. First, the stakeholder or researcher who intends to analyze different electricity market designs uses the *Morphological Box for Electricity Markets Categorization*. Then, a CCA is constructed by setting the characteristics against each other to create an n-dimensional configuration space. This process examines internal relationships between a pair of characteristics to avoid contradictory configurations. Each pair of characteristics is qualitatively evaluated based on whether it can coexist or if it represents an inconsistent relationship.

According to the CCA methodology, there can be three types of inconsistency: based on the nature of the concepts, judged as highly improbable from a practical approach, and others with normative constraints. The latter must be carefully assessed according to [Rit18].

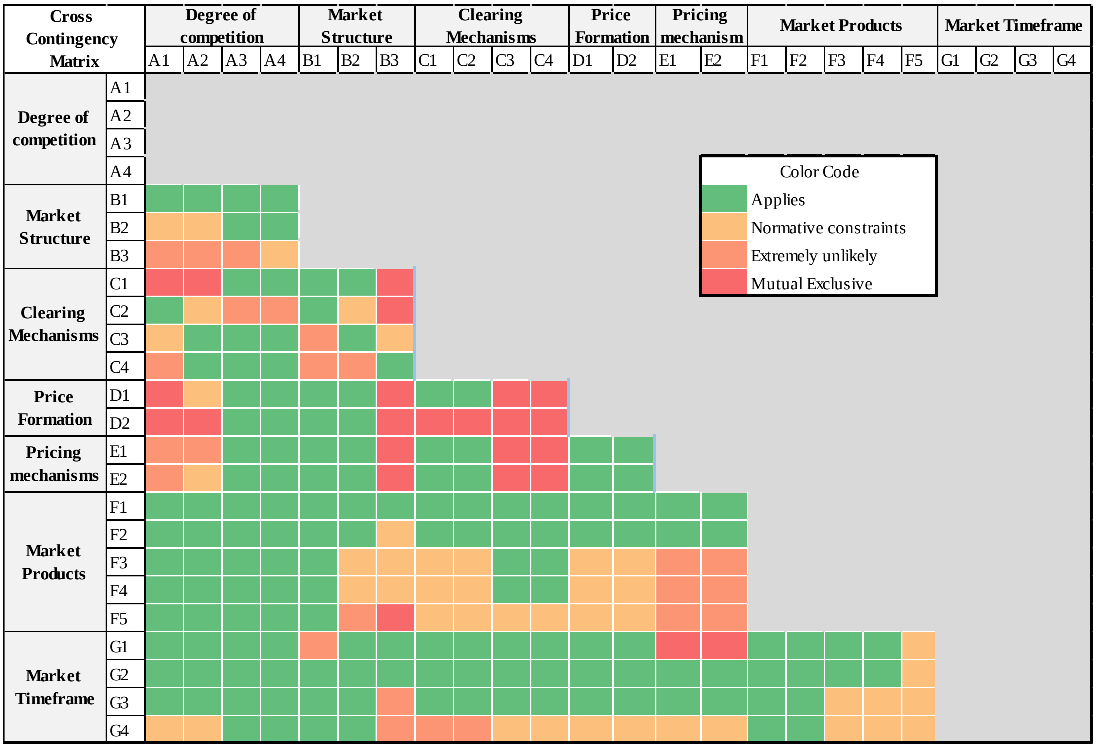
For implementing the CCA of the *Morphological Box for Electricity Markets Categorization*, it was necessary to determine the applicability, feasibility, practicality, and level of interest of each possible combination. Since the solution space comprises the subset of all configurations that meet certain requirements, the main factor is considering internal consistency. Marking internal inconsistencies as a *mutual exclusive* pair, the number of configurations in the cross-consistency matrix, defined as the $NCCM$, is reduced, as mentioned in section 2.1.

Additionally, a cross-consistency assessment matrix is developed for the market categorization MB to assist the researcher in avoiding the construction of *mutually exclusive* configurations. The *extremely unlikely* and the *normative constraints* configurations must be carefully analyzed. However, they are not eliminated since they may generate interesting research questions.

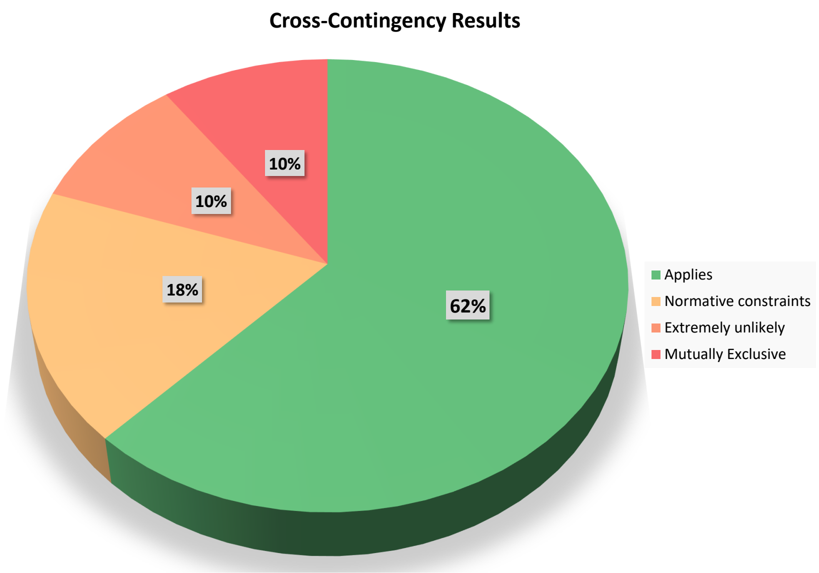
In total, 62% of the combinations are fully applicable, plus an additional 18% that correspond to market designs that can be implemented but may require normative constraints.

The qualitative assessment is implemented using a color code for the possible configurations as follows: green for *applies*, orange for *normative constraints*, dark orange for *extremely unlikely*, and red for *mutually exclusive*. Figure 3.3, part a), depicts the construction of the CCA matrix. As a result, 24 combinations are mutually exclusive, 24 are extremely unlikely, 44 combinations show normative constraints, and 151 combinations applied for feasible market frameworks. Additionally, Figure 3.3, part b), shows the results as percentages for each combination.

As inferred from the CCA matrix, some examples and considerations for the qualitative evaluation are:



(a) Cross-Consistency Assessment Matrix



(b) Pie diagram of the Cross-Consistency Assessment Matrix Results

Fig. 3.3.: Complete Results of the Cross Consistency Matrix

- In a central market (central scheduling and central dispatch), financial and physical-bilateral contracts belong to the clearing process (post-operation). Therefore, they do not affect the price formation for the intra-day market.
- Ancillary services and balancing market require some central control or coordination for the activation mechanisms, especially if small actors (producers and ADS do not have complete information about the grid topology). Therefore, these will be considered *Not Possible for self-dispatch*.
- For price formation, the characteristics *pay as bid* and *merit order (pool based)* are mutually exclusive. In addition, not all contracting parties will participate.
- All bilateral contracts will not be part of the pricing mechanisms. This configuration is considered *mutually exclusive*.
- Pool-based mechanisms are not directly related to capacity remuneration and ancillary services. Their implementation depends on the proposed changes based on the second-layer morphological box.
- It is considered likely that bilateral contracts (financial or physical) can be used for capacity mechanisms.

3.3 Use cases for evaluation

This research demonstrated the usability of GMA for categorizing the electricity market, as presented in [ALG22]. A practical approach based on use cases of the EOM of Germany and the wholesale market in Panama using a combination of the morphological box for smart grid development as a use case comparison is presented. The morphological boxes proposed are tested using several configurations of the European Market framework. The EOM is used as a reference to compare with the Panamanian framework described in [IRE18], where the flexibility assessment was conducted. Table 3.4 shows the results of selecting one category for each characteristic.

Bilateral contracts and power pool-based clearing mechanisms operate under distinct principles. Bilateral contracts are private agreements where the price is determined outside the centralized market, whereas power pool mechanisms set prices through centralized auctions. In this context, bilateral contracts should not be "settled" through a system based on the power pool price, as their prices are agreed upon outside the centralized market.

The table 3.4 aims to reflect a hybrid model within the European market, where both bilateral transactions and organized markets coexist. In this model, bilateral contracts are primarily used for long-term agreements, while short-term transactions are conducted through organized markets, such as the power exchange. This combination allows for the integration of the strengths of both mechanisms within a single market system. While the European market does utilize elements of central scheduling and central dispatch, particularly in real-time balancing markets, it generally relies on a hybrid approach. The market also employs a combination of organized market mechanisms (such as power pool or market exchanges) and bilateral contracts, reflecting the diversity and flexibility inherent in the European electricity market.

3.4 Process Summary

In this thesis, a novel approach using the two-layer morphological boxes with an actors' plane is implemented as shown in Figure 3.4. It explains how the two morphological boxes, the actors' plane and the objectives are collected. All this information, in conjunction with the standard CCA table, constitutes Artifact 1.

The GMA for the EMs categorization process assesses the answesr to the three research questions proposed for this chapter. The process illustrated begins when a researcher or stakeholder uses the morphological box for electricity market categorization to select a configuration of the electricity market design under evaluation. In this process, one characteristic from each category is selected to delineate the entire electricity market framework.

Figure 3.4 illustrates the complete Artefact 1, which encompasses the first-layer electricity market categorization morphological box, the second-layer MB for new market rules, and the actors' plane, detailing the roles of various stakeholders within the power system. The actors' plane is a unidimensional plane that organizes elements along a single logical or conceptual dimension, even though it is visually represented in a two-dimensional space. This approach facilitates the exploration of existing roles as well as the potential roles that could be introduced in a new market implementation.

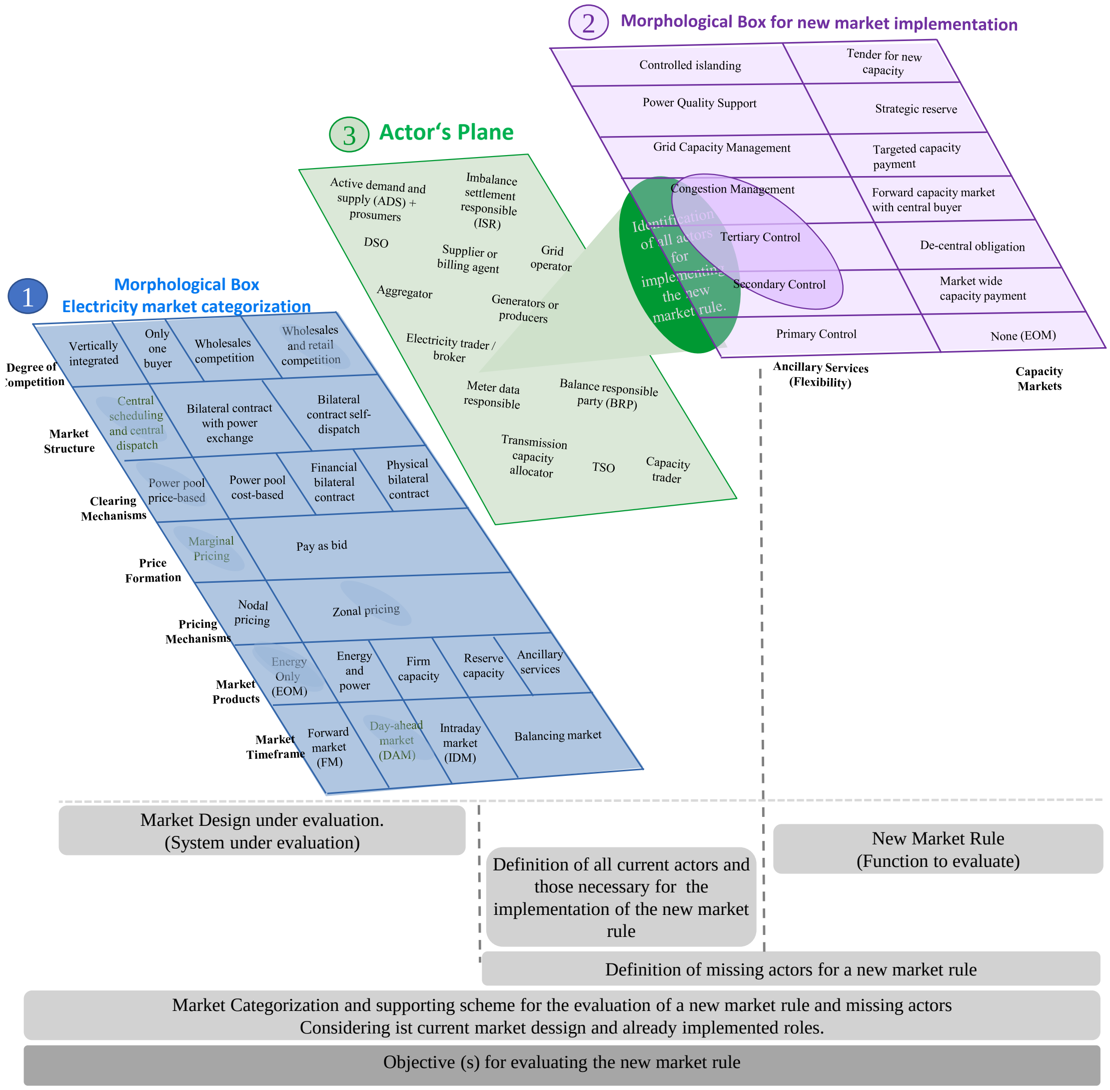


Fig. 3.4.: GMA for the Electricity Market Categorization Process

3.5 Conclusion

In this chapter, the first artifact is presented, based on a novel *two-layers morphological box approach* for a general morphological analysis. The method begins with identifying the most important characteristics of electricity market designs. The first-layer collects the information about the market and allows the definition of the market design under evaluation. The second-layer presents the possible new market characteristics to implement. An actors' plane is proposed to identify current actors and any potentially missing roles necessary to successfully develop the new market rule.

The implementation of the CCA reduces the solution space for different electricity market designs by 38%, and highlights the configurations that are normative constrained and extremely unlikely. Consequently, it assesses carefully the selection of the market design. Additionally, with the proposed second layer and the actor's plane the method facilitates not only the clear observation of gaps, but also the identification of possible missing roles as in the use case presented in [ALG22], summarized after applying the process illustrated in Figure 3.4, and whose results are shown in Table 3.4.

In addition, the presented artifact is used to set the basis for the foundation for a market class abstraction [Mau+23]. The market class abstraction is used as a further step of this research and pursues the further creation of simulation models that can support different market designs as proposed by this tool.

One observed limitation pertains to the ability to select only one market design or configuration at a time. At first glance, this may appear to impede the analysis of the impact of multiple market designs or changes. However, given that the primary purpose of the tool is to facilitate the delineation of markets before defining Key Performance Indicators (KPIs) that reflect these changes, it is anticipated that researchers or stakeholders will methodically define each market change and design to test and evaluate multiple impacts. This process should include the consideration of all relevant KPIs that best align with each market design.

Tab. 3.2.: Characteristics and Descriptions for the properties of the Morphological Box Electricity Market Categorization (Layer 1)

Morphological Box for Electricity Market Configuration		
Category	**Subcategory**	**Description**
Degree of Competition	A1- Vertically Integrated System	Only one company handles generation, transmission, distribution and commercialization without competition.
	A2- Single buyer	Opens the sector to competition in one sector, usually generation.
	A3- Wholesale competition	Market open for trading between generators and distribution companies, but only wholesale trading is allowed.
	A4- Wholesale and retail competition	Producers and consumers can actively participate in the market, allowing customers to choose energy suppliers.
Market Structure	B1- Central scheduling and central dispatch	Refers to a power pool with central scheduling of unit commitment.
	B2- Bilateral contract with power exchange	Refers to a bilateral contract model that implements central dispatch. These contracts could be financial or physical. It is also known as self-scheduling with central dispatch.
	B3- Bilateral contract and self-dispatch	Physical bilateral contract model with self-scheduling and self-dispatch.
Clearing Mechanisms	C1- Power pool price-based	Generators offer price and quantity for each time frame.
	C2- Power pool cost-based	Price formed based on marginal costs of last generation called to satisfy demand.
	C3- Financial bilateral contract	Traded between power producers or between producers and distribution companies, settled on price but not a physical delivery.
	C4- Physical bilateral contracts	Similar to financial contracts but with mandatory physical delivery.
Price Formation	D1- Marginal pricing	Price set at the intersection of offer and demand curves.
	D2- Pay as bid	Each generator paid according to its bid price.
Pricing Mechanisms	E1- Nodal Pricing	Each node of power grid has a price considering grid topology.
	E2- Zonal Pricing	Price calculated for area or zone without considering delivery points.
Market Product	F1- Energy Only Market (EOM)	Electricity-only market, generation is the commodity.
	F2- Electricity and power markets	Trading of power production and capacity.
	F3- Firm Capacity	Power capacity market to ensure long-term investment.
	F4- Reserve Capacity	Percentage of peak demand for capacity remuneration.
	F5- Ancillary Services	Market for primary, secondary, and tertiary reserves for balancing and regulation services.
Market Time frame	G1- Forward Market (FM)	Financial instrument with a delivery time ranging from days to years.
	G2- Day-ahead Market (DAH)	Trades for one day in advance.
	G3- Intraday Market (IDM)	Trading after DAH market is closed, with time frame ranging from hours to minutes.
	G4- Real-time or Balancing Markets	Markets for balancing real-time operation due to differences in production and consumption.

Tab. 3.3.: Morphological Box for Two New Markets (Layer 2)

Capacity Remuneration Mechanism	Ancillary Services (Flexibilities)
Tender for new capacity	Primary control
Strategic reserve	Secondary control
Targeted capacity payment	Tertiary control
Forward capacity market with central buyer	Congestion management
De-central obligation	Grid capacity management
Market-wide capacity payment	Controlled islanding
None (EOM)	Power quality support

Tab. 3.4.: Comparison of Markets by using the Electricity Market Categorization Morphological Box

Market Categories	European Market	Panamanian Market
Organizational Model	Wholesale and retail competition	Wholesale competition
Market Structure	Bilateral contract with power exchange (*)	Central scheduling and central dispatch
Clearing Mechanisms	Power pool price based	Power pool cost based
Price Formation	Marginal Pricing	Marginal Pricing
Pricing mechanisms	Zonal pricing	Zonal pricing
Market Products	Energy Only Market (EOM)	Energy and power
Market Timeframe	Day-ahead market (DAM)	Forward market (FM)
Actors Involved	All	Active demand and supply (ADS) + prosumers; Generators or producers; Grid operator DSO; TSO; Transmission capacity allocator.
Ancillary Services (Flexibilities)	Power quality support	Power quality support

(*) Bilateral contracts and power pool-based clearing mechanisms operate under distinct principles. Only the power exchange will be under the pool price clearing principle.

4 Bibliometric Analysis and Science Mapping

> *Science mapping goal is to reveal the structure and dynamics of scientific knowledge*
>
> — **Morris**
> Morris and van der Veer Martens 2008;

This chapter introduces a method for extracting KPIs aimed at supporting the assessment of changes within the electricity market, particularly those performed by means of smart grid trades. The overarching inquiry driving this chapter belongs to the second research question presented in this thesis: *How can relevant KPIs be identified for electricity market rules?*

To address this question effectively, a two-fold approach is proposed. First, it is essential to identify KPIs directly linked to smart grid functionalities, thereby relating them to their applicability within the power system. Therefore, the answer to the sub-question of *which KPIs are related to smart grid capabilities, and which are driven by market considerations* needs to be solved.

Once these KPIs are identified, the next step involves addressing the question *What is the relationship between the market rules and KPIs?*, which is necessary to classify which of those KPIs are influenced by the dynamics of the market.

This chapter presents a systematic methodology for representing the complex relationships between different electricity market rules and corresponding KPIs, elucidating their implications across diverse sustainability aspects within the power system. Bibliometric analysis and science mapping are the scientific methods used for the extraction and relationships for the concepts, as explained in Sections 2.3 and 2.4.

Hence, the chapter encompasses:

- A methodical process that implements bibliometric analysis and science mapping for both extracting and evaluating relationships between KPIs and smart grid functionalities.
- Compilation of a comprehensive catalog of KPIs, accompanied by correlation metrics grounded in sustainability aspects.
- Development of a coherent relationship map depicting interconnections among KPIs clusters and the sustainability aspects they assess.

4.1 Bibliometric Analysis Algorithms for Extraction of KPI

The first step in a bibliometric analysis aims to identify the key performance indicators that researchers use to evaluate smart grids and electricity markets. The use of an Application Programming Interface (API) is key for extracting the results of the queries from search engines. Implementing an API is preferable, even if in some cases, a subscription to databases is needed to request it. In the proposed algorithm (1), the search is implemented using the *SCOPUS API*. Nevertheless, the queries were also conducted using the editorial platform of the *Multidisciplinary Digital Publishing Institute (MDPI)* to access open-source journals.

As a preliminary step, this algorithm is used to conduct a general search focused on the keywords "Electricity Markets" and "Smart Grids". This broad scope provides an overview of the sub-topics related to them and the research trends from recent years. Only articles, review papers, conference papers, books, book chapters, and technical reports written in English or Spanish are included, while editorials, retracted documents, and notes are excluded.

Each retrieved document is then carefully examined, with close attention given to its title, keywords, authors, date, abstract, and number of citations. Similarly, the information regarding the abstract of the open-source papers is extracted. Data cleaning techniques are applied. In addition, a second review is conducted using the abstracts, keywords, and titles looking for specific terms related to KPIs such as "indicator," "metrics," "performance," or "KPI". Documents containing such terms are processed (downloaded and identified with a unique Paper ID). All data is stored for further analysis and reference. Documents that do not address electricity market applications or that do not propose any indicator or

Algorithm 1 Data Extraction and Review of KPIs for Smart Grid Capabilities, and Electricity Markets

Require: SCOPUS API key, List of keywords $Keywords$
Ensure: Clustered information $ClusteredInfo$

Connect to SCOPUS API using API key
$ScopusPapers \leftarrow$ SearchPapersInScopus("Electricity Markets AND Smart Grids")
$KpiInfo \leftarrow \{\}$
for all $paper \in ScopusPapers$ **do**
  if ContainsKeywordsInTitleAbstractKeywords($paper$, "smart grids", "electricity market") **then**
    if ContainsIndicatorsOrKPIsInAbstract($paper$) **then**
      DownloadPDF($paper$)
      ExtractTextFromPDF($paper$)
      ExtractSurroundingText($paper$, "indicator", "KPI")
      Extract $Title, Abstract, Keywords, Authors, Citations$ from $paper$
      $PaperID \leftarrow$ GenerateUniqueID()
      Save $Title, Abstract, Keywords, Authors$ into file with $PaperID$ in $CompletePapers$ folder
      $KpiInfo[paper.id] \leftarrow \{indicators, smart\_function, elect\_market\}$
    end if
  end if
end for
return $KpiInfo$

KPI are excluded. Additionally, the body of the text is reviewed for available open-access papers.

The information is then stored as *.csv* and as a*.ris* file to perform a bibliometric analysis. The *VOSviewer* software is used to elaborate keyword co-occurrence maps. This serves to depict the relationships between keywords as shown in Figure 4.2, where $k = 5$ is the occurrence variable. This means that the keywords need to appear at least 5 times within the data to appear in the diagram. The size of each term depends on the frequency of occurrence. Additionally, a thesaurus file is used to merge similar terms and to change plural forms to their singular form. Finally, the most relevant keywords based on their occurrence and strength to other topics are shown in Figure 4.1. *Query 1817* is the selected query for analysis. All queries and extracted data are found in the git repository and the main queries are listed in Table A.3.

Main Query for clustering (query 1817)

SCOPUS Query with the following search constrains: "*electricity*" ***AND*** "*markets*" ***AND*** "*smart*" ***AND*** "*grids*" ***AND*** "*key*" ***AND*** "*performance*" ***AND*** "*indicators*" ***AND*** *PUBYEAR* $<$ "*2023*" provides a total of 1817 papers.

To understand the structure of the electricity market research, additional queries are implemented to refine the pre-selected topics, which are flexibility markets and capacity mechanisms. Utilizing only the keywords, more than 110 different main topics are identified. These topics are then grouped and reviewed. Some topics are considered out of scope, even if they use the term *smart grid* but do not propose its applicability in the electricity markets or do not propose any key performance indicators. Some *out-of-scope* topics are related to the development of different techniques for hydrogen technologies, full cells, carbon trading markets, or gas technologies.

4.1.1 Clustering

To define the KPI clusters, the functionalities of smart grid implementations and their descriptions across various topics were utilized. Additionally, some main characteristics of smart grids presented in [Har17; CED+21; Fra+17] are included, along with research trends for new market rules as referenced in Section 3.1.3. Moreover, stored topics and pre-visualized keyword maps derived from the bibliometric analysis are employed to set the definitions for each cluster.

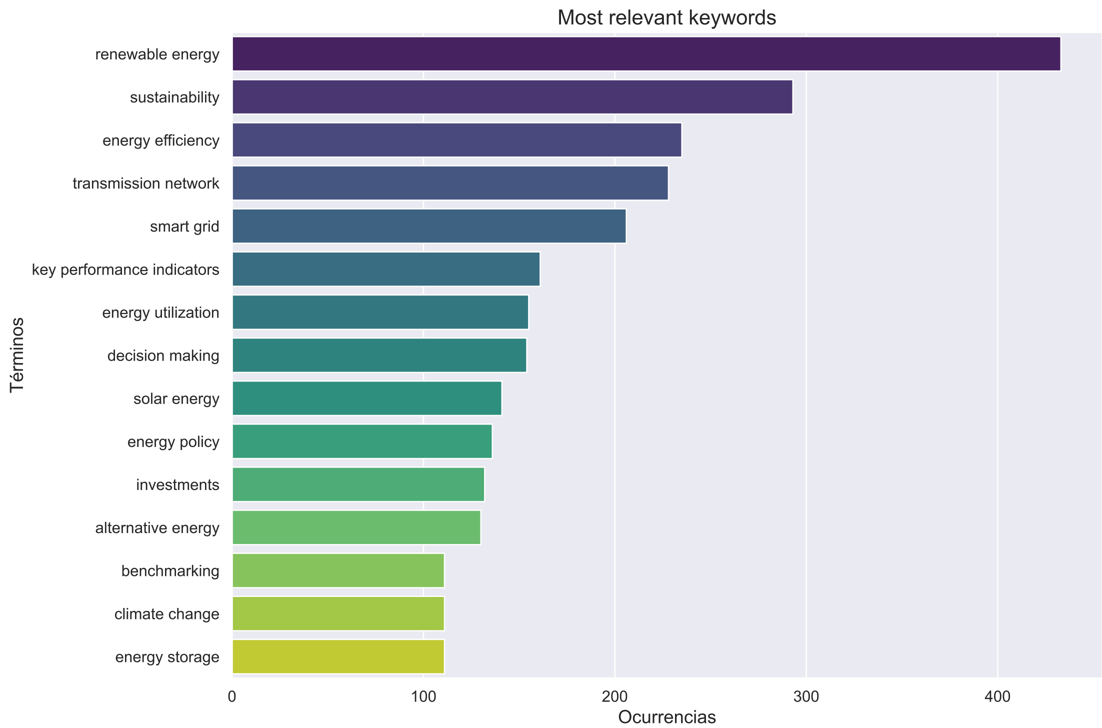


Fig. 4.1.: Most relevant keywords for query 1817

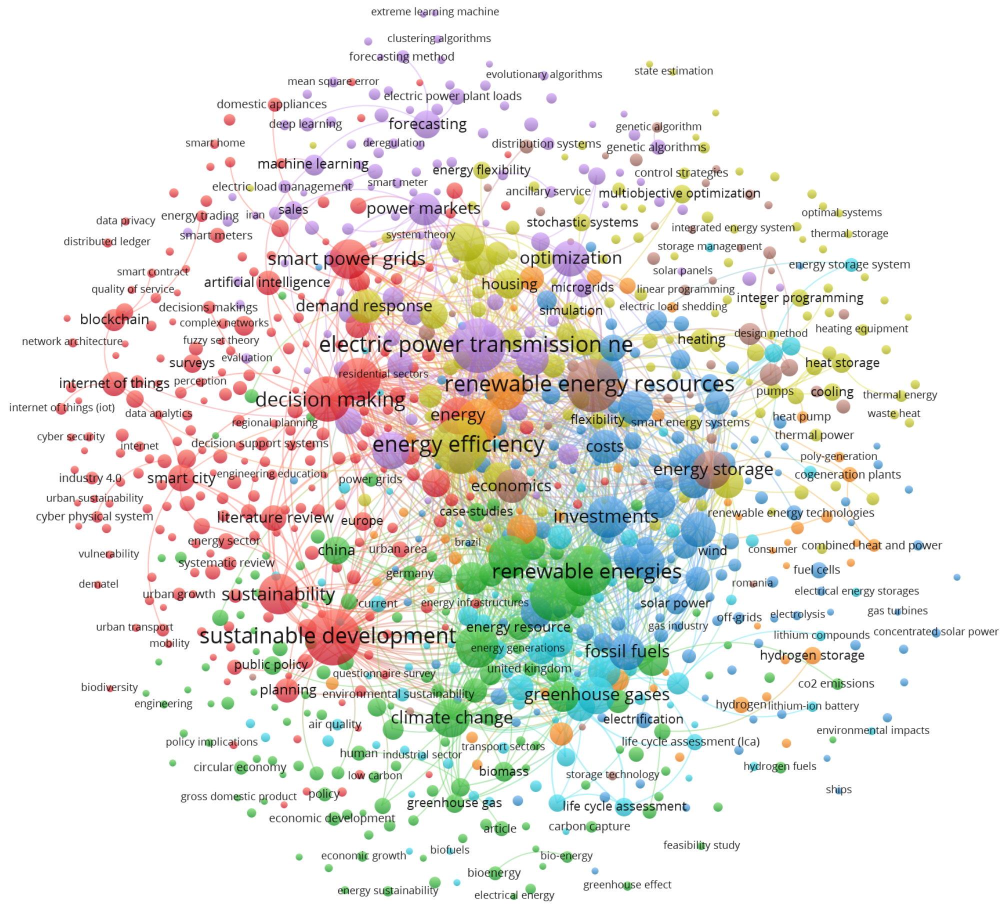


Fig. 4.2.: Keyword Co-occurrance map of k = 5. Data source: Scopus search 1816 "*smart grids*" *AND* "*electricity markets*".

The definition of the clusters based on smart grid functionalities and its description used for its organization are presented as follows:

(i.) **Renewable energy integration:** This cluster relates to indicators for the promotion and usage of distributed energy resources (DER). It includes topics like renewable energy integration and renewable resources such as solar, wind, hydro, PV, among others. Additionally, all possible indicators for mitigation actions to avoid climate change, reduce greenhouse gases, and support the energy transition are included. This includes the proposed indicators for the **SDO!** (**SDO!**) *7. Affordable and clean energy*.

(ii.) **Active system management:** This cluster includes KPIs related to the smart grid capabilities, such as the capabilities of observing and controlling actively the grid assets and several resources. Distinctions between real-time and non-real-time data-sharing and control capabilities are assessed separately, with the intention to further consider different degrees of smartness in the system. Additionally, it includes KPIsfor assessing the inclusion of smart meters with and without controlling capacity among different actors or assets in the power grid.

(iii.) **Transmission System Operator (TSO)-Distribution System Operator (DSO) coordination capabilities:** This cluster includes KPIs that depict the need for coordination capabilities between TSO and DSO. It can be related to the coordination needs between those actors and the Balance Responsable Party (BRP) and the needs or abilities for balancing mechanisms. This cluster is also related to the *Transparency data access sharing* cluster.

(iv.) **Capacity payments:** This cluster encompasses KPIs that represent specific payments for capacity to ensure the system's reliability. It includes KPIs proposed for direct capacity payment, capacity auctions or tenders for new capacity, with or without a target capacity payment, the requests of strategic reserves, and the forward capacity market, including the categories and definitions indicated in 3.1.3. In this cluster, keywords and topics related to transmission capacity rights are included.

(v.) **Market structure and bidding:** This cluster encompasses indicators that are related to the structure of the electricity market, such as market liquidity, electricity directly traded, growth of market trading power and Herfindahl–Hirschman Index (HHI) for market concentration. The Herfindahl–Hirschman Index (HHI) measures market concentration by summing the squares of firms' market shares, indicating competition levels: higher values suggest greater concentration and less competition. Additionally this cluster is divided into two sub-clusters: power grid and bidding. The sub-cluster *power grid* encompasses indicators typically used to assess the behavior and general properties of the electricity market. Nonetheless, the sub-cluster *bidding* groups indicators impacted only when a bidding mechanism is in place.

(vi.) **Balance mechanisms and balance responsibility:** This cluster considers KPIs that can be used to evaluate the impact of balance mechanisms for TSO's or between balance responsible parties, such as an acceptable imbalance rate, balancing group deviations rate, or nominated balancing group position. This cluster is also related to the cluster *acTSO-DSO and coordination capabilities* and transparency in data access sharing.

(vii.) **Customer benefits and customer inclusion:** This relates to all the KPIs that include customer services, customer participation, and customer benefits. Additionally, it encompasses the participation of neighborhood grids or energy communities and their capability to have peer-to-peer contracts or to offer grid services. In addition, some reliability indicators that have an impact on the customer benefits, like *Customer Average Interruption Duration Index (CAIDI)* or *Customer Average Interruption Frequency Index (CAIFI)*, are also considered into this cluster.

(viii.) **Reliability and quality of supply:** This cluster encompasses all reliability and quality of supply indicators from the grid perspective, for the distribution grid or transmission grid. This cluster has a direct relationship with *system indicators*, but a separation is made to distinguish their measurements from other system properties. Some examples are the *System Average Interruption Frequency Index (SAIFI)* and *System Average Interruption Duration Index (SAIDI)*.

(ix.) **Flexibility/Local markets:** This cluster involves KPI for the establishment and support of local markets or flexibility markets, independent of the traded product or service. It encompasses a broad range of products, including active or reactive power provision, procuring ancillary services, or ramping capabilities. Furthermore, the activation purpose may stem from the necessity of local reactive support, grid balancing services, and congestion management, among others.

(x.) **Prosumer trading:** This cluster encompasses KPIs for assessing the impact of prosumers on different markets. It also includes KPIs related to neighborhood grids, energy communities, or self-sufficient communities specifically focused on the payment mechanism incorporated for these trades. This cluster has a relationship with the *customer benefits and customer inclusion* cluster, but the main distinction lies on relating these benefits and inclusion to the peculiarity of being a customer with decision-making power.

(xi.) **System indicators:** This cluster groups mainly power system indicators proposed for the evaluation of the grid or topology, like *capacity factor*, *hosting capacity*, *market concentration index*, *Market benefits*, among others [Zen+18; Com+22]. Additionally, it is related to *customer benefits* and *power quality*. Some of the indicators such as SAIDI, CAIDI, SAIFI and efficiency measures that show a very strong social aspect present a relationship with this cluster. The main distinction between this cluster relies on the representation of grid conditions. Additionally, a sub-cluster can be created for specific evaluations, such as the evaluation of the power grid with and without flexibility mechanisms, supporting the comparison between different price mechanisms like a bidding process or a cost-based approach.

(xii.) **Transparency of data and access sharing:** This cluster relates KPIs which depict the ability to share data between different actors in the power system. Distinctions between real-time and non-real-time data are considered since the time frame is crucial for the market products to trade.

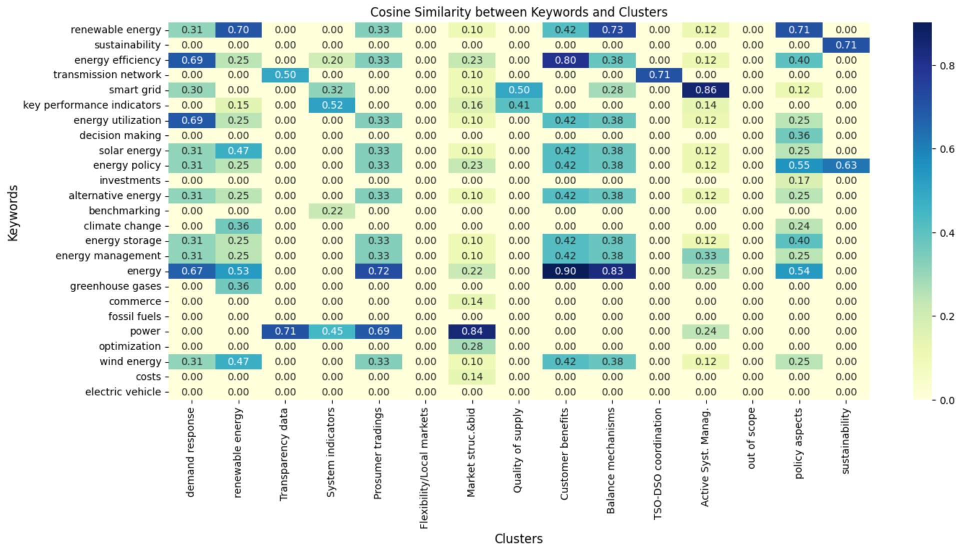


Fig. 4.3.: Relationship between keywords and clusters

4.1.2 Relating Main Keywords to Smart Grid Clusters

To determine the relationship between the smart grid functionalities (clusters) and the research topics, a co-word analysis is implemented between the most significant keywords from the queries and the smart grid clusters for the KPIs. The degree of similarity between keywords extracted from the queries and the smart grid clusters is used to calculate correlations. The values of the co-relationships are calculated using the cosine similarity between those vectors. The values support the expected relationship between the topics of discussion and the smart grid capability. The higher the cosine of the distance between the vectors, the stronger the semantic co-relation between the keyword and the KPI cluster. Certain *keywords* are indicative of a single cluster, showing no correlations with others, while others are more representative in multiple clusters. Conceptually, the same process is established to relate later the definition of each KPI encountered with the clusters by using the representative equations and terms for each KPI.

The cosine similarity between the vectors $keyword$ and $smartfunctionality$ is given by:

$$\text{Cosine Similarity} = \frac{keyword \cdot smartfunctionality}{||keyword|| ||smartfunctionality||}$$

Here, $keyword \cdot smartfunctionality$ denotes the dot product of vectors $keyword$ and $smartfunctionality$, while $||keyword||$ and $||smartfunctionality||$ represent the magnitudes of vectors $keyword$ and $smartfunctionality$ respectively. The result is the similarity between the keyword and the smart grid functionality (cluster).

NLP algorithms implemented in *Python* are used to tokenize the vectors and to calculate the correlations. The algorithm 2 depicts the process. Heatmaps shows the dispersion of the topics within the clusters and the keywords. Figure 4.3 depicts the relationship between the most frequent keywords processed after creating the co-word analysis from *VOSviewer* for different queries.

A similar process is conducted to determine the relationships between the cluster and the extracted KPI proposed and used in several papers. One of the major challenges in the method is that the abstract's information is usually insufficient to determine if key performance indicators are proposed within the text of the paper. In addition, since the query was too broad, a refinement of the query is needed to specify the particularities of the market under analysis for specific conditions.

Therefore, a refinement of the search algorithm for a specific market design is performed. Only the documents with content regarding indicators are selected. The text must be carefully reviewed, especially to understand if the KPIs are used to assess a specific market design. In addition, the relationship between the proposed indicator and the implemented market and its impact on sustainability aspects needs to be determined.

4.1.3 KPI Extraction for Different Market Types.

To obtain *Key Performance Indicators for the Evaluation of Smart Grid-Based Electricity Markets Considering Sustainability Aspects*, the algorithm 3 is implemented. A review of

Algorithm 2 Keyword-Function Relation Using NLP

Read Input Data:
Read a .csv file containing *keywords* and their frequency of occurrence.
Identify the keyword with the highest frequency of occurrence.
Define Smart Grid Functions:
Read a .txt file with the set of functions related to smart grid aspects (clusters) and their descriptions.
Text Pre-processing:
Pre-process *function descriptions* and keywords to remove special characters, convert text to lowercase, and tokenize the text into individual words.
Text Vectorization:
Utilize a text vectorization model (such as TF-IDF) to convert *function descriptions* and *keywords* into numerical vectors.
Calculate Cosine Similarity:
Compute the cosine similarity between each keyword and *function descriptions* using the generated numerical vectors.
Associate Keywords with Smart Grid Functions:
For each keyword, identify the *smart grid function (cluster)* with the highest cosine similarity to that keyword.
Generate Visualizations:
Create visualizations (e.g., bar charts) for the relationship between *keywords* and *smart grid function (cluster)* based on cosine similarity.
Generate a heatmap showing similarity between each keyword-function pair.
Associate Keywords with Smart Grid Functions:
For each *keyword*, identify the *smart grid function (cluster)* with the highest cosine similarity.
Print and Store Results:
for all *keywords* **do**
    Get the index of the *smart grid function (cluster)* with the highest similarity score.
    Get the corresponding *smart grid function (cluster)*.
    Store the result.
end for

major research contributions is conducted to identify scientific documents relevant to a specific market or new rule.

Algorithm 3 Integrated Algorithm for Reviewing Papers and Extracting KPIs

```
Require: SCOPUS API key, List of keywords Keywords
Ensure: Clustered information ClusteredInfo
Connect to SCOPUS API using API key
ScopusPapers ← SearchPapersInScopus("Electricity Markets AND Smart Grids")
ClusteredInfo ←
for all paper ∈ ScopusPapers do
  if ContainsKeywordsInTitleAbstractKeywords(paper, "smart grids", "electricity market") then
    if ContainsIndicatorsOrKPIsInAbstract(paper) then
      Extract information from paper
      title ← GetTitle(paper)
      abstract ← GetAbstract(paper)
      keywords ← GetKeywords(paper)
      indicators ← ExtractIndicators(title, abstract, text)
      Initialize smart_grid_capabilities, elec_market_type
      ClusteredInfo[paper.id] ← indicators, smart_grid_capabilities, elec_market_type

      if indicators not empty then
        for all indicator ∈ indicators do
          capabilities ← DetermineSmartGridCapabilities(indicator)
          smart_grid_capabilities ← smart_grid_capabilities ∪ capabilities
          market_type ← DetermineElectricityMarketType(indicator, keywords)
          if market_type empty then
            market_type ← "Notmarketrelated"
          end if
          elec_market_type ← elec_market_type ∪ market_type
        end for
      end if
    end if
  end if
end for
return ClusteredInfo
```

The algorithm performs queries in search engines, specifying a market type or new market intention, such as flexibility markets in distribution systems, capacity markets, and others. The articles that meet the search criteria are processed as explained in Algorithm 3, similar to the first algorithm used for the broad search. The text extracted from the papers after compliance with the query is evaluated by searching within the text for the words: *indicators, metrics, performance, and KPI*. Text that contains information related to KPIs is selected for further review. Similarly, a bibliometric analysis is conducted to identify the main keywords and the relationships between the proposed indicators within the paper and the predefined smart grid functionalities (clusters) proposed in Section 4.1.1. The stored text and the complete papers are reviewed to determine if the proposed KPIs have been used for the evaluation of a particular electricity market based on implementing smart grid technologies. The data is cleaned to extract the KPIs that were used for specific market implementations. A database is created as a compilation of all KPIs mentioned, along with related information such as authors, paper title, and paper identification number. An example of the methodology has already been implemented for flexibility trading schemes, which in the literature are known as flexibility markets.

4.2 Sustainability Plane

A sustainability plane is proposed to map the KPIs based on their impact on the four sustainability dimensions, as mentioned in Section 2.2. The corners of that plane represent each sustainability aspect. Since every KPI demonstrates influence on several topics, a mapping technique must be considered. To represent the main relationships in each aspect, the following considerations and examples are illustrated:

(i.) **Social dimension**, following the definitions presented in section 2.2, this dimension aims to assess social well-being beyond the scope of social welfare [Com+19]. It includes access to reliable and affordable quality energy services. It also involves customer engagement in the energy system through various means, including demand-response mechanisms [Dom+22], building flexibility [Air+21], prosumer participation, or the capabilities to actively participate in electricity markets. The main KPI is the Maximal Social Welfare with constant (relative) inequality aversion[BGG22]. To relate KPIs to this dimension, the following words in predefined semantics are applied to the definitions of the indicators: *customers, participants, actors, clients, consumers, demand, retail, aggregators, community, neighborhood, citizens, services, meters, buildings, demand response, prosumers*. Other words are also used to determine weaker capability, as they relate to social externalities to some extent. However, depending on the applicability of the KPI, they could also strongly represent other dimensions. These words and topics are: *efficiency, distributed, local, distribution, electrification, load, and relationship of the DSO with other actors*. In this dimension, it is evident that most KPIs are associated with three primary domains: customer-centricity, market dynamics, and grid infrastructure. For instance, indicators such as the community's market share savings, auction participation rates, and smart meter penetration levels are examples of indicators that represent the social dimension within these core areas.

(ii.) **Environmental dimension**, as mentioned in Section 2.2, relates to KPIs which support the evaluation of environmental externalities such as the use of clean energy technologies and the degree of reduction of greenhouse gases (GHG). Therefore, indicators related to the deployment of local renewable resources or that explicitly assess the evolution of emissions in the power sector directly impact this dimension. The environmental dimension is not limited to the generation of electricity, but also include the consumption and use of energy, such as the deployment of strategies to enhance energy efficiency. To relate KPIs to this dimension, the following words in predefined semantics are applied to the definitions of the indicators: *renewable, DER,* CO_2*, emission, RE, GHG, weather, seasonal, natural resources, predictability, curtailment, diversity, local and clean*. Other words such as *efficiency, self-sufficient, peak*, depending on the context and the equations could also present a weakerrelationship depending on the context and the equations.

(iii.) **Economic dimension** as mentioned in Section 2.2, relates to KPIs used to evaluate the economic aspects of the power system, particularly the economic implications arising from differences in market mechanisms. For example, variations in price-remuneration schemes for flexibility services are considered. Several technical aspects are directly associated with this dimension, as a cost-benefit analysis is typically conducted before implementing a new technical component in power systems. Moreover, market power implications and economic withholding indicators are also examined. The words utilized in the predefined semantics are *cost, payback, earnings, expectation, marginal, deviation, balance, position, share, bid, auction, trading, and price*, in addition, all operational wordings are considered related to the economic dimension with special consideration. These words are: *power, since it could represent different contexts, growth, provision, variations, hosting, operation, reserves, ramp, programmable, lost, efficiency, reliability*.

(iv) **Policy/legal dimension** aims to ensure the appropriate institutional framework and regulations to promote key aspects to achieve the energy transition (energy

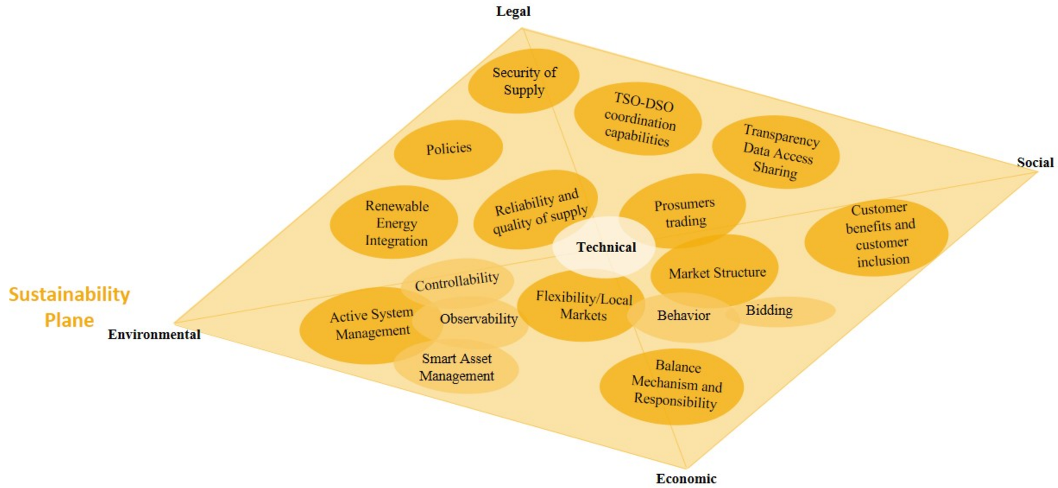


Fig. 4.4.: Sustainability Plane and Smart Grid Clusters without Relationships.

policy or political goal). The KPIs strongly linked to the policy dimension are those that ensure the security of supply through the deployment of renewable energy resources, manage interconnection policies, allow integration of common trading frameworks and regulations, implement carbon neutrality regulations, introduce social externalities into the power system, and create a legal framework for transparency within the power system. Depending on the applicability of the KPIs, the words that are strongly related to this dimension are: *interconnection, regulations, barriers, fulfillment, coordination, transparency, sharing, import, planning, regulation, border*. The concepts of *security of supply, policies, and institutionality* are also related to this dimension.

For each of the four sustainability dimensions, the technical dimensions are mostly implicit for every KPIs. Nevertheless, a set of KPIs that support the degree of smartness of the distribution system is also implemented to establish the basis for the technical capabilities. For example, smart grid technologies implemented in the distribution system are to provide a certain degree of observability and controllability in real time. It is worth mentioning that the *legal/policy dimension* is added to the sustainability assessment to support the identification of regulatory lags.

4.3 Smart Grid Market KPIs: Linking Indicators to Sustainability via Science Mapping Tools

The diverse market mechanisms exert varying influences on the four dimensions of sustainability. Some market mechanisms or market designs focus more on the economic aspects without paying attention to environmental constraints or social impacts, while other market mechanisms are more customer-oriented. In addition, every indicator can influence several sustainability dimensions to different degrees. Therefore, similar to the clustering section, it is necessary to identify the relationship between each KPI and its effects on each sustainability dimension.

The figure 4.4 depicts the different clusters proposed in Section 4.1.1 and the proposed sustainability plane. The relationship between them and each KPI found in the literature must be defined, following the methodology explained in 2.4.

The detailed process involves using predefined semantics and Natural Language Processing algorithms to find a relationship between each KPI extracted from a specific query and its cluster. Additionally, the texts proposing these indicators are reviewed to assess their interrelationships and their alignment with the electricity market in which they were implemented.

Science mapping is also used to evaluate the relationship between each indicator and the four sustainability dimensions. Science mapping is a tool that *examines the relationships between research constituents [Don+21]*. Science mapping, as explained in Section 2.4, uses citations, chains or networks, co-wording methods, co-citations, and word analysis to find influence across research questions.

Each KPI is evaluated with the co-word analysis to determine its degree of relationship to various smart grid capabilities. Figure 4.5 illustrates the process of extracting specific data from multiple search engines, processing all scientific papers and technical reports, and other relevant open source documents on smart grids and electricity markets, and collecting KPI information within the text if proposed in the paper. The degree of relationship is then established through a qualitative assessment based on the words defining the KPI and its equation. The degree of relationship between each KPI and the sustainability aspect is determined by carefully evaluating the KPI's underlying equation, its representative meaning, and its application in the context of this paper. This relationship is categorized as strong, weak, or nonexistent for each KPI in relation to the sustainability dimensions. This information aids in developing metrics to assess the strength of each KPI in evaluating specific sustainability dimensions.

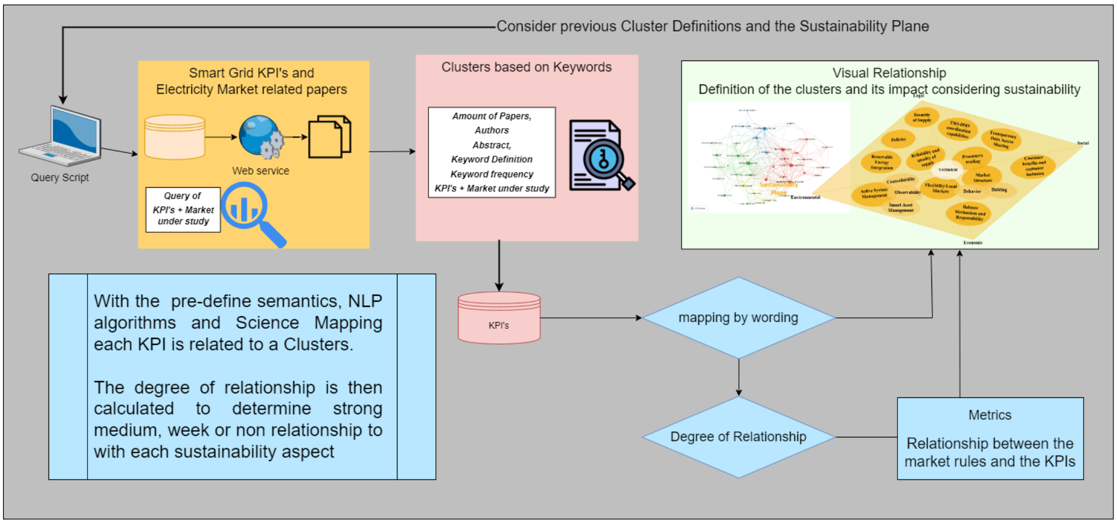


Fig. 4.5.: Relationship between the KPIs to their respective smart grid cluster and each sustainability aspect

The KPIs found are stored in a database with the related information about its source and a unique paper identifier (ID). Then, using visualization tools, the bibliometric relationships are created based on the main keywords of the KPI encountered in the papers. This process supports the relationship between topics for those KPIs, specifically if they are related to a particular market design or mechanism.

The database is cleaned to avoid duplicate indicators. A key challenge in this process is identifying related terms and variations in phrasing used to present the KPIs. To demonstrate the applicability of this method, a use case is presented, and published by the author of this thesis in the scientific paper [Aco+23a].

All the extracted indicators are grouped based on the sustainability aspects. Since one indicator can impact multiple aspects, weights are assigned to the indicators for a strong, medium, or no relationship for each aspect.

In the following subsections, the most relevant indicators, particularly those related to a query regarding flexibility markets, are extracted and discussed. The complete list of indicators and tables is available online in a Repository.

Fig. 4.6.: QR code for accessing the KPI Compendium repository

4.4 Use Case for Flexibility Markets in Distribution Systems.

Flexibility services enhance the reliability of the power grid and support various operations, such as self-balancing, voltage and reactive power control, congestion management, *islanding control*, and power-loss management, among others [Oli+18]. Additionally, research has explored how prosumers, neighborhood grids, and electric vehicle charging stations can aggregate their resources to offer flexibility in addressing grid issues [Aco+23a]. Furthermore, grid operators implement *redispatch* measures to optimize resources in response to renewable energy variability and to defer grid expansion investments.

Flexibility markets can serve various purposes within the power system. To comprehend and select the KPIs relevant to the behavior of flexibility markets considering different trading mechanisms, the logic presented in 3 is employed. The search criteria involved combining the outcomes from the data engines *MDPI* and *SCOPUS*, using keywords such as '*flexibility electricity markets*', '*indicators*', and '*performance*' to extract relevant data. The data are limited to flexibility markets specifically designed for distribution systems. This scenario serves as a practical demonstration of the methodology proposed in this thesis, to test the implementation of new flexibility markets, as published by this thesis author in [Aco+23b]. The scenario, queries and the possible market compensation mechanisms evaluated for the flexibility offers in the distribution grid, are presented in this section.

Additionally, the tool *VOSviewer version 1.6.19* is used to construct and visualize bibliometric networks. Duplicated papers are eliminated in the process. Papers that do not propose flexibility mechanisms for distribution grids or for balancing between distribution grids are excluded. Papers without any proposed indicators or metric are also excluded. The same clusters presented in Section 4.1.1 are used to organize the indicators from the papers.

To find the relationships of the occurrences within the text, equation 4.1 is used. The number of occurrences of the indicator's name is represented as (semantic unit u_k) within the corpus segment (s_i) of the abstracts and keyword (extracted text) of all the papers. The set of all topics is represented as $j \in 1, \ldots, J$ where J represents the topics to be distinguished [Van+10].

$$\rho(t_j \mid u_k) = \frac{n^j k}{\Sigma n^j k} \tag{4.1}$$

A co-word analysis is carried out to examine the content of the papers and support the creation of knowledge-related maps. These maps can show the relationships between important terms in the field and the sustainability aspects by identifying terms using bibliometric mapping [Van+10].

To evaluate new trading mechanisms for flexibility services, it is necessary to consider the characteristics of the flexibility products available. These characteristics influence the design of the market for its trading. [VBM18] proposed a taxonomy for flexibility products, organizing them into three groups: balancing flexibility in the transmission grid, balancing flexibility in the distribution grid, and flexibility for the distribution grid. Additionally, in [HKW20] certain flexibility services are related to existing markets, for example, the market for ancillary and/or backup services, but acknowledging the need to enhance such exchanges. Hence, the evaluation of use cases for flexibility markets needs consideration of the products essential for appraising the design of flexibility services tailored for (DSO and TSOs) [VBM18; HKW20].

Furthermore, flexibility characteristics such as *ramp rate*, *delivery time*, *controllability*, *location*, and *duration* [UA15], play a significant role in determining products that can be offered in a particular market. Therefore, these characteristics need to be examined through the performance indicators.

Smart Grid's key performance indicators have already been implemented to evaluate projects in distribution systems. However, they do not focus on market aspects, nor do they consider the social, environmental, and economic impacts of implementing new flexibility markets. Furthermore, electricity market indicators focus more on the economic, technical, and environmental aspects while neglecting the social and political aspects, which are deemed necessary for a sustainable and holistic evaluation [SS16].

In addition, the remuneration mechanisms and market considerations for flexibility have been discussed by several authors. [Hir+19] proposed a cost-based compensation mechanism for flexibility, while other reports consider that it is difficult to integrate flexible mechanisms into a regulatory cost-based approach [Win20]. For this reason, the flexibility market clearing mechanisms and new rules to be evaluated for trading flexibility in distribution grids within this use case include: Cost-based Market Mechanism, Bidding Market, Capacity Market, and Bilateral Contracts (Peer-to-peer).

The use of KPIs has also been implemented to evaluate markets [Ken+21; Ame04] and to evaluate the need for flexibility in the retail market, [KB16; Di +22; Bhu+22]. In addition, [Pra+19b; SZ19] consider the use of indicators for evaluating the sustainability of the power system. However, no KPIs have been proposed for the evaluation of different flexibility markets models considering the *economic*, *social*, *environmental*, and *legal* aspects of the power grid. Therefore, in this use case, the methodology here proposed is applied to find the KPIs that are smart-grid-related and support the analysis of flexibility markets in the distribution grid. The result will provide a database of KPIs that can be used to assess various aspects of the potential trading mechanisms for flexibility products, considering their impacts on sustainability aspects. The purely technical KPIs for distribution grids presented in [Har17] are considered, after extending them to include the evaluation of flexibility markets.The description of the structure, the trading products and the clearing prices that can be implemented to trade flexibility are based on the taxonomy presented in [DSS21] and on the considerations of [HKW20; SM20; Val+21]. The electricity market categorization framework is elaborated using the general morphological approach presented in [ALG22]. DSO-TSO capabilities are excluded from the final results of the KPI evaluation for this use case. The considerations gathered from a literature review to assess flexibility markets are summarized as in [Aco+23a]:

(i.) **Market Time Frame:** Real-time markets or balancing markets for distribution grid for intra-day and future markets (long term). This means that flexibility can be offered from seconds up to a few hours in the short term and months in long term.

(ii.) **Clearing and Pricing Mechanisms:** Physical and financial bilateral contracts, including peer to peer contracts, auctions based (pay-as-bid or pay-as-cleared), supermarket mechanism; centralized optimization (power pool cost-based approach) and fixed remuneration (cost-based).

(iii.) **Market Products:** Energy trade or utilization offer (capacity trade), both (energy and power), in addition the availability offer (the price in €/MWh for availability), the utilization offer (the price in €/MWh for utilization) as well as the maximum running time [SM20].

(iv.) **Market Objective:** Grid capacity management market or congestion management and Power quality support market, for example for Voltage control and for control *islanding*. However, this functionality is not to be tested in this use case.

For any flexibility products, it is important to consider the direction, since it could withdraw or generate the ramp-rate capacity (MW/min), the ramp duration (min), and the energy and power provision capacity of the resources. And for market rules, the minimal bid, incremental bid, price cap, fixed remuneration, and peak time rebates are considered [HKW20; Eid+16].

Each indicator is evaluated according to the relationship with the different market models. The compensation method or market characteristics selected for clustering the KPIs are the following:

- Cost-based compensation
- Bidding market
- Capacity market
- Bilateral contracts or peer-to-peer

The KPIs are related to the four (4) dimensions and organized by their topic of impact on the proposed cluster. To relate the indicators to the market mechanisms and to the clusters, a weighting method is used. The relationship is weighted considering the calculation procedure (equation for calculating the indicator) and its impact according to the authors that proposed the KPI using the bibliometric analysis. Each indicator is evaluated with a sub-cluster and a cluster. This gave a total of 4824 combinations. The weights assigned to the relationships between the clusters are:

- No relationship between the selected pair: graded with zero (0)
- Moderated or indirect relationship between the selected pair: graded with one (1).

- Strong or direct relationship between the selected pair: graded with two (2).

Following the establishment of these relationships, the mean weight per indicator and the standard deviation (σ) are employed to gauge the degree of dispersion exhibited by each indicator in relation to its mean value. Furthermore, this analysis assesses the extent of interconnectivity between the indicator and other clusters. In particular, a higher standard deviation for one indicator suggests greater dispersion among the clusters, potentially indicating their association with a single cluster or topic rather than exerting significant influence across multiple dimensions or clusters.

Table 4.1 shows a summary of the metrics of all the KPIs found with the degree of relationship to different markets based on the amount of indicators and on the type of relationship (strong, weak, none). In addition, Table 4.2 presents a summary of the metrics between the KPIs found for each cluster. The number of KPIs found within the queries in each cluster and their references are also presented.

Tab. 4.1.: Key Performance Indicators metrics per Market Type under consideration.

Cluster	Amount of Indicators Directly Impacted	Amount of Indicators Indirectly Impacted	Avg. Weight of the Indicator	Std. Dev. σ
Cost-Based compensation	45	45	0.671	0.820
Bidding market	90	37	1.080	0.902
Capacity market	80	35	0.970	0.910
Bilateral contracts (Peer-to-peer)	38	24	0.497	0.794

Table 4.2 shows the complete relations between KPIs per cluster with its metrics. The line *References*, under each cluster, presents the citations of the papers in which KPIs were proposed. Some references are presented in several clusters; this is the case of [Bra+22; Har17]. This because the the KPIs for smart grid applications were proposed without indicating its usage for a specific market assessment. To evaluate its applicability, qualitative assessments and predefined semantics are employed.

Results After conducting the bibliometric analysis, 87 papers are partially selected to extract KPIs in the smart grid domain, electricity markets for distribution grids, and other services. From these papers, 201 indicators are extracted and clustered according to their main impact. In addition, the identified indicators are used to assess the impact

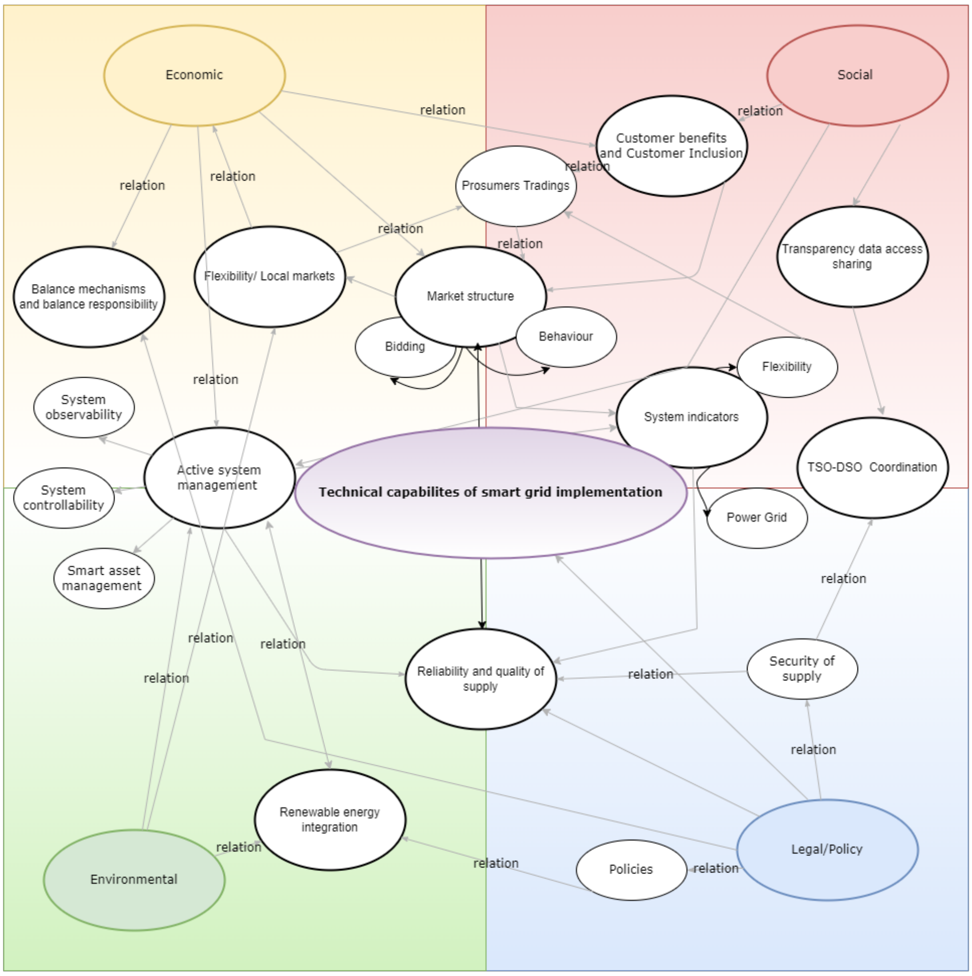


Fig. 4.7.: Relationship between the KPIs to their respective smart grid cluster and each sustainability aspect

on cost-based compensation vs. bidding markets. From the results the following can be emphasized:

- The percentage of scheduled flexibility has been used mainly in cost-based compensation and for the planning process.
- The power flow within the grid is a strong indicator in a cost-based market.
- The average production cost per MWh is a value needed for cost based compensation but omitted in bidding forms.

In contrast, when bidding mechanisms are implemented, indicators show a strong influence on the relationship with wholesale electricity prices, transmission capacities, and the directly traded power ratio vs. market-traded power ratio. The following insights are observable based on the KPIs that showed a strong relationship with bidding mechanisms [Aco+23a]:

- **Share of individual savings for trading in local markets:** This indicator supports a comparison between participation in the local market and the absence of a market. It supports the assumption that cost-based compensation will not incentivize the willingness to trade.
- **Market Concentration:** The Herfindahl-Hirschman Index (HHI) is applied to assess market concentration within distribution systems. For certain flexibility products, only a limited number of market participants may have the capability to provide the necessary rapid response and ramping capacities.
- **Real-time observability and controllability capabilities:** The presence of IT that ensures real-time observability and controllability is crucial to effectively transmitting appropriate market signals as necessary. Due to the need for fast response mechanisms, the technical infrastructure for the development of such a market is mandatory.
- **System Operators market coordination:** The coordination among system operators is essential to foster close collaboration with other market entities and mitigate potential gaming behaviors within the market framework.
- **Active and Reactive Power provisions market:** Evaluation of the increase in flexible active and reactive power provided to other network operators primarily

pertains to the establishment of reactive power markets and local markets. The duration required for the active and reactive clearing process of the electricity market is important, especially considering the shorter time frames involved [Con18].

- **Other indicators:** Various indicators, including auction participation rates, bid price estimations, earnings, risk analyses, and surplus market benefits, warrant careful examination within bidding mechanisms [Rad+18], [Dun+06].

After assessing all the KPIs found, two indicators are proposed as part of a holistic assessment for flexibility markets in distribution grids. This indicators were proposed in [Aco+23a].

- **Market activation needed to avoid grid congestion in flexibility markets** which relate to the energy traded when a market proposal is activated to avoid grid congestion from the distribution grid perspective.

- **Market activations needed to support voltage regulation in flexibility markets**, which relates to the market proposal to increase the voltage qualified rated or to support voltage regulation.

4.5 Clustering Indicators Based on Sustainability Dimensions: The Case of Flexibility Markets

As elaborated in Section 4, each indicator identified through this methodology can be associated with one of the four predefined sustainability dimensions. Using the same key performance indicators (KPIs) from the use case, each indicator is independently reviewed to determine its effectiveness in assessing sustainability dimensions. This section provides an overview of the indicators that can be related to these four sustainability dimensions. The complete list of indicators and their relationship is available in the repository [Aco+23a].

Tab. 4.2.: Key Performance Indicators metrics per cluster.

Cluster	N Direct	N Indirect	Avg.	σ
Active system management	63	48	0.866	0.864
References	[Bra+22; Har17; Far+21; KGG21; Dom+22; Vit+21; TB20; Zen+18; Con18]			
Balance mechanism and responsibility	26	22	N/A	N/A
References	[Bra+22; Har17; SZ19; Vit+21; Rad+18; Con18; Bhu+22]			
Customer benefits and customer inclusion	32	47	0.552	0.754
References	[Bra+22; Har17; Air+21; Okw+22; SZ19; Dom+22; Vit+21; Com+19; Ang+19; Zen+18; Con18; Bhu+22]			
Reliability and quality of supply	43	20	0.527	0.825
References	[Bra+22; Har17; Far+21; Vit+21; TB20; Ken+21; Rad+18; Con18; Bhu+22]			
Market structure				
(Behaviour)	23	18	0.318	0.669
References	[Bra+22; Sun+22; SZ19; Vit+21; Ang+19; Zen+18; Dun+06; Con18; Bhu+22]			
(Biddings)	40	37	0.582	0.803
References	[Bra+22; Air+21; Sun+22; Hir+19; HA11; KB16; SZ19; Vit+21; Ken+21; Ame04; Zen+18; Dun+06; Con18; Bhu+22]			
Flexibility/Local markets	74	31	0.890	0.915
References	[Bra+22; Har17; Air+21; Okw+22; SZ19; Dom+22; Vit+21; TB20; Ang+19; Zen+18; Dun+06; Rad+18; Con18; Com+22; Bhu+22]			
Prosumers tradings	6	5	0.398	0.735
References	[Bra+22; Har17; Okw+22; SZ19; Dom+22; Vit+21; Ang+19; Zen+18; Con18]			
Renewable energy integration	12	23	0.234	0.548
References	[Bra+22],[Har17], [Nou18; Vit+21; TB20; Zen+18; Bhu+22]			
System indicators				
(Power grid)	98	13	0.552	0.859
References	[Bra+22],[Har17; Air+21; Sun+22; Far+21; Nou18; KGG21; VBM18; SZ19; TB20; Ken+21; Com+19; Con18; Zen+18]			
(Flexibility)	63	34	0.796	0.891
References	[Bra+22; Har17; UA15; Sun+22; KGG21; SZ19; Vit+21; Ken+21; Zen+18; Rad+18; Con18; Bhu+22]			
Transparency data access sharing	24	31	0.413	0.695
References	[Bra+22; Vit+21; Rad+18; Con18; Bhu+22]			
TSO-DSO coordination capabilities	37	15	0.443	0.786
References	[Bra+22; SZ19; Rad+18; Con18; Bhu+22; Vit+21; Ang+19]			

4.5.1 Social Dimension

From the literature review, 32 indicators demonstrated a direct relationship with social aspects. These indicators are categorized based on their relevance to customer engagement, market participation, and the ability to trade/share customer data.

Electricity Market Customer Oriented Indicators: Indicators that assess social aspects in a customer oriented market are crucial for evaluating the implementation of a flexibility market (local market). These indicators consider the ability of customers or aggregators to interact with the grid operator and to share data about their demand and forecasts.

Most of the indicators in this category pertain to energy traded by prosumers or in demand response markets. These indicators primarily analyze energy volumes that are beyond the trading capacity of small customers. Examples of these indicators are: *Volumes of energy traded by prosumers, availability of power from demand response programs, or amount of customers with DER*. The primary focus is to determine customer participation and involvement in the market, to understand elements in assessing market integration, and to determine elasticity of the demand, thereby gaining insights into energy consumption behavior.

Grid-Related Social Indicators: These indicators evaluate indirect benefits to customers through grid enhancements. They relate to the capabilities of devices within the grid and their interactions with customers. Key indicators in this category include grid configuration capabilities and the percentage of customers with automatic metering. Notably, the transparency of data access sharing, as proposed by the European Federation of Local and Regional Energy Companies [CED+21], is a significant indicator.

Transparency Data and Access Sharing Indicators: This indicator aggregates the communication capabilities of various stakeholders. It is calculated by combining several indicators that assess data sharing capabilities among the following entities: meters to customers, customers to Distribution System Operators (DSO), Aggregators to DSO, and DSO to Transmission System Operators (TSO). These indicators are weighted based on the degree of real-time and non-real-time information sharing, providing a value between 0 and 1 [CED+21]. The capability of customers to receive information or data is related to social aspects, since it could support their decision-making process and engagement. Therefore, this thesis proposes the use of this indicator while maintaining separate indicators to evaluate data-sharing capabilities at lower voltages (customer side) and among coordinating stakeholders (DSO-TSO).

4.5.2 Economic dimension

The most representative economic indicator is price. Consequently, various aspects of market implementation are supported by cost-benefit evaluations. In electricity markets, key topics within this dimension include market well-being evaluations, the marginal price, or the average cost of electricity. The implementation of smart grid technology devices is closely linked to the benefit they bring to the power system, especially in terms of evaluating the dynamics of the market. A total of 152 strong economic indicators and 28 weak indicators were identified. To better understand the usability of the KPIs, these indicators could be grouped into three types: System indicators, grid performance indicators, and performance indicators based on specific markets. The list of indicators can be accessed via the QR code shown in Figure 4.6.

System Indicators: These indicators provide an overview of the power system and its economic effects, encompassing also technical aspects. In electricity markets evaluating the potential for introducing competition, it is essential to assess the overall economic efficiency of the system. Examples of indicators that support a general evaluation of the system include: *Herfindahl-Hirschman Index (HHI), Market Power, Market Liquidity, System Operator's Market Coordination Index, Transmission Capacities and Import Capacity, Transmission Usage in Percentage, and Power Loss Cost*

Power Quality Indicators: These are commonly used grid performance indicators, also related to economic aspects due to the cost and repercussions on the system due to non-compliances. These indicators support also cost-benefit analysis when implementing smart grid devices. Examples include *ramping rate capabilities*, SAIDI, and CAIDI.

Performance indicators based on specific markets: This refers to indicators that relate to specific market types, such as the flexibility market with different mechanisms, including bidding schemes or cost-based schemes. Moreover, in the case of flexibility markets, or the implementation of local or flexible markets, some performance indicators specific to this market type can be found. These include *activation rate of local energy markets (LEMs) to avoid grid congestion from the DG perspective; activation rates of LEMs to support voltage regulation; decrease in cost for flexibility service provision; bidding price estimation for providing active or reactive power; and the degree of grid expansion deferral by applying peak shavings, among others*.

Energy Intensity: This is a valuable indicator that quantifies the energy required per unit of Gross Domestic Product (GDP), and it is used to evaluate and understand a country's behavior. It is manually included since it was absent in the papers for the bibliometric analysis. This indicator, and in particular the evolution of this indicator over time, is very effective for assessing the evolution and efficiency of a country in terms of energy usage. However, it should be noted that the energy intensity indicator must be carefully considered, especially for cross-country comparisons, as industrialized countries tend to exhibit higher values than service-oriented ones.

4.5.3 Environmental Indicators:

A total of 20 strong indicators and 9 weak indicators have been selected. Among these, the most relevant are the share of renewable energy production, the proportion of clean energy installed capacity, and the amount of CO_2 and greenhouse gas (GHG) emissions. These indicators are significant, as they also contribute to reporting on the European and United Nations goals.

In the specific context of smart grid technologies that support the environmental dimension, indicators such as *Predictability of Load Profile, Weather and Seasonal Variability, Degree of Curtailment, Increase in Local Renewable Energy Generation, Energy Not Withdrawn from Renewable Sources Due to Congestion or Security Risks, and Redispatching Reduction* can support the usability of smart grid technologies in increasing and managing the variability of resources.

4.5.4 Legal/Policy Indicators

A total of 27 strong indicators have been identified. Some of these relate to the presence or absence of adequate regulation, market mechanisms, and policies for GHG reduction or renewable energy goals. Additionally, indicators reflecting trading capabilities across borders, regional planning coordination, grid expansion among countries, and entry barriers in markets are also identified and included.

One of the most critical policy-related and country-specific indicators is the *Electricity Import Dependency from Neighboring Countries*. This indicator can be extended to non-EU countries and any geographical zone, supporting the need to evaluate external dependency. Additionally, *Power Trade Ratio* and *Import Capacity* can be developed as key indicators to understand capacity expansion across borders as a result of political decisions. Therefore, this thesis proposes a modification of some indicators to incorporate these aspects, as discussed in Chapter 5, particularly for the implementation of the Energy Security Indicator (ESI) [MDA18].

4.6 Conclusion

This chapter presents the method for extracting and relating smart grid electricity market-oriented KPIs for different trading market mechanisms and designs based on bibliometric analysis. This holistic approach encompasses economic considerations, as well as social, environmental, and legal aspects for a comprehensive evaluation of the sustainability of the power system.

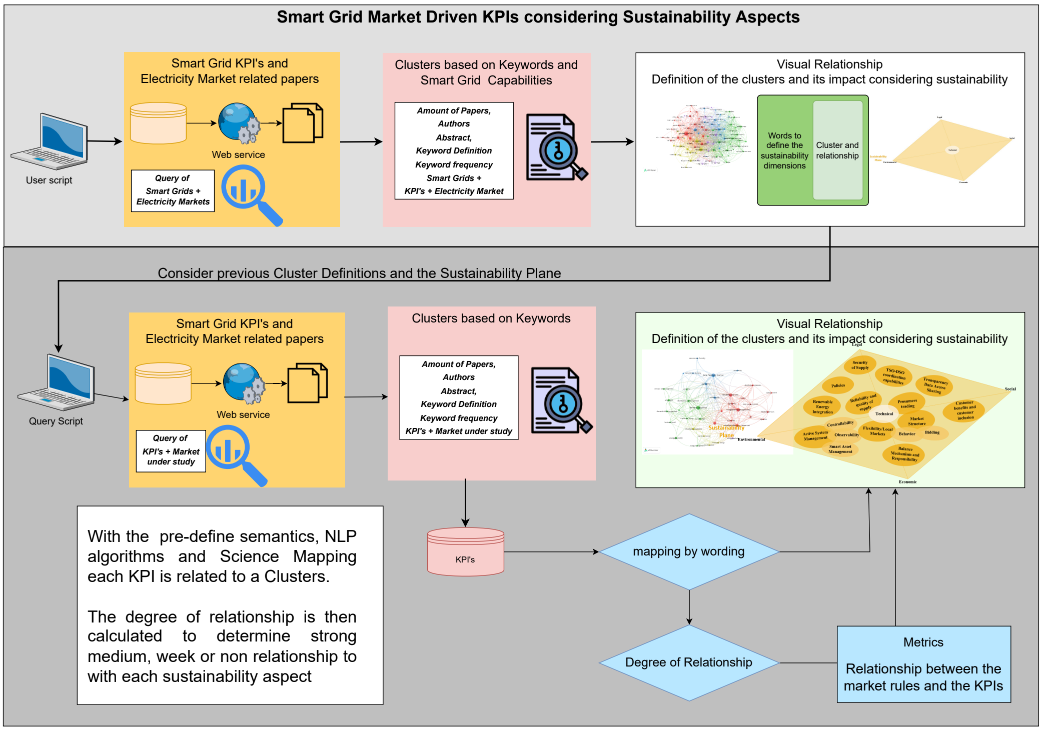


Fig. 4.8.: Process Structure for Extracting KPIs and Establishing Relationships Between Keywords and Clusters

Figure 4.8 describes the overall structure of the process. It starts with the first block, which involves the query for searching "*("Electricity Markets" and "Smart Grids")*. This search supports the definition of several smart grid clusters and the need to relate them to the sustainability dimensions for a holistic assessment. The second part involves refining the method, in which, after considering the definitions of the previous clusters and the sustainability plane, a query is performed with the objective of searching "*key performance indicators and the market under study*". This second query searches for open-source papers and the information presented within each document, such as authors, keywords, abstracts, and the keywords *indicators, performance, KPI, and the particular market under study*. The information is then stored in a database. The process supports the extraction of these data and the mapping using pre-defined semantics. It is enhanced with NLP algorithms to relate those KPIs to the cluster and determine the degree of relationship between each indicator and its sustainability dimension. The degree of relationship allows the creation of metrics to evaluate the spread of the indicator and the market rules. Additionally, a review of the qualitative assessment is performed to support the evaluation and relationship between each indicator, particularly with non-clearly defined semantics. All indicators are clustered, related, and shown in the sustainability plane.

Since there are no standardized indicators to evaluate new market implementations for trading flexibility services, the presented use case and method are not only limited to proposing KPIs that depend on the researcher's assumptions but also map the information, creating relationships between the KPIs, their market applicability, and their impact on the sustainability domain. From this compilation, it is observed that the implications of policies and regulations affect several aspects of the system. For this reason, mapping the relationships is necessary to understand different impacts.

The communication and information shared between actors support real-time and non-real-time grid knowledge and provide the opportunity for greater customer inclusion and the possibility of creating a new market. Therefore, smart grid technologies are necessary to increase the dynamics of the current electricity system by allowing changes in market rules or even the possibility of performing new trades.

From a social perspective, the implications of subsidy policies, incentives, and taxes for the integration of renewable energy must be carefully considered, as these policies can impact both costs and social benefits. Equity and income distribution have also emerged as significant concerns, especially in the context of variable electricity prices and the implementation of systems like Locational Marginal Pricing (LMP).

In terms of environmental aspects, the focus has been placed on the "Share of Renewable Energy" indicator, which seeks to increase the participation of distributed renewable energy sources in markets. Aggregating these sources offers significant opportunities if flexibility markets are created, but good regulation and effective market interaction must be in place.

Indicators play a crucial role in decision-making and assessing the sustainability of electricity markets. Striking a balance between the promotion of clean energy, social equity, economic efficiency, and effective coordination will be essential to ensure sustainable and efficient electricity systems.

5 Experts Interview and Data Mining

> *"If men define situations as real, then they are real in their consequences."*
>
> — **William I. Thomas** (1863-1947)

Semi-structured interviews provide an exceptional platform for exploring the complexities of human perception and experience. William I. Thomas famously stated, *'If men define situations as real, then they are real in their consequences,'* underscoring the significant impact of individual interpretations on shaping reality. Building on these concepts, semi-structured interviews, with their flexible and dialogic nature, effectively capture and elucidate diverse perspectives, clarify viewpoints, and facilitate a deeper exploration of the knowledge-producing potentials inherent in human interactions. Semi-structured interviews serve then as a research strategy which harnesses the knowledge-producing potential of dialogues.

This chapter presents the results of the interview process to examine the relationships between various concepts of the electricity market and the impacts on the four sustainability dimensions. Additionally, concept mapping tools are employed to summarize each interview, allowing a visual representation of the main ideas expressed by each interviewee. The similarities, major differences, and relationships between the concepts expressed by each interviewee are emphasized.

Content analysis and text mining are utilized to deduce patterns and knowledge from the interview data, such as recurring themes, common trends, and underlying relationships. These techniques enabled the extraction of valuable insights into the perspectives and experiences shared by the interviewees regarding the electricity market and its sustainability dimensions. The final outcome is the creation of concept maps that support the relationship between smart grid capabilities and the sustainability dimensions presented in Chapter 4. Furthermore, experts' opinions and concerns aided in selecting KPIs for each sustainability dimension when evaluating various market mechanisms. This process supports the final mapping of the KPIs in the evaluation of electricity markets. Moreover, based on the interpretation of the interviewees, this thesis proposes KPIs that address the specific requirements identified by experts.

5.1 Overview of the Interview Process

The interview process starts with a guide, in the form of a questionnaire designed for semi-structured interviews. The questionnaire features open-ended questions to provide the interviewees with space to elaborate on their experiences. The main topics to be discussed during the interviews are:

- Overview of Smart Girds.
- Implications, emerging trends and challenges of the electricity market, with special emphasis on new market rules.
- Current evaluation process of new market implementations and possible recommendations.
- Consideration of sustainability aspects both for the evaluation process and for the considerations of new market rules.
- Principal clusters of indicators pertaining to the evaluation of market rules modifications.
- Expectations and future steps of the electricity system.
- Depending on the interviewee, questions are also discussed regarding their international experience.

The interviews were conducted by teleconference (video and audio were available all the time). Only one interview was conducted physically (face-to-face). The interviewees were informed about the objective of the interview, the duration, and the recording method to be used. In addition, all agreed that the audio is to be recorded. The comments of the interviewee are then processed and fully anonymized. For processing each interview a code was created.

In addition, the interviewees were informed that they were categorized into three main groups, representing either a region or a country based on their field knowledge. Each respondent represents a unique stakeholder sector, encompassing energy policymakers, academia, and industry representatives, both from Germany and Panama, or regional consultants specializing in either European or Latin American contexts. All interviewees have more than 10 years of experience working in the sector, with regional consultants possessing even longer experience in the electricity sector. The selection of Panama and Germany as the focal countries was deliberate. Germany, with a degree of competition of 4 (an open market), and Panama, with a degree of competition of 3 (only wholesale market), are chosen to reflect diverse market structures. This choice supports the investigation of how to implement new market regulations effectively. Countries with a degree of competition of 2 and 1 (only one buyer and vertically integrated) are overlooked for the interview process. This decision was made because the influence of the market is minimal in such settings, as the system operates based on different regulatory frameworks.

The interviews were initially scheduled for 45 minutes to one hour, but some interviewees expressed a willingness to continue beyond the allotted time. Given the semi-structured nature of the interviews, which aim to encourage interviewees to discuss topics at their own initiative, the duration was extended accordingly.

No statement represents the organization for which the interviewee work. The language of the interviews was Spanish for those interviewees who are Spanish native speakers. The rest of the interviews were conducted in English, which was not the native language of these interviewees.

All audio information is transcribed using the open source desktop software *Whisper*, and all data is stored locally. The transcripts are processed to identify the main topics (clusters for each topic) discussed, and the relationship among the topics. Text analysis is performed for each interview individually, using *QualCoder* software in desktop version to codify and extract the main ideas, and the open-source tool *Voyant*. In addition, *Voyant* is used for text analysis to extract more quantitative measures from each interview as well as for the complete interview corpus.

The interviews with key stakeholders served as a central methodological approach to evaluate the main concepts with respect to electricity markets and smart grids. It also supports the relationships among them and the usability of KPIs in the evaluation of real-world scenarios. Central to this endeavor are the contributions of regional consultants, whose extensive experience spanned over 15 years in both the Latin American and

European energy markets. Their insights encompassed a comprehensive overview of current practices in the implementation of new market regulations, its challenges, and recommendations for improvement based on past experiences.

Furthermore, all interviewees provided observations about the regulatory change assessment process and their most relevant needs regarding KPIs. The interviewees also expressed their opinion on the effects of some market mechanisms on the system based on their experience and past use cases. Finally, interviewees commented on the process of the KPIs presented in this dissertation, pointing out which of them are more relevant for a holistic evaluation of the energy system after implementing a new market rule.

To codify the text within the interviews, the code presented in A.4 is utilized. The code is similar to the one used in the chapter 4 and is implemented in all interviews to categorize topics and statements, which supported the selection of terms. Since some topics are related to each other, the code allows to linked relationships among the concepts. In the following sections, the resulting mind map per interview is presented. The color selection is not representing a direct relationship among topics between different interviews, since each interviewee is exposing the terms freely according to their main concerns. Table A.4 presents the relationships to sustainability aspects and the main terms associated with the codification. The singular and plural forms are coded.

Some considerations regarding translations and coding process are that the terms "*Comercializador*" in Spanish speakers interviews are translated as "*retailer*". This term refers to the role of a retailer - a market actor - that sells electricity to the final user, but it is not the owner of the distribution grid. In addition, the term "*Gran Cliente*" that is directly translated as "*Big Customer*", is used as for the actor or customer who has a demand greater than 100 kW and complies with the regulation to buy electricity in the wholesale market. This figure is implemented in Panama to allow energy-intensive customers to access better prices by directly negotiating with generators.

After the codification, the main aspects are presented in concept maps. Concept mapping functions as a systematic approach to visually organize and analyze interview data by transforming qualitative insights into structured, interconnected themes. The process begins with thematic coding, where specific codes are assigned to text segments that represent central ideas within the interview corpus. These codes are then grouped into categories or clusters, forming the basis of the concept map. This approach is implemented using the open-source software *QualCoder 3.4*. The text analysis software *VoyantServer 2.6.10* is used to conduct a qualitative examination of interview transcripts.

Both tools facilitated the extraction of keywords and generation of word clouds to identify themes, enriching the concept map with data-driven insights. The coded data is further analyzed through content analysis and text mining techniques to identify patterns, trends, and underlying relationships within the interview corpus. Together, these techniques provide valuable insights into stakeholder perspectives, forming a robust framework for evaluating the impacts of smart grid technologies on electricity markets and their connections to several sustainability dimensions.

The following subsections present the concept maps for each interview and discuss the main considerations. A color code and an alphanumeric system are employed to facilitate the comparison of concepts across interviewees. Both the final concept map and individual mind maps for each interview are available in the Git repository as shown in Figure 5.1

Fig. 5.1.: QR code for accessing the mind maps repository

5.1.1 Policy Perspective

Every country or region follows a long-term directive to implement its respective energy policy. These directives serve as foundational frameworks that guide strategic decisions and initiatives to enhance the energy production, consumption, and sustainability of the energy sector. However, policymakers regularly examine changes in market dynamics along with systemic needs to formulate new policies or amend existing ones. In addition, policymakers have a broad outlook on emerging trends and the underlying motivations behind regulatory changes.

Consequently, two countries are chosen to exemplify their perspective on smart grid technologies and elucidate how the incorporation of more IT systems (smart grid technologies) could enhance the formation of new markets.

To avoid steering the interviews, the experts are invited to explain potential short-term and long-term market changes. The objectives of these changes, and their process for assessing the effects of induced changes due to new electricity market rules. The interviewees are prompted to discuss the main challenges they have identified and their possible solutions. Open discussion topics are: the path to achieve the energy transition, possible new market mechanisms, and other energy policy considerations.

The main topics discussed during the interviews are depicted in concept maps shown in Figure 5.2 for the Panamanian system, and in Figure 5.3 for the German perspective. It is important to recall that the Panamanian system, according to the compilation of information presented in Chapter 3, corresponds to a level 3 in the degree of competition. This means that there is no retail market. Therefore, it is noticeable that the policy representative mentioned the possibility of increasing competition by allowing retail markets. Additional topics and the relationships among them mentioned by the interviewees are discussed accordingly, as well as the similarities and differences in their perspectives. Some relationships among topics are illustrated by the use of concept maps referencing the codification of the statements in each interviewee's mind map.

The interviewees mentioned the need to implement a comprehensive and innovative strategy for regulatory changes that allows the introduction of step-by-step adaptations in the system. For evaluation strategies, the possibility of including sandboxes as an international learning method applied to the reality of the country would like to be considered. However, regulatory adaptations are required for both the implementation of pilot projects and for the recognition of grid investments for each specific pilot project. The interviewees also emphasize the need for validation and assistance mechanisms, in addition to the typical cost-benefit analysis, to implement regulatory changes.

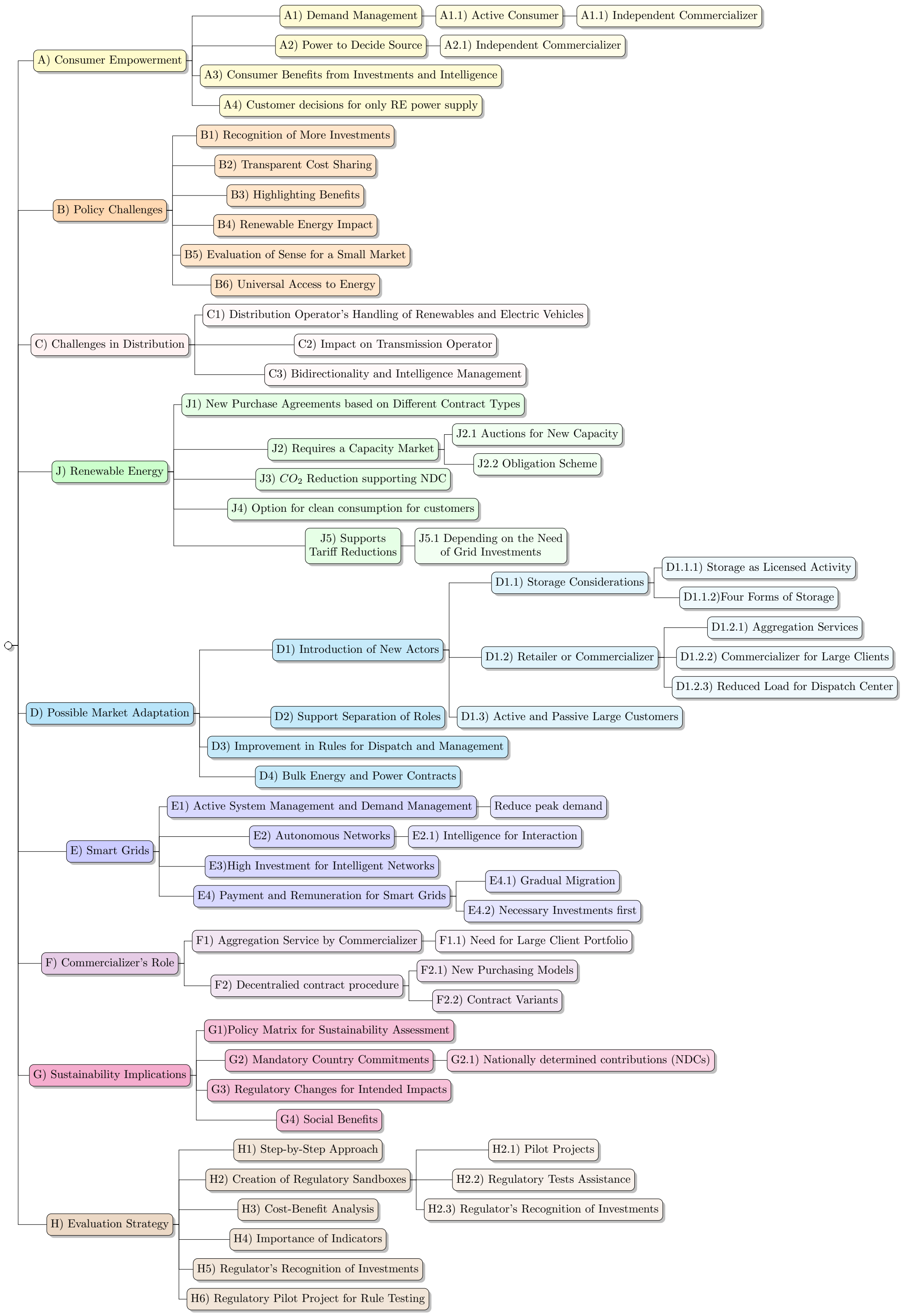


Fig. 5.2.: Concept maps of the interviewee 3. Policy

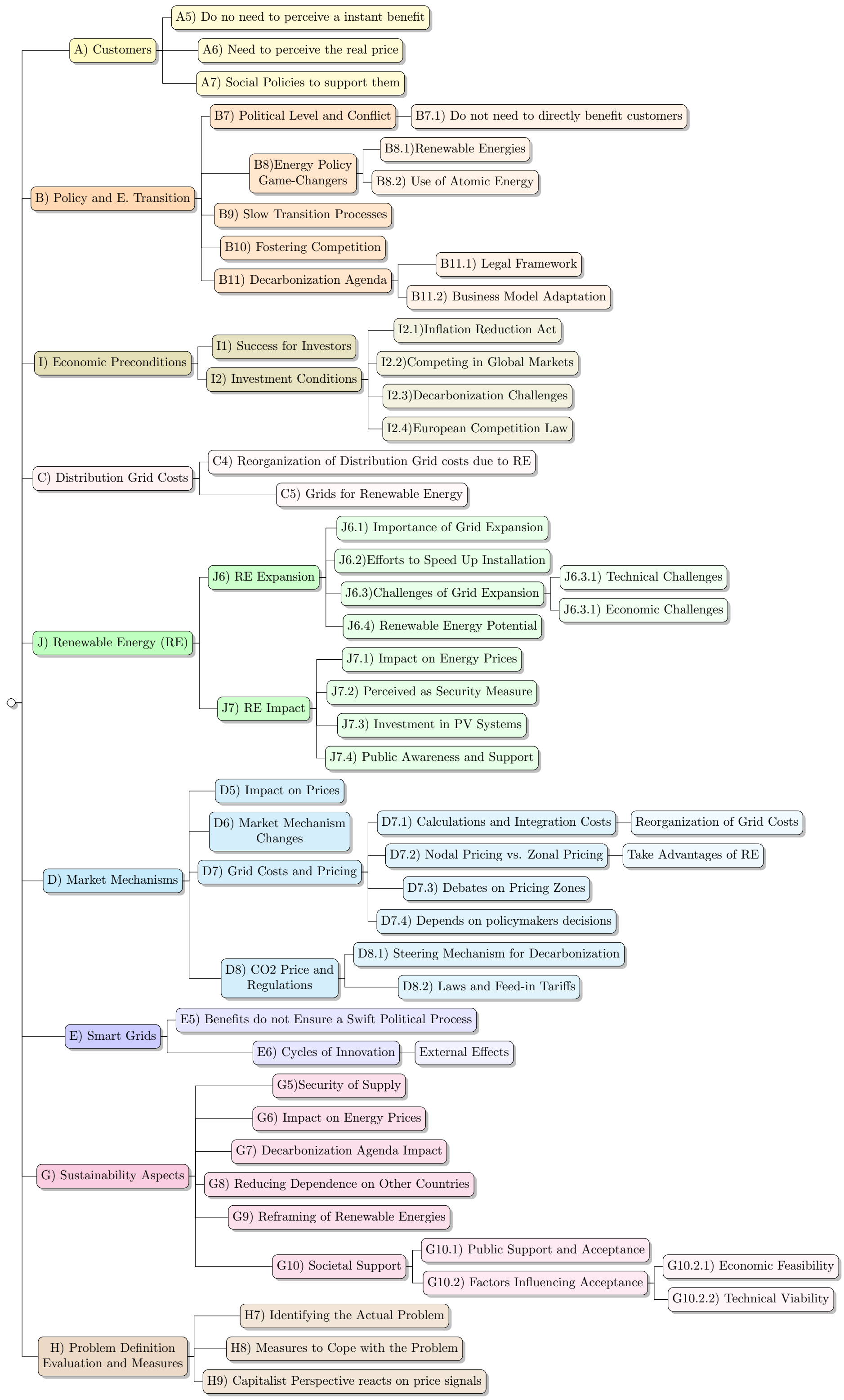


Fig. 5.3.: Concept maps of the interviewee 7. Policy

Smart grids enhance customer interaction through an advanced IT infrastructure. However, effective payment mechanisms and a clear remuneration process for such investments require a thorough cost-benefit analysis to ensure that final tariffs do not burden end users with excessive grid enhancement costs. Figure **??** presents a concept map with relationships among key concepts. For interviewee 3, the concept of *Smart Grids (E)* primarily refers to implementing *Active System Management (E1)*. This approach, however, raises concerns about establishing suitable *Payment Mechanisms for that Investment (E4)*. Furthermore, active system management is proposed as a tool to support *Demand Management (A1)*, linking it to *Customer Empowerment (A)*. Empowering customers aligns with the concept of *Customer Benefits from Investment and Intelligence (A3)*. These concepts are also connected to the *Cost-Benefit Analysis* (H3), which forms part of the *Evaluation Strategy* (H) and the consideration of *Social Benefits* (G4). Figure 5.4 illustrates the resulting relationships among these concepts as discussed during the interview.

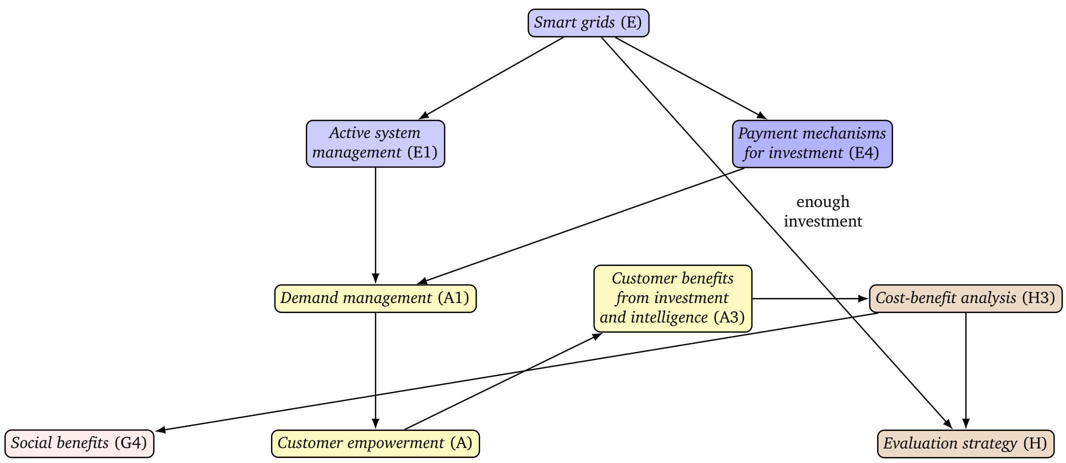


Fig. 5.4.: Relationships between smart grid concepts, customer empowerment, and social benefits, including the need for evaluation

The interview findings underscore the importance of substantial investments in smart technologies yielding tangible social benefits, as reflected in Figure 5.9. Notably, the analysis of interviewee 3 highlights how investment in smart grid technologies should implement a strategic evaluation, subsequently leading to societal benefits without imposing undue burdens on end-users. However, Interviewee 7 questioned the correlation between customer benefits and the outcomes of investments in smart grids. According to interviewee 7, policies aimed at the implementation of smart grid technologies do not exclusively prioritize direct customer benefits. Instead, the sustainability of the system depends on the attainment of societal support. To achieve this support, decisions must be influenced by public acceptance, in which both technical and economic factors must be considered.

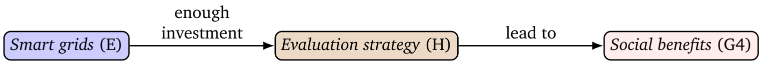


Fig. 5.5.: Optimizing investments in smart grid implementations through strategic evaluation to enhance social benefits

Hence, the depicted relational model illustrated in 5.5 necessitates refinement akin to the schematic delineated in Figure 5.6, in order to effectively pursue the overarching goal of system sustainability.

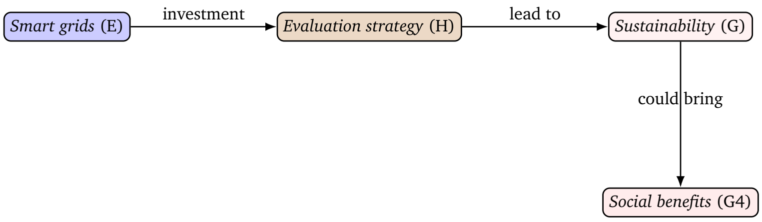


Fig. 5.6.: Investments in smart grid implementations, guided by a strategic evaluation framework, have the potential to lead to social benefits, though outcomes are not always guaranteed.

Addressing these concerns, interviewee 7 emphasized the significance of policy adjustments that may not yield immediate customer benefits but are instrumental in advancing overarching objectives. Consequently, the pursuit of sustainability, particularly in terms of fostering social benefits, requires robust societal support. This assertion is underscored in Figure 5.7, which illustrates the interdependence between sustainability initiatives and societal support.

Regarding the implementation of smart grid technologies, active system management, and demand management are significant contributors to reducing *peak demand*. Furthermore, to invigorate competition and market dynamics, evaluations of role separation in the retail sector are crucial. According to interviewee 3, in the primary market design, the distribution company is the actor responsible for the distribution and commercialization of electricity to the final user. Nevertheless, this can change as the market matures. Therefore, the retailer's role is linked to the smart capabilities and the possibility to empower consumers. A summary of the statement is:

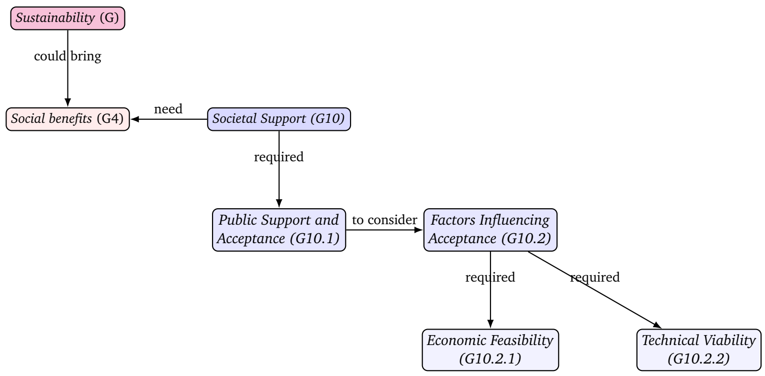


Fig. 5.7.: Factors influencing public support and acceptance impact the social dimension of sustainability

> "...The service of aggregation could be provided by the retailer/(in spanish "comercializador"). Through the retailer, both demand and energy injection aggregations can be conducted, allowing for the consolidation of energy and power bulk. The retailer can engage in internal energy exchange with end-users, or alternatively, elevate the aggregated energy to the market. The role of a large-scale customer could transition to the retailer[...] Our objective is to encourage consumers to adopt a more participatory approach, facilitated through the involvement of an independent retailer [...]. All this requires a high level of intelligence in the networks to handle and facilitate interactions, as the system operator will no longer be able to manage these issues directly."
>
> **Rephrased from interviewee 3.**

According to this statement, in *Smart Grids*, the *Active system management (E1)* and the *Demand Management (A1)* to reduce the peak demand, are highly related to the *retailer's role (F)* and to the *Agggregation Service (F1)*, which the retailer can offer to large clients or big customers. This last concept is linked to the possible market adaptation of introducing new actors as "retailers" with a *Retailer's role (F)*. Concurrently, the *Retailer role (F)* and the *Active system management (E1)* are linked to the *Demand management* (A1) that belong to the *Consumer empowerment* (A).

Therefore, following the ideas expressed by the interviewees and relating those concepts to the predefine smart grid clusters presented in chapter 4, the *Demand Response* that is related to the cluster *Customer benefits and customers inclusion* has a relationship with the *Active System Management* cluster. This relates the technical aspects of smart grid capabilities such as demand management response and active system management with the possibility to empower customers through the retailer's role. Therefore, the following cluster relationship can be extracted:

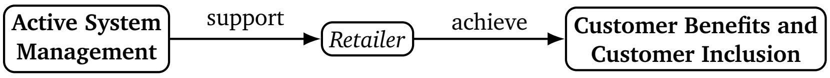


Fig. 5.8.: Relationship between active system management and customer benefits

Other points mentioned by the interviewees, which will additionally support other relationships and may vary by country, are:

- Interviewee 3 stated that sustainability evaluation is currently implemented in accordance with international directives, aimed at supporting the country's Nationally Determined Contributions (NDCs), and is limited to this sustainability matrix. Consequently, market regulations are not directly considered. Moreover, since Panama's NDCs have already been achieved and surpassed, the policy-formulating entity in the country is seeking greater impacts that can be reflected in customer benefits.

- Another important aspect to consider is the size of the market. According to interviewee 3, the market size could impede the introduction of multiple actors or roles, such as aggregators and commercializers. They find it then interesting to assess new regulations by implementing special sandboxes or pilot projects. However, to achieve this, certain legal changes are necessary to allow the regulator to recognize such investments. These topics are mentioned as part of the evaluation strategy (H), specifically in points H2, H5, and H6.

- The most critical smart grid clusters for evaluating various sustainability dimensions are the *Market Structure* (as evaluations of prices and procedures are essential for policy assessment), *Coordination (TSO-DSO)*, and *Power Quality*.

- The imperative of ensuring universal energy access remains a pertinent concern and a fundamental policy objective in Panama. As such, the strategic allocation of investments towards emerging technologies is fundamental within the realm of energy policy. This premise underscores the necessity for a comprehensive evaluation framework aimed at mitigating the financial burden on marginalized user demographics. This subject is addressed in the *Evaluation Strategy (H)* regarding the use of a *Step by Step approach (H1)* in interviewee 3 and in the *Impact on Energy Prices (G6)* in interviewee 7.

Both interviews emphasize the importance of expanding grids and support the IT infrastructure to accommodate renewable energy sources, acknowledging that the infrastructure improvements require investments that could be reflected in the electricity tariff adversely affecting industries or final customers. In addition, the overall goal should also be to foster a more reliable and more efficient power system.

The main differences are related to the surrounding pricing mechanisms, such as nodal pricing versus zonal pricing, and the effectiveness of CO_2 pricing as a steering mechanism for decarbonization.

Both interviewees expressed that clear investment conditions and legal frameworks are necessary to drive forward the energy transition initiatives. The German perspective considers necessary to present a policy framework attractive for new investors in comparison with other regions. Therefore, the addition of strict carbon prices or social externalities to the price could hinder this goal. At least to fairly compete, all countries in a region, should have the same CO_2 carbon price.

Fig. 5.9.: Strategic evaluation of smart grid investments for maximizing social benefits

Figure 5.10 depicts specific points mentioned in interview 7, which are:

- The implementation of a nodal pricing system in conjunction with a bidding mechanism for renewable energy integration ensures that stakeholders can promptly capitalize by deploying renewable energies within a specific area.

- The development of renewable energy ensures the security of supply while supporting the reduction of the CO_2 emissions.

- Due to the energy crisis, individuals are increasingly cognizant of the need for an energy transition, thereby leaning towards more sustainable green energy alternatives whenever feasible. An important motivation is to reduce dependency on volatile fuel prices. Note that the interviewee's definition of sustainability is closely tied to the increasing production of electricity from clean domestic sources rather than establishing a dependence on international resources (optimizing cross-border renewable resources). Therefore, it is essential to clearly define what each evaluator considers as the concept of sustainability, as individual interpretations may vary significantly.

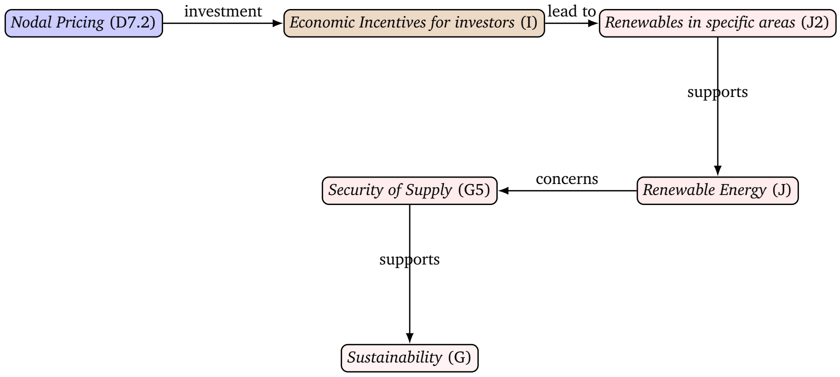


Fig. 5.10.: Nodal prices and its effects on the deployment of renewable energy

5.1.2 Industry Perspective

Two representatives from distribution grid operators and retail companies in Germany and Panama were interviewed with the aim of gathering their perspectives on the electricity industry, the challenges of the electricity market, and their opinions on strategies for integrating renewable energies within distribution companies. This also serves to collect their experiences with the implementation of smart grid technologies and how they are evaluated, especially considering the sustainability dimension. The main points extracted from each interview are synthesized into concept maps, visually representing the discussion. Figure 5.11 depicts the concept map for the interview with the CEO of a distribution company in Panama, and Figure 5.15 depicts the concept map for the German counterpart. While these perspectives offer a broad overview of distribution companies, they do not intend to attribute statements to any specific company.

Due to the extensive nature of the mind maps, the market sections from both interviewees have been extracted and are presented separately. However, the complete mind map includes a mention of the main topics discussed. The interviewees representing the industry perspective are identified as Interviewee 4 and Interviewee 8. Interviewee 4 addressed the challenges of the transition and potential changes, emphasizing the need for market surveillance and transparency. This includes maintaining data consistency across various sources and conducting continuous market evaluations. Similarly, Interviewee 8 discussed challenges and potential changes, specifically in local markets and flexibility markets. Both interviewees emphasized the value of gaining knowledge through the sharing of experiences and comparisons among countries regarding the implementation of new technologies and market frameworks.

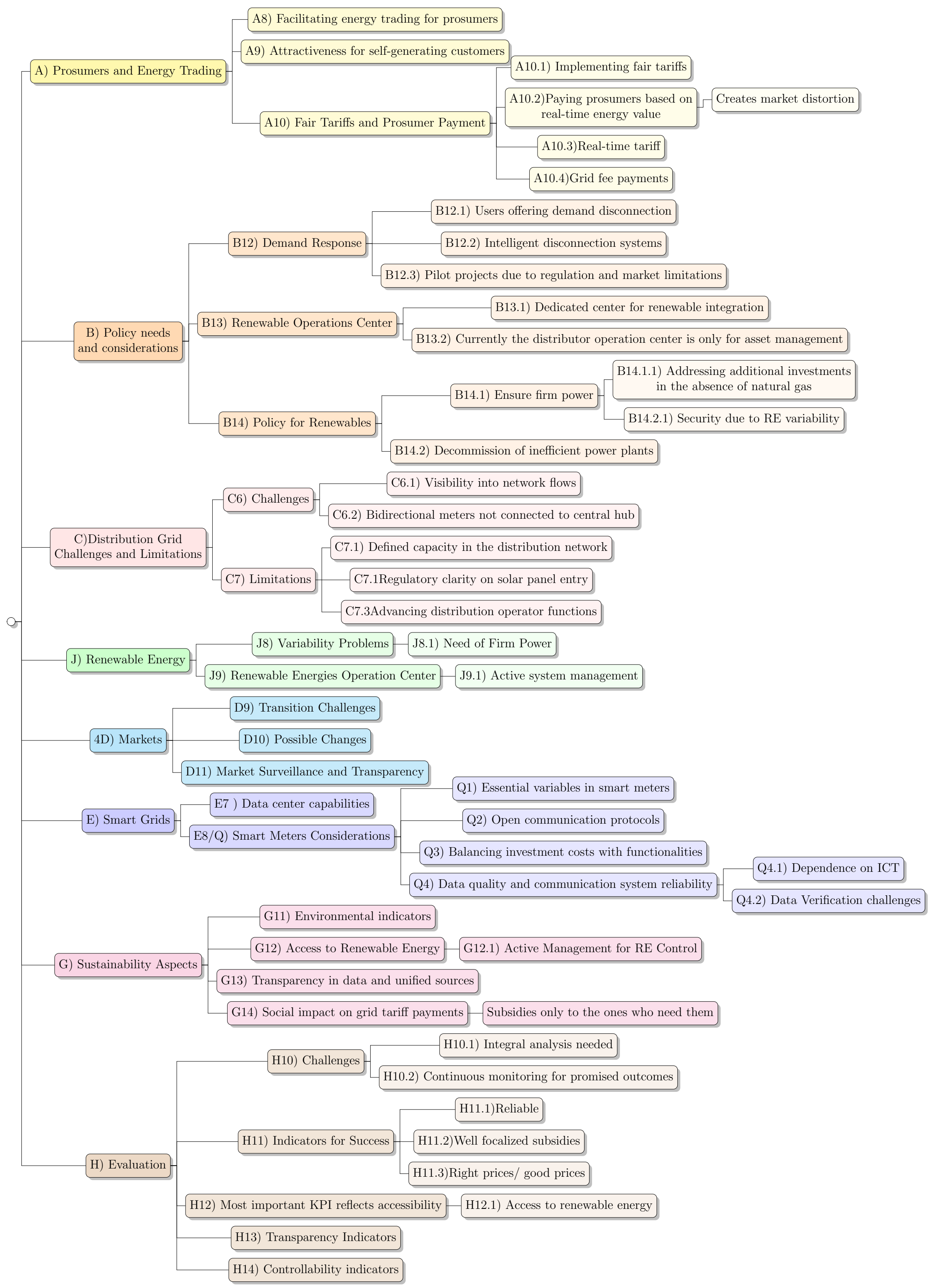


Fig. 5.11.: Mind Map Interview 4, CEO of a Distribution Company

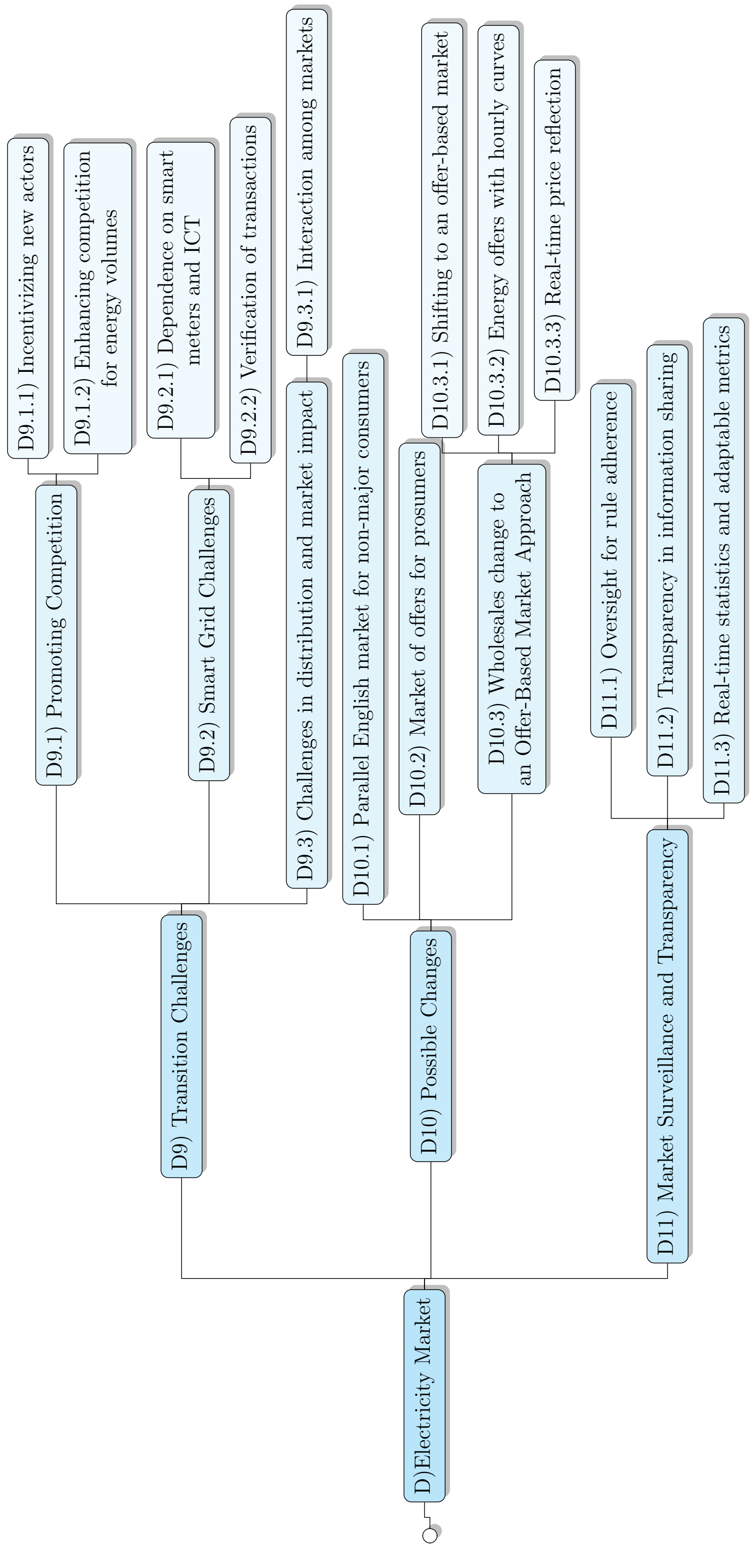


Fig. 5.12.: Mind Map Interview 4 only market, CEO of a Distribution Company

The ideas elucidated by both interviewees provide insight into the relationships among various concepts. For example, a renewable energy policy aimed at achieving sustainability in the environmental domain must be intricately linked with the subsequent requirement for reliable power to mitigate the variability inherent in weather-dependent resources. Moreover, it is imperative to address the issue of firm power, especially if a policy aims to decommission fossil fuel or nuclear plants that are capable of providing firm power, unless there is an alternative mechanism to ensure its provision, as depicted in Figure 5.13.

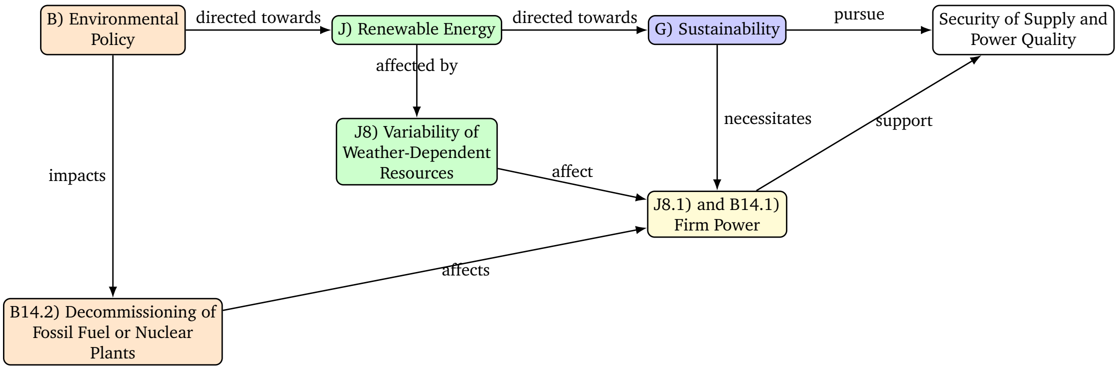


Fig. 5.13.: Interrelationships among Key Concepts in Renewable Energy and Firm Power for Security of Supply

Both interviewees mention challenges related to grid reinforcement, whether through regulation or market solutions, and express concerns about firm power and storage facilities across all market segments. They note the market inertia in implementing changes and evaluating regulations due to the necessity of KPIs and the incorporation of sustainability aspects. Both interviewees agree that the integration of renewable energy is mandatory and essential for assessing market performance. They also highlight the importance of instruments for coordination and controllability of the entire system to ensure transparency and security of supply.

The primary difference between these interviews lies in the focus of the interviewees' concerns. Interviewee 4 exhibits a comprehensive perspective on the multifaceted implications inherent in the system, manifesting uncertainty regarding the implementation of numerous emerging technologies. This concern stems from the potential for higher investment needs, which could result in higher tariffs and subsidies, along with the looming risk of rapid obsolescence. The standardization of the communication protocol across multiple devices and the range of variables they can measure requires careful consideration to preempt potential compatibility issues.

Interviewee 4 emphasizes the necessity of ensuring a reliable energy supply, particularly in terms of firm power, and the ability to bill actors with high accuracy. This interviewee underscores the importance of a holistic approach, highlighting the interrelationships among various concepts.

In contrast, Interviewee 8 is more focused on market performance and potential changes, rather than adopting a holistic approach. Interviewee 8 highlights market challenges, including liquidity concerns and the need to ensure investor confidence. Furthermore, this interviewee stresses the importance of market flexibility and the implications of market design, particularly regarding the need for future contracts. In this final point, a similarity with Interviewee 4 is identified, as both agree that certain changes in contract procedures are necessary to accommodate the integration of renewable energy quotas.

Interviewee 8 focuses exclusively on market-related themes, potential changes, and sustainability and evaluation aspects, without directly addressing topics related to customers or energy policy, unlike other interviewees. Consequently, the color-coding scheme employed is not applicable to this interview.

Regarding Interviewee 4, it is pointed that:

- The distribution company demonstrates a proactive stance towards the adoption of emerging technologies aimed at optimizing operational processes and enhancing power quality. This is evident in some *Demand Response Pilot Projects*. However, the expansion of these endeavors is impeded by regulatory procedures, thus presenting a barrier to a widespread implementation.

- Furthermore, the interviewee discusses various contract mechanisms that could facilitate the adoption of renewable energy, such as hourly curve contracts. However, when considering the potential for multiple markets, the interviewee notes that:

  > "[]... Consideration must be given to the scenario where there are two dispatch structures: the wholesale dispatch and the retail dispatch. It would be interesting, at the very least, to evaluate a retail market and to evolve the issue of contracts at the wholesale market level."
  >
  > **Paraphrased from Interviewee 4**

- A major concern is the grid fee payment for renewable energies. Certainly, the payment exemption incentivizes high-income customers to invest in DER, but the proliferation of this results in the more vulnerable sectors of society perceiving higher tariffs based on necessary grid investments. This is one of the reasons for which new markets should be promoted to avoid the market distortion that causes high amounts of prosumers "*who are currently not paying the grid fee*". According to the Panamanian Law, renewable energy projects smaller than 10 MW are exempt from grid fee payment. Similarly, Interviewee 8 mentions the need to implement variable tariffs, especially to address the challenges of offering flexibility. The consideration that a customer will be charged extra for feeding into the system could indirectly disincentivize customers with decision power from offering flexibility or investing in DERs. Figure 5.14 summarizes both ideas.

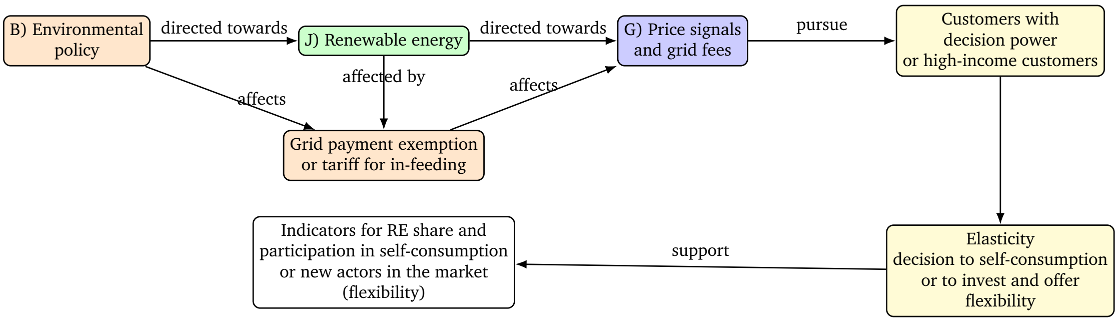


Fig. 5.14.: Interrelationships among customer decisions, environmental policy, and grid fees

- In the realm of smart grid controllability and data access, interviewee 4 underscores the importance of expanding the deployment of smart meters and enhancing data resources. In addition, the proliferation of data requires the establishment of an operational center capable of efficiently managing the significant volume of generated data. Moreover, the specifications of smart meters, such as the minimum number of variables required to justify their deployment, need to be carefully evaluated. The objective is to incorporate functionalities such as demand tracking, power quality monitoring, and communication systems in an affordable and scalable manner, leveraging the existing communication infrastructure. Essential features include redundancy and backup systems to ensure uninterrupted data flow, as well as data centers to identify discrepancies in measurements.

- In the context of proposed smart grid functionalities, three primary themes are identified in the discussion: *renewable energy integration*, *transparency of data and access sharing*, and the *active system management*, which includes the controllability of energy systems.

- The interviewee emphasizes that *access to renewable energy* serves as a pivotal mechanism for widespread adoption of new markets and business units, and for the proliferation of new actors and roles. In addition, *transparency of data and access sharing* emerges as a foundational principle, encompassing not only the vigilance of market regulators to ensure regulatory compliance, but also the accessibility and reliability of information. Lastly, the *active system management* and controllability of energy systems play a crucial role, exerting significant influence on environmental outcomes by fostering the use of resources.

The main points made by interviewee 8 are presented in Figure 5.15. Further considerations are:

- Interviewee 8 mentions that splitting the market into several areas or by implementing local markets would further reduce liquidity. Therefore, running several markets in parallel is not envisioned. The current energy market already allows already flexibility trading, not as envisaged from Distributed Energy Resources (DERs) in the distribution grid, but for the wholesale market. Interviewee 4 partially echoes this sentiment, expressing concerns about the consequences of operating multiple dispatches, highlighting the structural implications of having two energy dispatches: the wholesale dispatch and the retail dispatch. The statements that highlight Interviewee 8's ideas are:

  > "Many of the models we are discussing today will result in overlapping markets, including balancing markets, the national energy market, and regional ESO markets. It is essential to develop a system that minimizes the issues this overlap causes. One way to achieve this is by ensuring that flexibility is not confined to a single system [...]"
  >
  > **Paraphrased from Interviewee 8**

- Moreover, interviewee 8 considers *Security of Supply* the most important cluster, followed by the *Renewable Energy Integration* and the *Market Structure and Coordination Capabilities*. In addition, the interviewee mentions that the security of supply also includes the needs to balance of supply and demand in every moment.

- Interviewee 8 discusses the potential for mitigating curtailment through the introduction of a price signal. The interviewee asserted that regional price signals, tailored to accomplish specific objectives, would inevitably exert influence on the overarching regional pricing mechanism. The ultimate market impact would depend significantly on the execution strategy. Moreover, Interviewee 8 underscores that market dynamics would undergo alteration since: 'stakeholders who can trade flexibility invariably weigh opportunity costs.' Consequently, it becomes imperative for each stakeholder to ascertain the market where they can maximize profits and the rationale behind adopting a particular course of action.

For these reasons, Interviewee 8 highlights that current market challenges include resolving line congestion to prevent the curtailment of renewable energy sources, potentially through the implementation of market mechanisms utilizing appropriate price signals. Additionally, the interviewee emphasizes that local regulations will inevitably affect upstream markets, necessitating careful coordination and balance to ensure firm power delivery and security of supply.

- Other topics mentioned in this interview include the possibility of implementing variable or dynamic tariffs to support the DSO grid. These changes also encompassed the introduction of dynamic grid usage tariffs, which could alleviate congestion. Furthermore, the interviewees emphasize the importance of considering international comparisons to learn from successful use cases where challenges faced by distribution networks have been effectively addressed. Such international use cases are regarded as valuable insights for addressing these challenges, with the understanding that they must be adapted to the specific characteristics of their regulatory framework.

- Regarding the topics of market challenges and possible changes, interviewee 8 emphasizes the challenge of integrating flexibility into wholesale markets, highlighting the inertia of the power system to implement changes. Interviewee 8 stresses the necessity of aggregating flexibility to the regional level, pointing out the lack of sufficient incentives to do so, especially given the presence of similar compensations at the Distribution System Operator (DSO) level. It is indicated that:

> ...It might take at least five years before you see on a large scale that flexibility is added to the original intraday market, and if aggregators do that, I would be glad to extend that flexibility also to the Distribution System Operator (DSO) level, but the critical thing is providing that flexibility at the inter-regional level. [...] and also, it is worth mentioning that price incentives at the inter-regional level tend to be quite similar to what you aim to achieve at the DSO level.
>
> **Paraphrased from Interviewee 8**

Moreover, interviewee 8 stressed that these two tasks of providing flexibility for the national system and creating some regional incentives for variable grid tariffs are the two most important problems to solve in the coming years, not only in Germany but across Europe. Additionally, it is expressed that "...it is hardly likely that a fully reactive power market will be achieved within the time horizon". It is pointed out that:

> "The challenge for the next almost 10 years will be to provide flexibility for the national system. Additionally, there might be some regional incentives for variable grid tariffs or similar initiatives. However, implementing these measures on a larger scale, not only in Germany but across Europe, will pose a significant challenge. Personally, I'm skeptical that we will achieve a fully reactive system within this time frame."
>
> **Paraphrased from Interviewee 8**

Both interviewees discuss the transition of energy markets towards renewable energy, focusing on grid management, communication systems, and metering systems. In addition, the interviewees discuss the differences in market structures, pricing mechanisms, and current policy implications based on their geographical realities. For example, the security of supply in Europe and the policy influence of the Russia-Ukraine conflict in the case of Germany are discussed, while in Panama, the discussion is related to the implication of a subsidy policy and its effects on the electricity price. Nevertheless, both agree that the customers react to prices and that electricity is starting to be a bit more elastic than it used to be due to storage systems and distributed energy resources.

In addition, the reorganization of distribution costs and the recognition of investment in the distribution grid is crucial if the policy intention is to promote renewable energy.

The need for communication technologies, renewable energy distribution centers, better forecasts, and grid reinforcement, among others, will increase the cost of the grid and as interviewees mentioned, "*someone will have to pay for this integration*".

Nodal pricing and adding more pricing zones are also mentioned by both interviewees, recalling that it would increase the chances and opportunities differently within the population, leading to unfair situations that the energy policy has to consider. Henceforth, the decision is more political than purely technical. "*...what happens with the common pricing zone is the fact that you can't harvest the advantages of the renewable sources in your grid, so nodal pricing and price zones are debated...*"

In addition, both interviewees mention similar clusters for the evaluation of the sustainability in the electricity market emphasizing the *renewable energy integration* and the coordination among market and actors. Indirectly, both interviewees point out the impact of the regulation on the decisions and the inertia of the system to implement any change. Therefore, the evaluation of changes cannot be easily assessed in the short term.

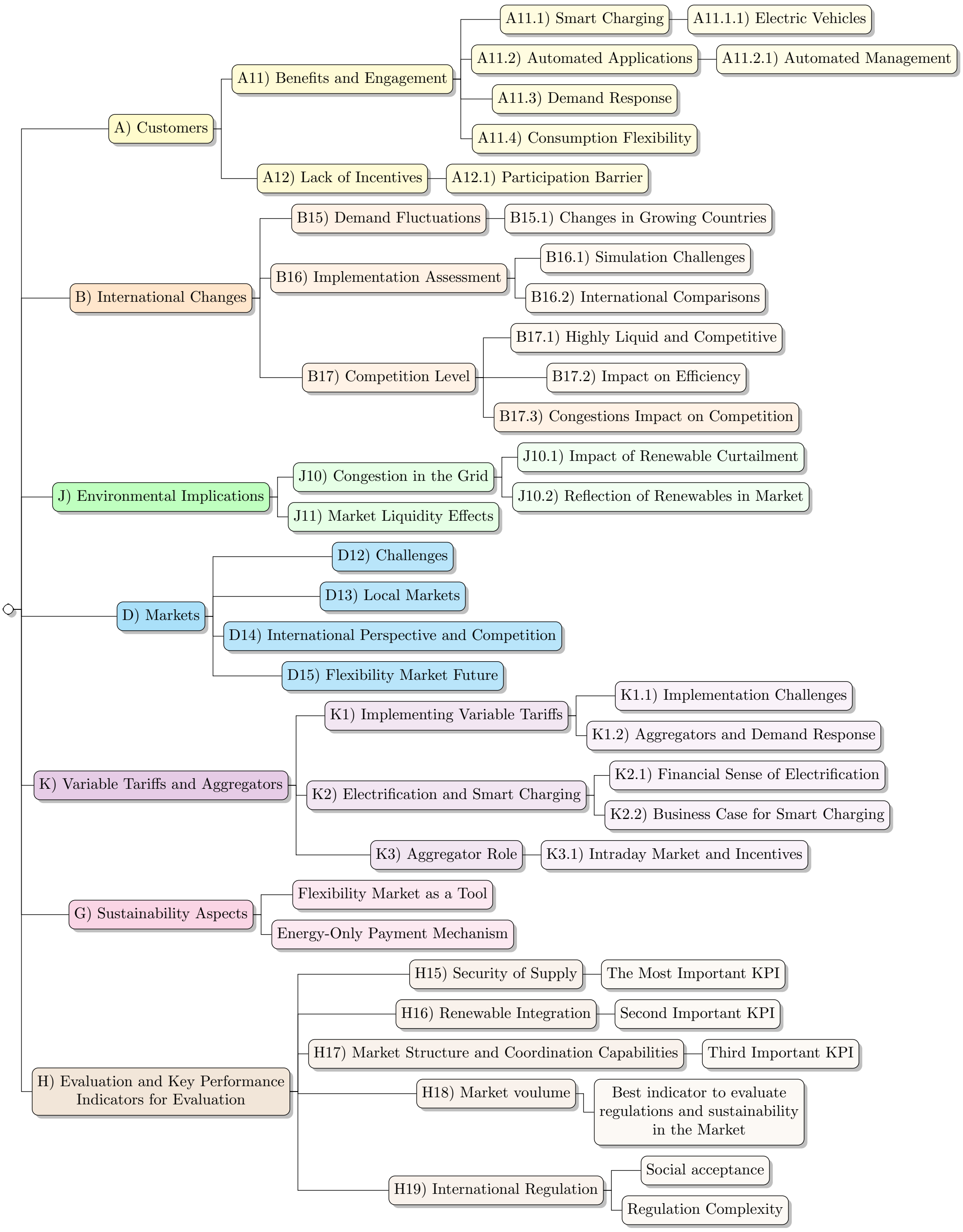


Fig. 5.15.: Mind map for Interview 8: Distribution company representative, excluding market concepts

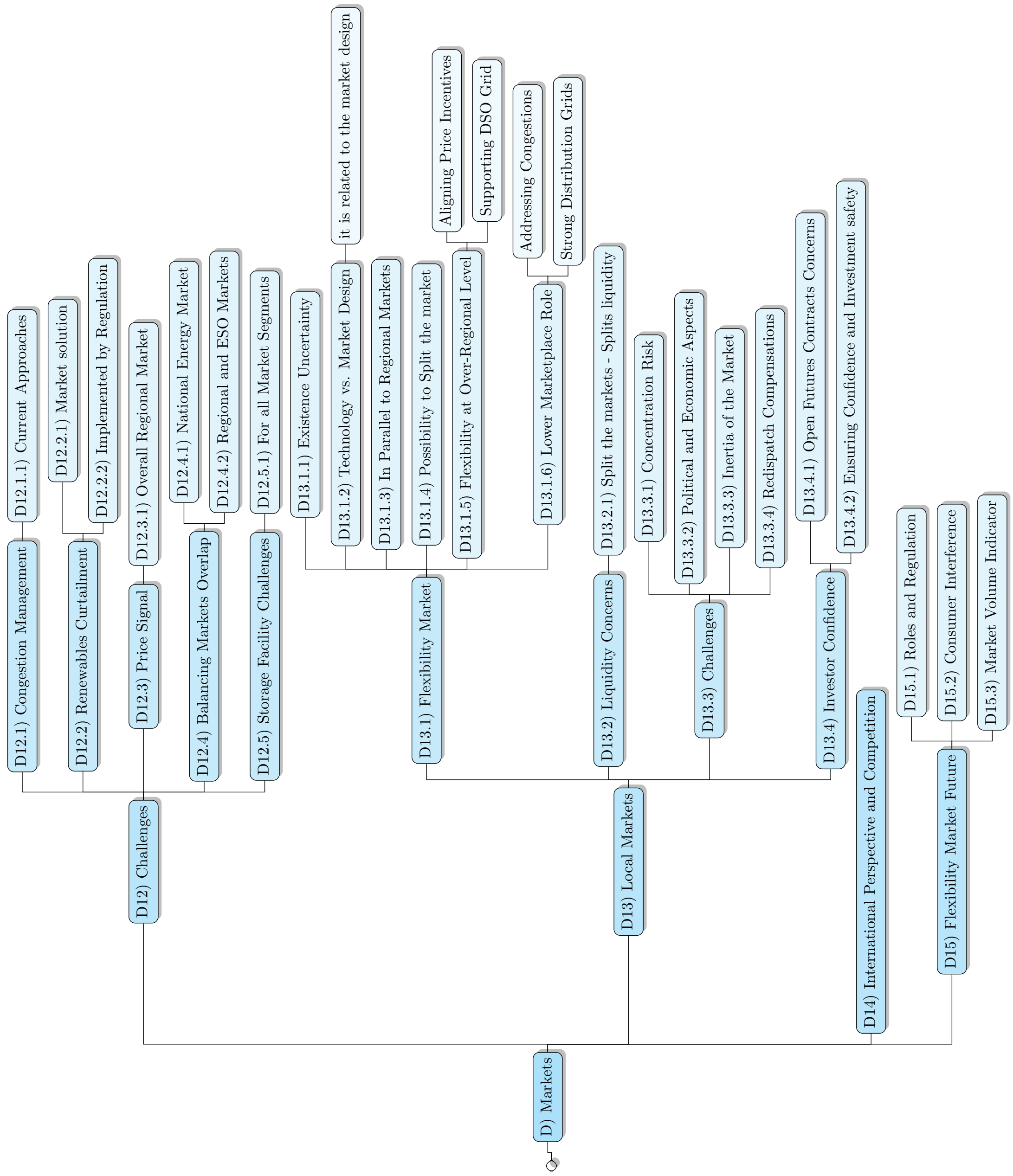


Fig. 5.16.: Mind map for Interview 8: Distribution company representative, market discussion only

Finally, the main difference between these approaches is that one interviewee considered that openness to more competition is still necessary, while the other considered that the regulations are already open to competition and that other grid issues, such as congestion or curtailment, need to be solved at a technical level.

5.1.3 Academia Perspective

The academic and research perspective plays a pivotal role in determining the most relevant topics currently under investigation. Consequently, two professors, each with more than 15 years of experience in the energy sector, were interviewed. The concept maps of the main themes discussed in each interview are depicted in Figure 5.17 for interviewee 2, and in Figure 5.18 for interviewee 6

Both interviewees propose restructuring the electricity market to accommodate new technologies and business models. This includes creating retail markets, introducing new market players such as aggregators and virtual generators, and establishing market mechanisms beyond traditional cost considerations. The goal is to promote innovation, competition, and consumer choice. The Panamanian interviewee underscored the possible creation of *retail markets* to encourage customer participation, since there is no retail market in place.

While the Panamanian interviewee emphasizes the need for contracts and a contract market, the German interviewee emphasizes the next step of introducing different markets for system services and the need for digital connectivity to enforce them. Some new market trends mentioned by the German representative are market-based procurement of inertia, market-based procurement of reactive power, market structure for flexibility, and market-based flexible network charges. Nevertheless, both highlight a shift towards more dynamic and innovative market structures.

In addition, both interviewees address various challenges such as investment uncertainty, regulatory bottlenecks, and the need for better market indicators. They propose solutions such as shorter contract durations, improved data analysis using digital technologies, and regulatory frameworks that consider technical, social, and political factors.

A contrary statement is identified: the German interviewee suggests a market structure primarily based on cost, especially for redispatch markets and other compensations. However, the Panamanian interviewee advocates for the establishment of retail markets

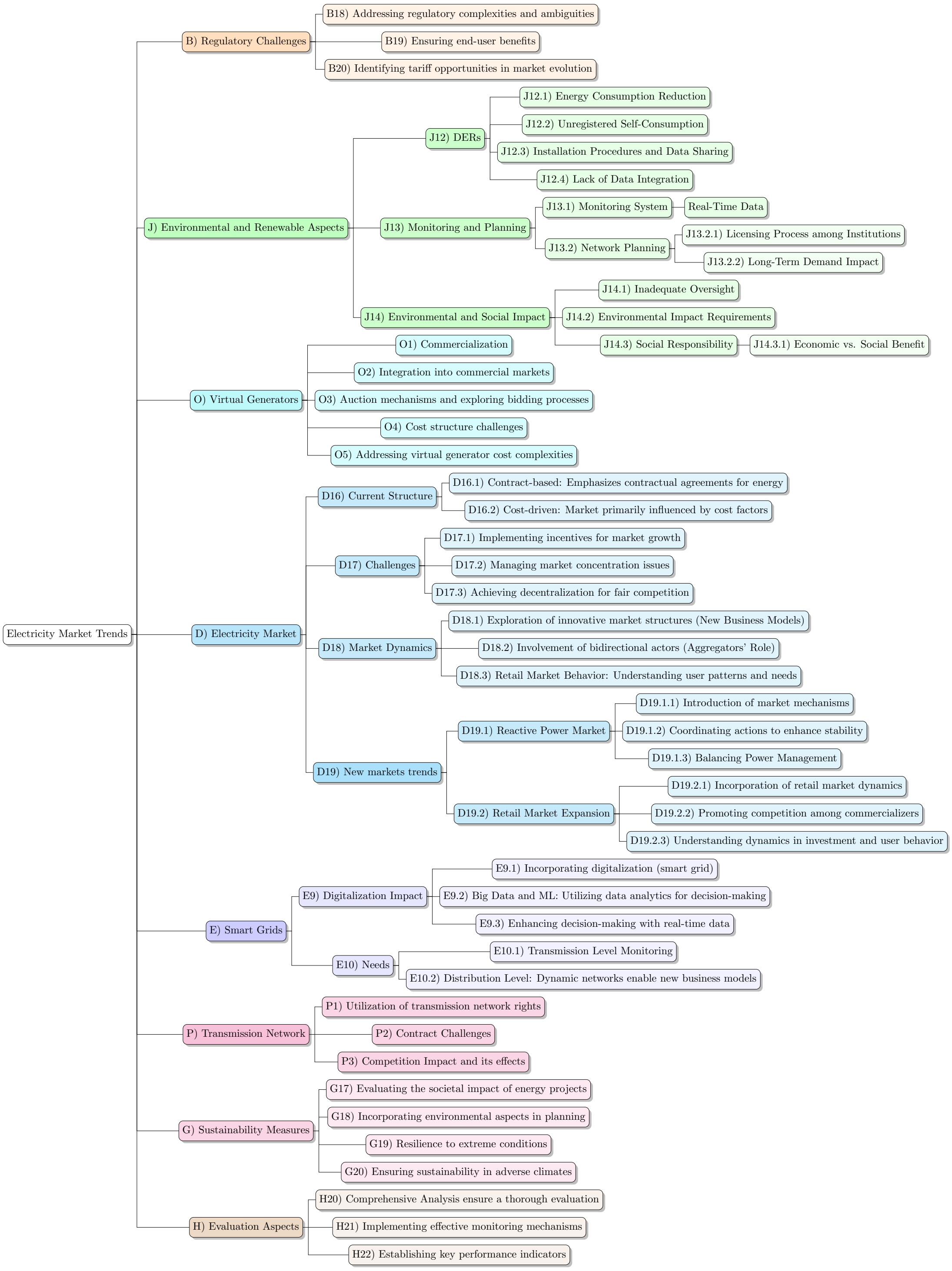


Fig. 5.17.: Mind Map Interview 2, Academia Perspective

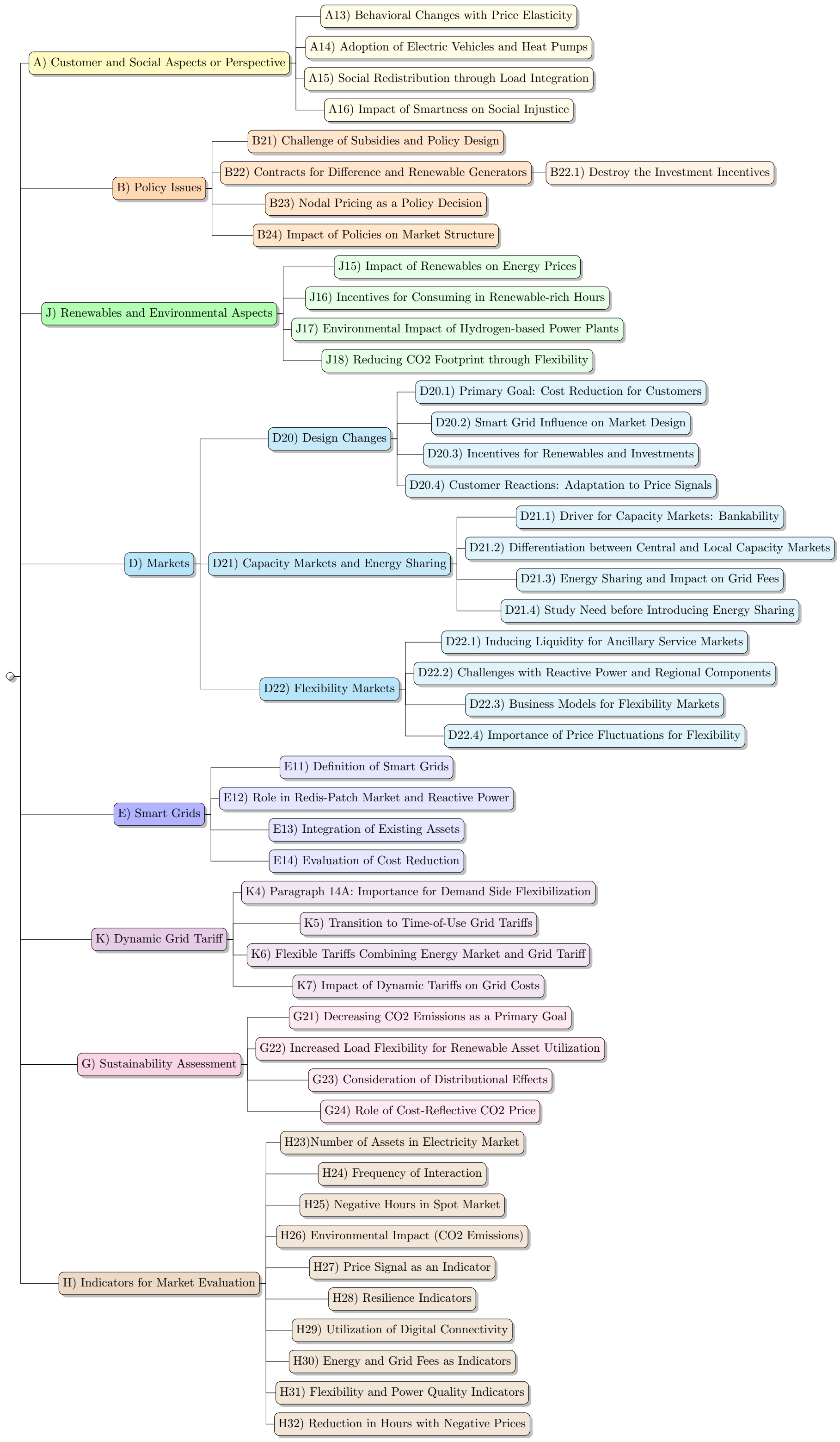


Fig. 5.18.: Mind Map Interview 6, Academia Perspective

and new market mechanisms beyond cost considerations, which are evoked by the current compensation mechanism.

The following main ideas can also be extracted:

- Digital connectivity is necessary to allow distributed loads, electric vehicles, and other technologies to participate in electricity markets. According to interviewee 6, a flexibility market allows actors (loads and generators) to react to negative prices thanks to digitalization, indicating that "*This is the main objective of introducing smart grids*". Moreover, smart technologies such as smart meters can implement dynamic tariffs, not only for energy consumption but also for grid usage (dynamic grid tariff). In addition, smart meters are necessary to send the right price signal to consumers, either from the retailer or from an aggregator.

- The primary goal of changes in market design is to reduce costs. Therefore, changes are intended to procure the integration of existing assets, primarily at the consumption site, with the implication of setting the right incentives for investments.

- The expensive price-setting power plants, which produce to cover the peak demand (e.g., hydrogen-based power plants), could incentivize the load to participate in the market to drop the prices during those hours by allowing flexibility trades. According to interviewee 8, it is crucial to allow the participation of such actors within the system to produce the interaction.

- A primary economic indicator for the effectiveness of smart grids is the ability to "**bring down the costs**". This motivates *re-distpatch measures*, reactive power market, balancing, flexibility trades, and even an alternative market design with smart grid devices. The other main indicator is **reducing the need of conventional power plants in the spot market**, ensuring that gas-fired power plants or even hydrogen-fired power plants do not set prices.

- The average electricity price needs to send real incentives to promote investment, not only at the generation site, but also for the power grid usage. This opens the discussion for dynamic grid fees.

- If the intention is to promote renewable energy connected to the distribution grid, some changes in the market design can be considered. Some of them are: the dilemma of grid fees and market design, which promotes dynamic fees; the simultaneous behavior of agents, especially when all get the same price signal; and a consideration to avoid contracts for difference as a standard mechanism. According to the interviewee *Contract for Difference* decreases the incentive to participate in a market and the mentioned two-side market premium.

- The grid capacity would need to increase, however, the potential of *"other market measures"* has to be contemplated, to reduce/avoid or defer the cost of natural expansion.
- Fostering competition in the retail market is also necessary for the applicability of flexibility markets. The price mechanisms are not agreed between the interviewees.
- Supervision of the regulation is necessary to foster changes. However, according to the interviewee 2, the evaluations and changes are too slow. Therefore, the muscle for the interventions is provided by the entities (regulator, policy makers, etc). This is expressed as institutionally.
- Information and data transparency are needed to understand changes and for planning.

Regarding markets, the following points are made by the interviewees:

- One idea of introducing more competition was to change to a price-based market. In that case the current contracting form would have to disappear. If a contract-based approach is the intention, then a good balance between the contract duration has to be found to avoid fewer auctions and Power Purchase Agreement (PPA) could reduce the opportunities to create new projects. Interviewee 2 considers it interesting to have short term contracts up to 5 years.
- The idea of flexibility is to have more liquidity on the market and to integrate existing assets. However, the regulation should avoid the implementation of price caps. Price caps crumble the business model for flexibility because they destroy the price signal.
- The main driver for capacity markets is bankability. Capacity markets are created to secure founding at low interest rates. Thus, it can be implemented that transmission operators buy capacity certificates from aggregators.
- Smart grids have the potential to significantly enhance real-time decision-making processes for energy trades. However, the successful implementation of a real-time market depends not only on the availability of energy resources, but also on the

development of a robust IT infrastructure capable of managing these dynamic interactions. In the case of Panama, both the physical infrastructure and the regulatory framework would need to be developed to enable the creation of a functional retail market. The adoption of such a market would require careful consideration of market design principles, stakeholder engagement, and mechanisms to ensure transparency and reliability in energy transactions.

- One interviewee emphasized the critical need for infrastructure, highlighting the importance of dedicated operation centers for renewable energy sources. These centers would facilitate real-time monitoring, control of renewable generation, as well as enable the observation and management of prosumer measurement points. Similarly, the implementation of a common platform for communication between prosumers or aggregators is underscored as essential to ensure efficient coordination and integration within the system.

- The role of the aggregator and the *big customer* are key actors in the dynamism of the market. However, in a cost-based approach, the aggregation cost to be presented in the market needs the creation of a specific methodology. Moreover, from the regulatory perspective, if the aggregator is the figure in charge of bidding, the distribution system does not need to activate the market, but needs to manage the system and the problems that will arise, especially because the normal pricing can only solve the TSOs' problems.

- The storage system and ancillary service markets in which fast response and reactive power can be compensated, especially for grid stabilization purposes, need to be coordinated. Especially if a local market is created, the bidding will occur if they can make more money than at the normal price.

- The creation of several markets and the participation process could lead to power market issues.

Regarding sustainability and the main clusters of smart grid functionalities to evaluate the system, the interviewees consider that the market structure is the number one aspect and provides the ability to have an active system management. The second cluster in importance is the effects on flexibility and local markets. The third most important cluster is the system observability, since the observability shows the status quo, without which it is impossible to react.

According to one interviewee, three main points need to be considered to evaluate the sustainability in the electricity system: First, reduction of CO_2 emissions. Therefore, market design must address the usage of renewable energy sources and investment centers for these sources. Second, increment of flexibility (from the customer load) to make use of the renewable assets as much as possible. And third, perform the clearing process with the overall smallest CO_2 footprint possible. This means including CO_2 emissions in price setting. From this perspective, the distributional effect on the consumer side needs to be considered. Distributional effects refer to the percentage of people that are impacted by a market rule. According to interviewee 6, distributional effects (G23) are crucial for assessing the equity implications for the population.

The interviewee indicates that the design of the market should only consider distributional effects and not try to address social injustice by distributional effects. In this case, both interviewees agree that price signals should be presented, even if it seems to be unfair, but efficient. Fairness, redistribution of income, taxes, vulnerable households, and other societal aspects should be compensated by a social policy, not by an anti-market design. Subsidies must be carefully applied or even avoided, and only vulnerable households should be compensated.

"If we want to come to a more sustainable energy system, we cannot subsidize electricity because everyone needs to see the price signal. However, not everyone should be hitting on the price signal in the same amount."

Paraphrased from Interviewee 6

In addition, the Panamanian interviewee mentions that some regulation regarding the proliferation of renewable energy must be reviewed, especially since it is currently mandatory for every distribution company to have 100% of its demand contracted. This requirement, due to self-consumption, can lead to over-contracted demand.

"The behaviors and profiles of demand, particularly with the introduction of factors such as self-consumption, alter the system's requirements. This shift often leads to over-contracting because the forecasted and contracted demand no longer aligns with the actual need."

Paraphrased from Interviewee 2

Moreover, the Panamanian interviewee highlights that the absence of complete information, whether real-time data or data on forthcoming self-consumption projects, can result in significant planning challenges. This issue affects both long-term grid planning and the short-term dynamics of the market. The problem of incomplete information arises from the lack of requirements for data measurement and sharing, and from the extensive permitting process involving various institutions. This situation reveals the need for a unified review system.

"Nowadays, we should have a system that monitors self-consumption, but there are instances of self-consumption that are not registered...[]. The lack of this information negatively impacts our planning, as we need to plan the distribution networks and determine the requirements for bidding and contracts."

Paraphrased from Interviewee 2

Two international consultants in the electricity market and sustainability are part of the interview process, both of whom have more than 15 years of experience in the energy sector. The main goal is to obtain an overview of how electricity markets have been evolving in the Latin American and United States perspectives, while Figure 5.21 does so for the European perspective.

For interviewee 1, most of the electricity market issues that Latin American countries face are due to the institutional framework. In the mind map, code *B* is related to policy issues, while institutional issues are denoted with the code *M*. Although institutional frameworks fall within the purview of energy policies, this is highlighted in Figure 5.20, where the color code for policy issues is additionally denoted as (B-M). The importance of institutional frameworks is highlighted by this interviewee, who stated:

> "In Latin America, it is important to highlight the necessity of addressing institutional issues and governmental policies that foster consumer freedom of choice. There is a tendency among governments to safeguard consumers, presuming that they will make grave errors. However, this approach engenders significant debates [...] Consequently, the regulator tends to shield consumer decisions."
>
> **Paraphrase from Interviewee 1**

A particularly salient topic in the area of institutionality is the need for clear objectives, both for the creation and evaluation of new regulations. The precise definition of objectives within regulations is crucial not only for assessing impacts but also for evaluating sustainability. Furthermore, the evaluation process itself must be objective-based. As the interviewee noted:

> “Every regulation must have clear objectives so that one can determine if these objectives are being met. For instance, if the goal is to enhance consumer flexibility and the consumer does not respond, then the objectives are not being achieved. The issue often arises when objectives are not explicitly stated.”
>
> **Paraphrased from Interviewee 1**

Therefore, the definition and clarity of regulatory objectives are fundamental for evaluating the effectiveness and sustainability of the electricity market due to new rules. Additionally, the evaluation of new regulations or changes within the electricity market must be aligned with these clear objectives, ensuring that sustainability aspects are thoroughly considered. This aligns with the discussion from Chapter 3, where the need to define regulatory objectives is emphasized when implementing morphological boxes for market adaptations.

However, as the interviewee highlights, the definition of sustainability is country-specific, since not all regions will interpret sustainability in the same manner. Therefore, it is necessary to determine also the framework and externalities linked to the region.

> "... To evaluate sustainability or to assess the aspects, it depends on each country’s definition of sustainability. For example, some countries can afford to eliminate thermal energy entirely due to their hydroelectric resources. However, if you go to a Caribbean island that relies only on thermal energy, what do we call sustainability there? Thus, it all depends on the country, its system, and the government’s objectives."
>
> **Paraphrased from Interviewee 1**

Another topic that has been impacted due to country or regional considerations has been the aggregators. The aggregator role faces an institutional problem depending on the specific country, since:

> "On the other hand, the notion of demand aggregation varies among different countries; while some perceive it merely as another trader, others recognize it as a separate and essential activity, governed by its own operational mechanisms."
>
> **Paraphrased from Interviewee 1**

Moreover, the aggregator can be a crucial actor in achieving consumer engagement and proactive consumers. Nevertheless, it is expressed that the demand aggregator has several challenges to overcome. The main one is to build customer trust, but also to offer enough incentives and have a well-organized campaign that encourages participation. Some concerns are stated:

> .. "How do you persuade the consumer to want to participate? And how do you earn their trust? [. . .] How do you communicate how much they will be charged, and what they will be charged for? What does the consumer gain? The consumer might wonder why they should bother and why not just continue purchasing as they always have without any issues? [...] Therefore, there is not yet a market. If all consumers were eager to be active, aggregators would be emerging rapidly, knowing that there is a market and a demand."
>
> **Paraphrased from Interviewee 1**

The problem of encouraging participation is compounded by the historical practice of subsidized energy prices for consumers. As elucidated by interviewee 1, along with corroborative insights from other interviewees, this practice engenders *market distortions (B27.1)*. Consequently, interviewee 1 advocates for the discernment of the drawbacks associated with *subsidies (B27)* as a means of strengthening the roles of aggregators and traders while fostering *Consumer Engagement (A)*. Furthermore, this topic is additionally related to the *Government's Role in the Implementation of Flexibility (D25.1)* for the creation of *flexible demand (D25)* and the *active participation of consumers (D24.2)* in the possible *Market Mechanisms (D24)*. Figure 5.19 depicts the general concepts between institutional issues and the market through consumer engagement.

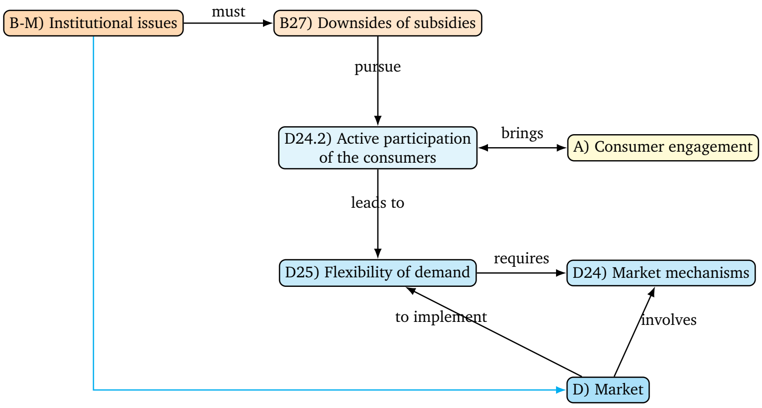


Fig. 5.19.: Relationships between institutional issues and related concepts

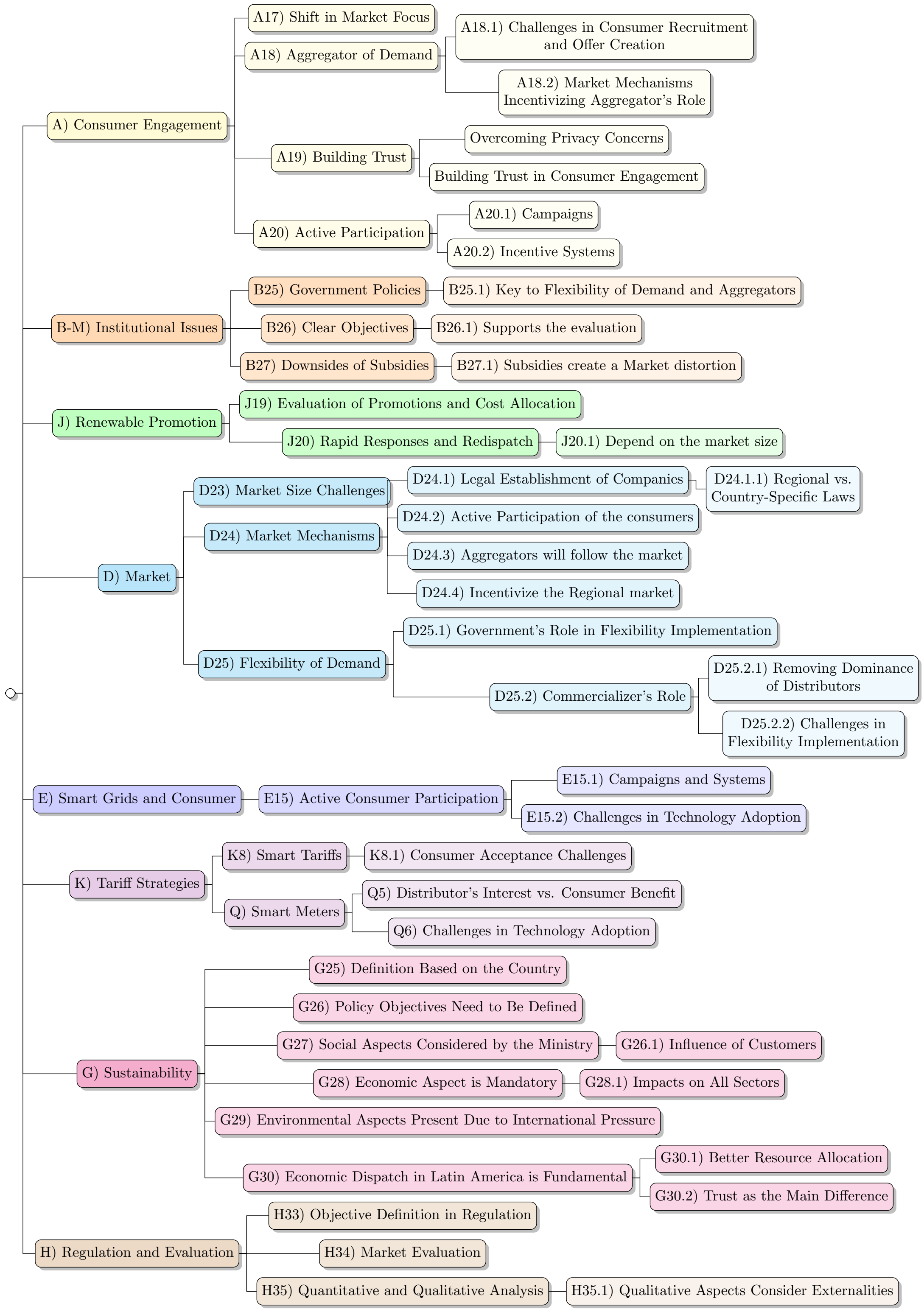


Fig. 5.20.: Mind Map Interview 1, Latin American Consultant

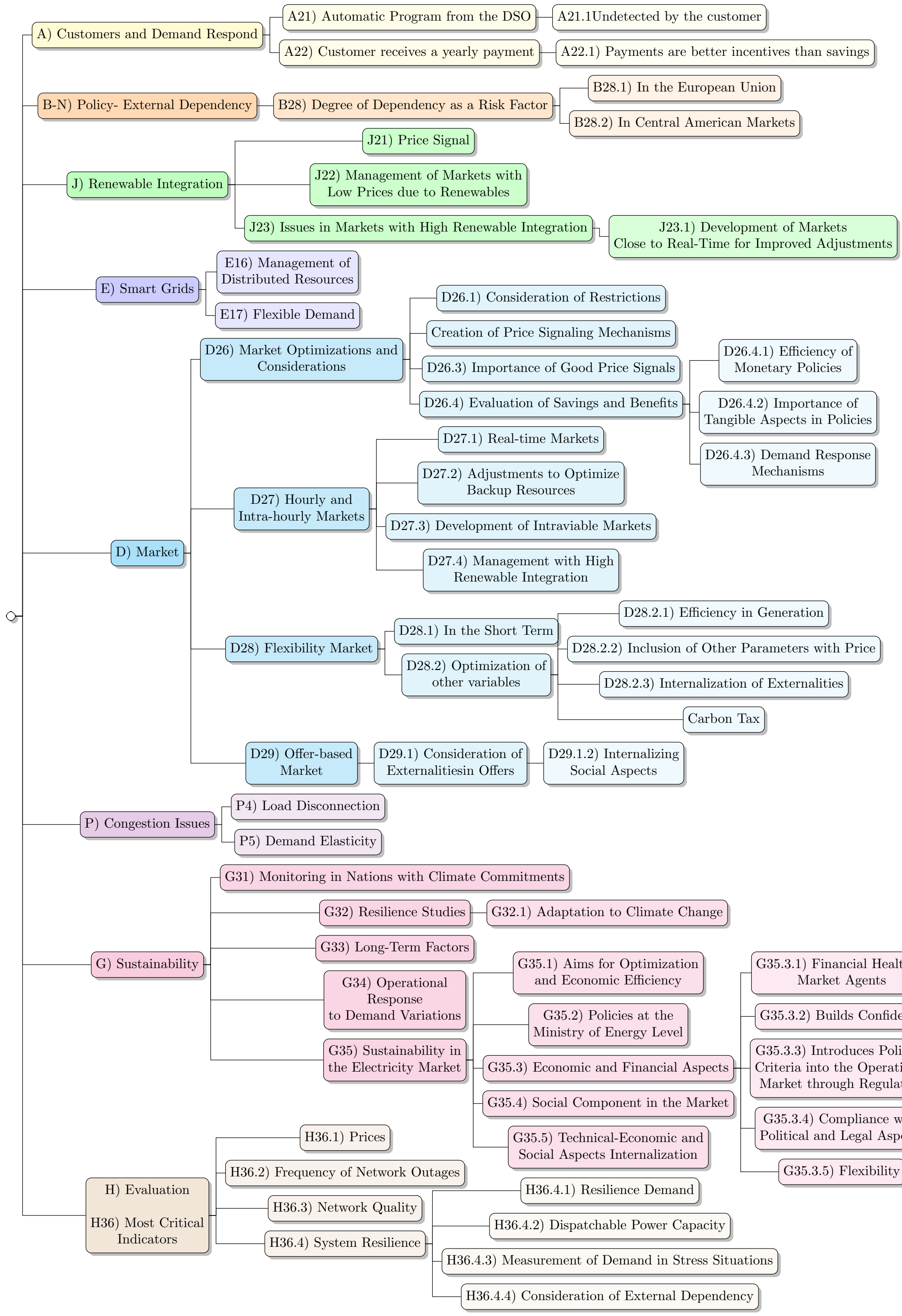


Fig. 5.21.: Mind Map Interview 5, European Consultant

Other suggestions on how to incorporate sustainability criteria in the electricity market are addressed. In this topic, interviewee 5 mentioned that:

> "The market is sustainable, but if it is not, the sector will also not be sustainable. I would like to make an important distinction here: the market itself does not necessarily require environmental considerations to be sustainable over time. The primary goal of the market is optimization. Therefore, it can supply electricity to consumers with or without incorporating environmental criteria. However, it is crucial to emphasize that the overall electrical system is not sustainable without considering these environmental criteria.[...] and the externalities including social aspects"
>
> **Paraphrased from Interviewee 5**

Furthermore, according to the perspective of interviewee 5, the legal and political aspects are more *Ad Hoc*. Therefore, the regulatory framework is the one that introduces the externalities into the market framework, to promote *Sustainability in the Electric Market G35*. From this vantage point, electricity markets aspiring to optimize all resources can also incorporate social aspects emanating from policy directives. Notably, the financial stability of market agents emerges as a crucial consideration at this juncture, particularly concerning bankability and the feasibility of active participation in such a dynamic market.

For interviewee 5, it is important to indicate that markets are optimization tools and should continue seeking the optimization of the electricity price. Therefore, to support a sustainable power system through market changes, the technical, economic, and social aspects should be internalized with the price signal. For that, the regulation has to be in charge of introducing those political criteria into the operation of markets. In this sense, all of those 'externalities' must be considered, resulting in a good price signal that builds confidence among investors, similar to the implementation of a carbon tax.

This relationship among these concepts is observable in the mind map of the interview by relating the *Creation of Price Signaling Mechanisms (D26.2)* and the *Importance of Good Price Signals (D26.3)* that belong to the market considerations and optimization with the *G35 Sustainability in Electricity Markets*, *G35.3.3* that propose the introduction of the political criteria in the operation of markets, the *D29.1*, *D28.2.3*, *D28.2.2*, and *D28.2.4 Carbon Tax*.

Regarding the indicators and evaluation procedures to consider the sustainability dimensions when evaluating new market rules, interviewee 5 mentioned that:

> "... The primary indicators at the operational level include quality, frequency of network outages, and the duration of these outages. At the market level, the most critical indicators are prices and the market's response to changes in demand. Additionally, long-term factors such as system resilience to external effects, dispatchable power capacity, and sustainability of demand are essential for a comprehensive assessment."
>
> **Paraphrased from Interviewee 5**

In addition to discussing potential market changes due to the proliferation of renewable energies aimed at achieving the energy transition, the interviewee also highlights several issues and possible adaptations. One significant issue is the near-zero pricing resulting from renewable energy sources and the need to adapt this scenario within different markets:

> "When there is a high penetration of renewable energy, market prices can become zero or even negative. This indicates that these technologies are receiving minimal compensation. There is significant discussion, particularly at the European level, on how to manage the market under conditions of very low marginal prices"
>
> **Paraphrased from Interviewee 5**

The interviewee also proposed some potential strategies for market adaptation, such as making the market more dynamic by moving toward real-time operations or even establishing intravariable markets. Intravariable electricity markets refer to electricity markets that operate on a shorter time scale than traditional day-ahead or hourly markets, allowing for the adjustment and trading of electricity in real-time or within short intervals. This includes managing various products, such as backup or reserve, more efficiently. The shift involves transitioning from traditional day-ahead markets, where forecasts are made based on relatively accurate demand predictions and predictable generation, to markets that operate on an hourly or intra-hourly basis. This change aims to address the variability introduced by renewable energy sources. The development of these markets, which already exist, is being accelerated to mitigate the impact of this variability. Furthermore, instead of planning costly backup for the following day, markets can evolve into intravariable markets that can define products multiple times a day:

> "In general, one way to adapt could be to move the markets towards real-time operations. With the variability introduced by renewables, there has been a shift towards including hourly and intra-hourly markets. Another consideration is the reserve: instead of planning backup for the following day, which is very costly, markets are now defined practically hour by hour or two to three times a day, known as intravariable markets."
>
> **Paraphrased from Interviewee 5**

In summary, both interviewees emphasized the necessity of a well-defined incentive system to enhance consumer participation. Interviewee 1 highlights the importance of campaigns and incentives (*A20.2*), while Interviewee 5 underscores the effectiveness of yearly payments (*A22*), arguing that "payments, being tangible, are more effective incentives than savings." Privacy concerns are also addressed; Interviewee 1 stresses the need to build trust between energy providers and customers, while Interviewee 5 suggests that participation should not impose additional burdens, such as extra tasks or cognitive load. Instead, participation should be seamless and undetectable in terms of workload but evident through economic incentives. This can be achieved by integrating customers into automatic programs managed by the *DSO* (*A21*, *A21.1*), where participation is nearly invisible but recognized through regular payments, such as annually. Proper ICT systems are essential for managing both customer load and distributed resources (E16). However, it is crucial that customers trust both the service provider and the technology to ensure their privacy and satisfaction are maintained.

In the context of market considerations, both interviewees deliberate on various pertinent issues, notably encompassing market size (J20), the management of low or even negative market prices, and the intricate challenges entailed in integrating a substantial volume of renewable energies (J22 and J23). Interviewee 1 underscores the imperative for comprehensive qualitative assessments, predicated on predefined regulatory objectives for any new market regulations. This underscores the crucial role of objective definition in regulatory frameworks (H33). Correspondingly, Interviewee 5 emphasized that the market, functioning as an optimization tool (D26), possesses the capacity to effectively allocate resources based on appropriate price signals which introduce externalities, such as carbon taxes and social considerations. However, this allocation is contingent upon the inclusion of these externalities within the regulatory framework. In such a scenario, market optimization tends to converge towards fostering a more sustainable power system.

Finally, in the discourse surrounding flexibility markets and demand response, Interviewee 1 emphasizes the pivotal roles of governments and commercial entities in implementing flexibility (D25.1 and D25.2). Conversely, Interviewee 5 regards flexibility as a tradable commodity, irrespective of specific actors or roles within the power system. It must be considered that a plausible rationale inherent to the interviewees' perspectives lies in their regional focus. While Interviewee 5, affiliated with the European Union perspective, may not perceive the necessity for additional actors, Interviewee 1, whose association lies with the American continent, where energy systems vary from vertically integrated to diverse levels of competition, acknowledges the necessity to streamline and incorporate roles to facilitate such exchanges.

5.2 Content Analysis and Data Mining

"Text mining generally refers to the process of extracting interesting and non-trivial patterns of knowledge from text" [Tan+99]. As detailed in Section 2.5, content analysis serves as a research methodology to identify the presence, meanings, and relationships of specific words, themes, or concepts within a text, in this case, the interview transcripts. Consequently, a comprehensive text analysis is conducted on the entire corpus of interviews to discern patterns and insights. Text mining consists of two components: "*Text refining that transforms unstructured text documents into an intermediate form; and knowledge distillation that deduces patterns or knowledge from the intermediate form*" [Tan+99]. The mined data from the interviews offer valuable insights into the linking of different sustainability aspects and their implications for market mechanisms that arise due to smart grid capabilities embedded in power systems. Understanding the link among concepts, the assessment process is supported by using the indirectly collected knowledge from experiences.

The following sections explain the text analysis of the interview and the methods to find relationships among terms.

5.2.1 Text Analysis

As a preliminary step, the open-source tool *Voyant Server 2.6.10* is employed to conduct text analysis. Text analysis tools are designed to calculate various metrics from interview transcripts, such as word frequency, term occurrence throughout the interview duration, and average words per sentence. The tool *Voyant Server 2.6.10* relies on natural language processing (NLP) techniques to segment the text, extract linguistic features, and compute relevant statistics, including term frequency graphs, concordance tables, and word clouds. These metrics are instrumental in identifying trends within each interview corpus, as they not only facilitate the analysis of the most frequently used terms but also provide the context of the usage of selected words, thereby supporting the examination of potential relationships between words.

Each interview transcription is processed with *Voyant* to analyze word frequency and the temporal distribution of word usage during the interview process. Two types of analyses are conducted: the first involved extracting metrics from each interview independently, and the second entailed processing the entire corpus of the interviews. The entire corpus comprises an English translation of all interviews collectively, without distinguishing between interviewees. Based on the entire interview corpus, Figure 5.22 illustrates the 205 most frequently used words. From the figure, it is evident that the word "market" is the most mentioned term during the interview process, with a significantly higher frequency compared to other terms such as "*energy*" and "*price.*" Additionally, terms specific to certain aspects of the interviews, such as "*sustainability,*" "*policy,*" *and* "*distribution,*" are used less frequently than more general terms.

As a subsequent step aimed at understanding the presence and usage of terms within the interview corpus, each interview is individually examined in its original language. Bubble diagrams are used to graphically represent the frequency of term usage per interviewee and their potential relationships with other terms. Figures 5.23 and 5.24 depict bubble diagrams illustrating the usage of the most significant terms pertinent to this thesis. In these diagrams, the x-axis represents the progression of each interview, while the y-axis differentiates between the various interviewees. The size of each bubble corresponds to the frequency of term usage at specific points.

Notably, the term "*markets*" appeared throughout the corpus, along with "*energy*" and "*price*". However, more specific topics such as capacity mechanisms and flexibilities are discussed at particular points within the interviews. Sustainability and the evaluation procedure are predominantly mentioned towards the conclusion of each interview or at specific points. This is observable in Figure 5.23a), where the frequency of usage of the word "*market*" is represented. The blue bubbles denote terms in Spanish, while the magenta bubbles represent terms in English.

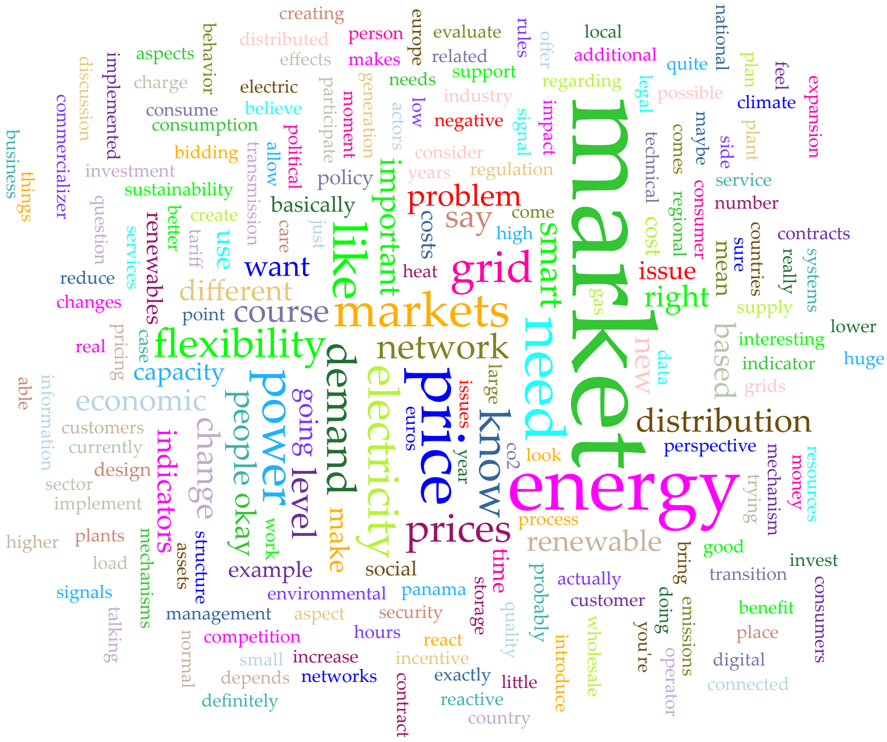


Fig. 5.22.: Keywords discussed during the interviews

In addition, Figure 5.23 b) shows the frequency of the terms "*flexibility*" and "*capacity*". These terms are mentioned during the interview at different moments with different frequencies of usage as well. It is observable that all interviews discuss "*flexibility*" topics more than "*capacity*" mechanisms, and that both terms are mentioned at specific points during the interview process.

Similarly, Figure 5.24a) illustrates the relationship between "flexibility," "price," and "sustainability" across all interviews. The term "flexibility" (flex*) in both English and Spanish is represented in lilac. Turquoise and orange represent the term "price" (pric*), with turquoise for English and orange for Spanish. Magenta and green depict "sustainability" (sust*), with magenta for Spanish and green for English. Although English terms are occasionally mentioned in Spanish interviews, it is evident that the usage of "price" and "flexibility" is smoothly distributed throughout the interviews. In contrast, interviews 6 and 7 exhibit a more intense discussion involving "flexibility," "price," and "sustainability." Furthermore, in interviews 5 and 6, the discussions of "flexibility," "price," and "sustainability" often occur together, highlighting their interconnectedness.

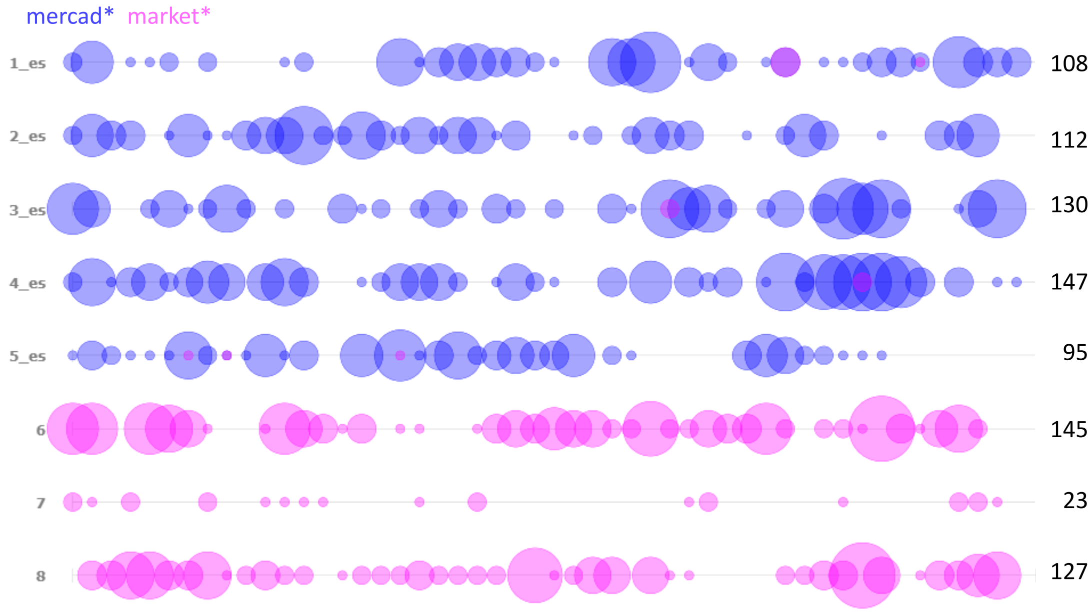
Regarding interconnectedness between the terms "*evaluation*" and "*sustainability*", Figure 5.24 b) depicts how the "*evaluation*" term is consistently mentioned across all interviews, often related with the term "*sustainability*". Interviewees 3 and 5 show the strongest relationship between sustainability and evaluation. When reviewing both graphics together, it is possible to infer that the high frequency of the terms "evaluation" and "flexibility" suggests that these concepts are core to the discussions. Moreover, while all interviews consider the term "*sustainability*", the depth and focus differ and it is emphasized based on the interviewee's perspective (policy or regional interviewees) and often overlaps with economic considerations.

Despite this analysis, linking concepts necessitates more than merely examining word proximity. It requires understanding the relationships followed by the use of different concepts. Consequently, *Qual Coder* open-source software and NLP techniques in Python are employed for the systematic coding of each interview as explained in Section 5.2.2. This coding process facilitates a deeper comprehension of the meaning of words within the context.

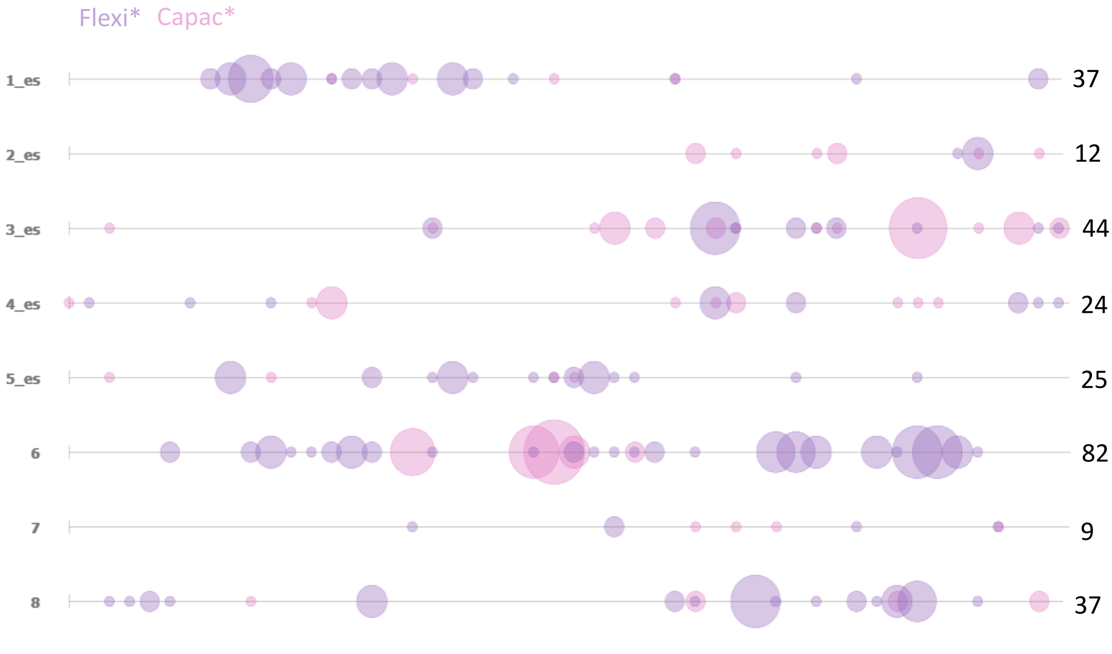
5.2.2 Data mining and relationship among topics

The second analysis is coding each statement of the interview to one main topic. To code the interviews, the tool *Qual Coder* is used. The relationships among concepts from each interviewee are processed in the language of its realization. Therefore, Spanish transcripts are analyzed to find relationships and to evaluate the use of words and concepts before translating them to English. The main advantage of coding the original text is to avoid confusion among terms due to the translation process.

Additionally, the corpus of each interview is processed in Python, utilizing NLP techniques to perform semantic analysis and identify patterns and relationships within the text and the main clusters, thereby supporting the codification and clustering process. The NLP Python library is also used to tokenize each interview corpus and support the extraction of relationships. A review process is required since some words refer to different concepts. For example, the word "*energy*" is used in reference to *Energy Only Markets*, a market type, but also in "*energy consumption*", which refers to the customer's demand or user behavior. This process is utilized to find the relationships mentioned in Section 5.1, making the interconnection between various conceptual domains discernible.

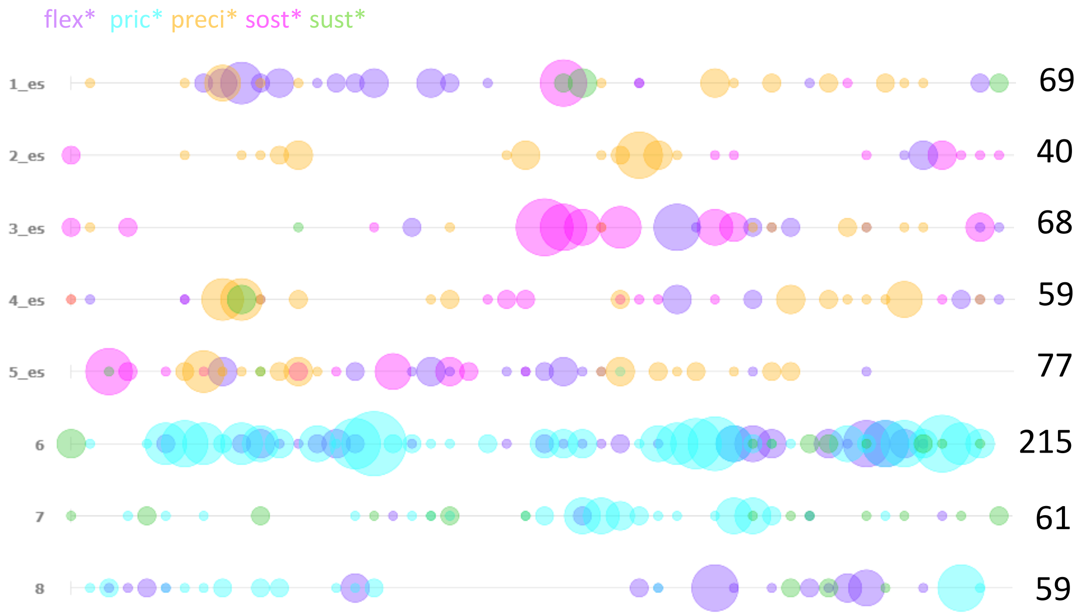


(a) Frequency of the term *market* in both languages

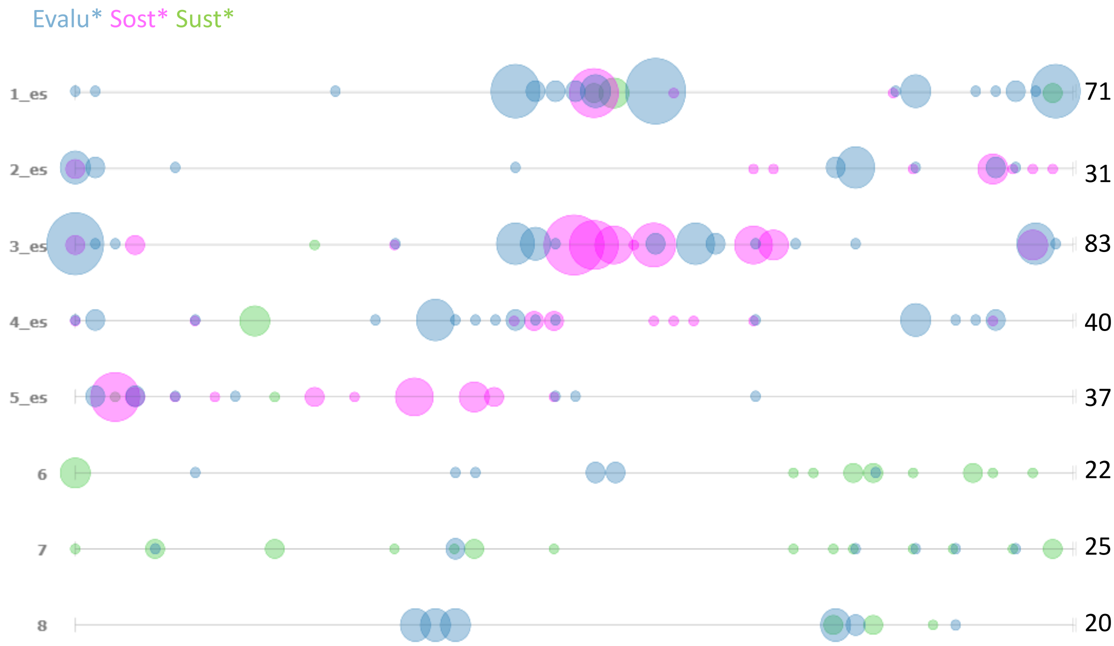


(b) Frequency of the terms *flexibility* and *capacity*

Fig. 5.23.: Frequency and occurrence of terms *market*, *flexibility* and *capacity* per interview, analyzed in both languages.



(a) Frequency of the terms *flexibility*, *price*, and *sustainability*



(b) Frequency of the terms *evaluation* and *sustainability*

Fig. 5.24.: Frequency and occurrence of terms per interview, with *flexibility*, *price*, *sustainability*, and *evaluation* analyzed in both languages.

For instance, interviewee 1 notably underscored the consideration of rapid responses and redispatch measures to advance renewable energy initiatives, contingent upon the dimensions of the market (*market size D23*). This contention is exemplified through a comparative analysis, contrasting regions endowed with a substantial proportion of hydropower facilities featuring reservoirs against geographically isolated regions lacking such renewable energy storage infrastructure or resources (island).

Consequently, the pivotal role of market size emerges as a significant impediment to overcome during the implementation of novel regulatory frameworks. This nuanced discourse is graphically represented in Figure 5.25, depicting the intricate nexus between market size challenges and the promotion of renewable energy.

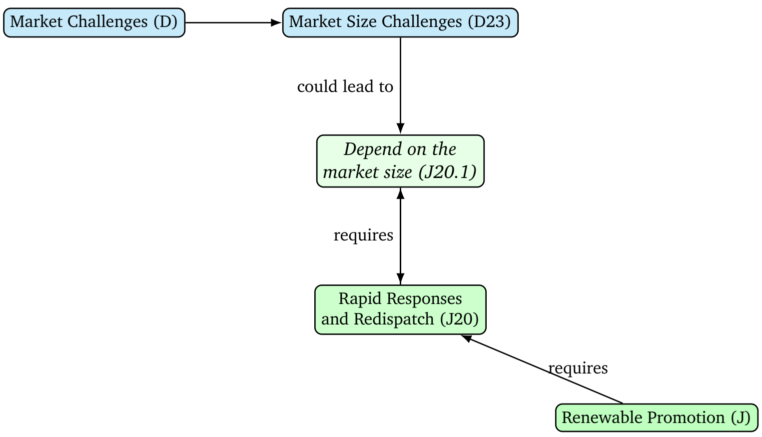


Fig. 5.25.: Relationships between market size and renewables

The analysis conducted for each interviewee results in a unified mind map accessible via the QR code provided in Figure 5.1. The relationships among words and topics are analyzed to extract a list of common indicators and themes that can be utilized to evaluate impacts on sustainability dimensions, considering potential changes in market rules. This is possible because these concepts are also linked to the four dimensions of sustainability.

5.3 Results on the Relationships Between Sustainability and Markets from the Interview Process

Evaluating the frequency of words from the interviews and their associated topics is the first step in understanding and clustering several aspects of the interviews. This approach allows for the identification of key themes and categories, which are subsequently organized into meaningful themes that are coded and then related based on the content of the interview. The relationships among the concepts expressed by the interviewees in the 8 mind maps are systematically analyzed to identify key sustainability indicators and considerations for different market mechanisms. These mind maps encapsulate diverse perspectives on economic, social, environmental, and regulatory and legal aspects, which are then synthesized into a comprehensive unified mind map.

By aligning these concepts, specific evaluation criteria are discovered based on the combinations of market mechanisms and characteristics as used for Chapter 4. The selected combinations are: Cost-Based Approach, Bidding Mechanisms, Contracts or PPAs, and Neighborhood Grids or Energy Communities. These aspects offer specific perspectives and considerations when aiming for change in their implementation, particularly for flexibility markets.

An important parallel aspect is that economic aspects extracted from the interviews, such as "Aims for Optimization and Economic Efficiency" and "Financial Health of Market Agents," are highlighted across different market mechanisms, emphasizing their centrality to evaluating market efficiency and stability. Similarly, social indicators, such as "Influence of Customers" and "Social Responsibility," are critical aspects in assessing the impact of market rules on consumer engagement and societal well-being.

The analysis revealed that some indicators are common across multiple market mechanisms, demonstrating their broad applicability. For instance, statements such as "Decreasing CO2 Emissions" and "Renewable Energy Management" are relevant to various market mechanisms, highlighting the importance of the environmental dimension of sustainability. Some concepts expressed in several mind maps are not directly represented by an indicator but are essential in understanding the context and the major concerns in the evaluations of changes in electricity markets. Examples of this include concepts like "*The Aggregator Roles and the Customer Inclusion*", "*Institutional*", and "*Data Volume and the Needs of Control Centers.*"

Table 5.1 relates the most important indicators mentioned by the interviewees. Table 5.2 summarizes the most important considerations for each sustainability aspect based on different market mechanisms mentioned based on the interviews. While "*neighborhood communities*" is not defined as a market mechanism, it possesses special considerations for its development within a regulatory framework either with level 3 or level 4 of competition.

Tab. 5.1.: Sustainability dimensions and common indicators

Sustainability dimension	Common indicators
Economic	H3) Cost-benefit analysis H27) Price signal as an indicator G35.1) Aims for optimization and economic efficiency D27.4) Management of markets with high renewable integration H18) Market volume H15) Security of supply H16) Renewable integration H17) Market structure and coordination capabilities
Social	G27.1) Influence of customers G28.1) Impacts on all sectors A11.3) Demand response A8) Facilitating energy trading for prosumers G27) Social aspects considered by the ministry G10.2.1) Economic feasibility and technical viability A20.2) Incentive systems D24.3) Aggregators will follow the market J14.3) Social responsibility
Environmental	G29) Environmental aspects present due to international pressure H26) Environmental impact (CO2 emissions) G21) Decreasing CO2 emissions as a primary goal J18) Reducing CO2 footprint through flexibility G22) Increased load flexibility for renewable asset utilization J16) Incentives for consuming in renewable-rich hours G24) Role of cost-reflective CO2 price J17) Environmental impact of hydrogen-based power plants J9.1) Active system management E16) Management of distributed resources
Legal	H20) Comprehensive analysis ensures a thorough evaluation H22) Establishing key performance indicators B23) Nodal pricing as a policy decision H33) Objective definition in regulation D29.1) Consideration of externalities in offers H35.1) Qualitative aspects consider externalities B22) Contracts for difference and renewable generators H34) Market evaluation

Tab. 5.2.: Sustainability aspects and considerations for market mechanisms

Sustainability aspect	Cost-based approach	Bidding	Contracts	Neighbourhood communities
Economic	G35.1) Aims for optimization and economic efficiency D27.4) Management of markets with high renewable integration	D26.3) Importance of good price signals D8.1) Steering mechanism for decarboniza-tion	G35.3.1) Financial health of market agents B2) Transparent cost sharing	G23) Consideration of distributional effects A16) Impact of smartness on social injustice
Social	G27) Social aspects considered by the ministry G10.2.1) Economic feasibility and technical viability	A20.2) Incentive systems D24.3) Aggregators will follow the market	G27.1) Influence of customers J14.3) Social responsibility	A11.3) Demand response A8) Facilitating energy trading for prosumers
Environmental	G21) Decreasing CO2 emissions as a primary goal J18) Reducing CO2 footprint through flexibility	G22) Increased load flexibility for renewable asset utilization J16) Incentives for consuming in renewable-rich hours	J9.1) Active system management E16) Management of distributed resources	G24) Role of cost-reflective CO2 price J17) Environmental impact of hydrogen-based power plants
Legal	B23) Nodal pricing as a policy decision H33) Objective definition in regulation	H20) Comprehensive analysis ensures a thorough evaluation D29.1) Consideration of externalities in offers	B22) Contracts for difference and renewable generators H35.1) Qualitative aspects consider externalities	G19) Resilience to extreme conditions D22.1) Inducing liquidity for ancillary service markets

5.4 Identification of Key Indicators Based on the Analysis of the Entire Interview Process

The interviews played a pivotal role in identifying connections among topics that may initially appear unrelated but are essential for implementing a comprehensive sustainability assessment of market changes. Through the interview process, and by addressing the primary concerns of each participant regarding the evaluation of new market rules, a list of concepts that can be related to the indicators corresponding to the four sustainability dimensions is developed. These KPIs and concepts are further validated using a synthetic use case which encapsulates the main considerations for different payment mechanisms to facilitate trading flexibilities in the retail distribution system. Additionally, all concepts derived from the interviews are systematically evaluated against the sustainability dimensions, ensuring that the core concerns of the interviewees are adequately reflected in the proposed indicators for each dimension.

Figure 5.26 synthesizes the primary considerations for different payment mechanisms to facilitate trading flexibilities in the retail distribution system (implementation of a flexibility market). This figure evaluates cost-based approaches, direct contracts, and bidding mechanisms, and the feasibility of enabling neighborhood communities to trade energy surpluses among themselves. These potential "*new market rules*" incorporate several key concepts derived from stakeholder interviews, alongside the indicators employed to assess these concepts.

The elements in Figure 5.26 are systematically organized around the central objective of achieving sustainability in the context of changes in the electricity market. The overarching objective is described in Chapter 3. Each proposed concept is linked to findings from the interviews and considers the relevant indicators to thoroughly analyze the resulting changes in the intended sustainability objectives (aligned with specific market changes).

It is important to address the complexity of the concept of sustainability, whose definition significantly depends on contextual considerations, including the policies implemented in each region. In this thesis, the evaluation of changes in the electricity market and their impact on sustainability is carried out by analyzing the legal, economic, social, and environmental dimensions. Finally, it is proposed that these results be compared against the objective for which the change is implemented. Considering key indicators and concepts within each of these dimensions supports a holistic evaluation approach.

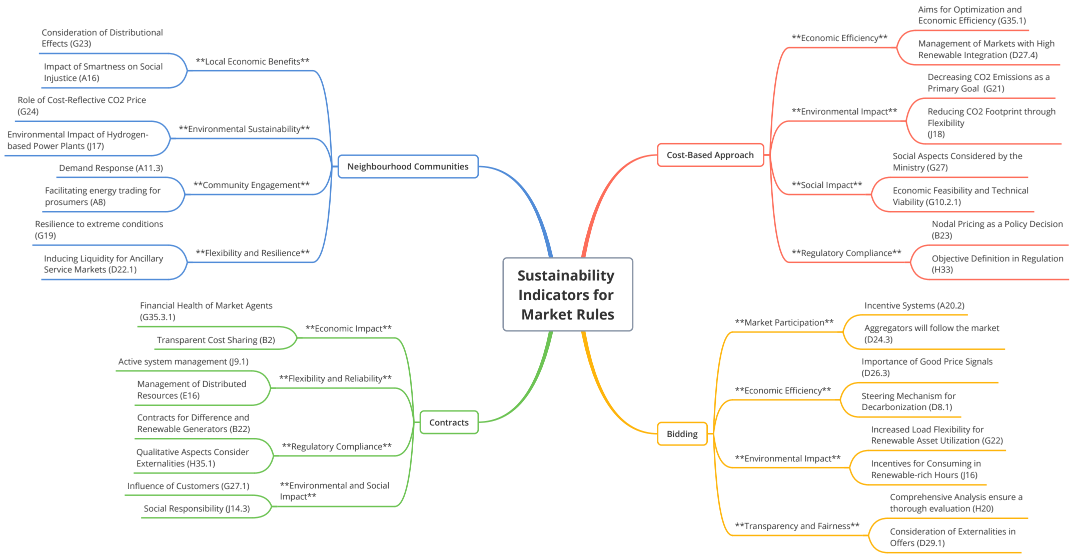


Fig. 5.26.: KPI for evaluating various market types.

Figure 5.27 presents a concept map that highlights the main indicators and concepts for evaluating each sustainability dimension. This representation identifies market aspects that are *strongly* linked to each dimension. These concepts are used in the evaluation phase to ensure a comprehensive sustainability assessment of market changes.

Moreover, additional indicators are proposed, which are not derived from the bibliometric analysis, but are designed to address specific concerns raised by interviewees regarding the assessment of particular market changes. These indicators are:

- **Social benefits for the customer with inequality aversion.**
- **Simpson Index of Diversity Performance Indicator represented as** $(1 - D)$**.**
- **The Electricity Security of Supply Dependency Indicator (ESSDI).**

Social benefits for the customer: Even without the introduction of new markets, these indicators provide insights into system behavior from the customer's perspective. The most relevant KPI is the "*Maximal Social Welfare*", adjusted for constant (relative) inequality aversion [BGG22].

$$\text{SWF} = \frac{1}{(1-\varepsilon)} - \sum_r P_r w_r^{(1-\varepsilon)} \tag{5.1}$$

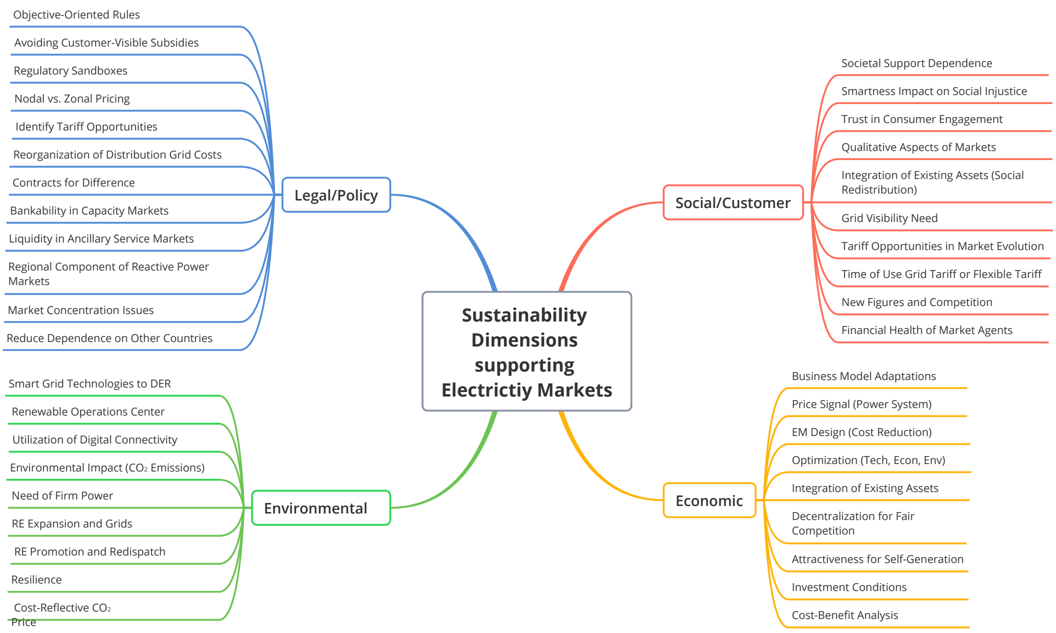


Fig. 5.27.: General interview concepts considering sustainability dimensions.

Where w_r represents the money-metric per-capita welfare level, P_r the population of the region under study and ε is the inequality-aversion coefficient. This indicator supports the social concern about the consumers' benefit perception and the uncertainty of investment in smart technologies as they might, at the end, hinder the less accommodated user.

In this thesis, additional indicators are proposed to evaluate the participation of actors in different markets, serving as a measure of performance diversity. Such indicators can be applied to analyze the behavior of actors who place bids within a specific market. In this context, the *Simpson Index* is used as a tool for assessing the social dimensions when a market system is designed for customer interactions.

The Simpson Index of Diversity, denoted as $(1 - D)$ is shown in equation 5.2. This indicator is employed to determine the dominance of accepted offers by a specific actor. In the equation, S is the total number of actors that offer in the particular market, N is the total of accepted offers in the market for the evaluation period, and n is the number of accepted offers from the actor i.

$$D = 1 - \frac{\sum_{i=1}^{S} n_i(n_i - 1)}{N(N - 1)} \tag{5.2}$$

The indicator yields a value between 0 and 1. Higher values indicate a greater diversity of offers. An example case involving three actors offering flexibility over the course of a year. The percentages represent the number of accepted offers for each actor. Figure 5.28 illustrates the distribution of accepted offers among three actors over a one-year period, along with the corresponding values of the *Simpson Index of Diversity*, denoted as $(1 - D)$ Index. Each month is represented by a stacked bar, where the segments indicate the percentage of accepted offers attributed to each actor. The graphical representation of the Simpson indicator is depicted by the black line overlaying the bars in Figure 5.28.

The Simpson Indicator provides insight into the relative participation of each actor within the market, which measures the diversity of accepted offers. A higher value signifies a more equitable distribution of accepted offers among the actors, indicating that no single actor is dominant. This implies a balanced participation among actors, indicative of a competitive and diverse market environment. Conversely, lower values indicate a concentration of accepted offers by fewer actors, suggesting limited diversity, reflecting a scenario where nearly all accepted offers are concentrated with a single actor. For instance, during months like November, where only one actor is predominantly active, the index value is notably low.

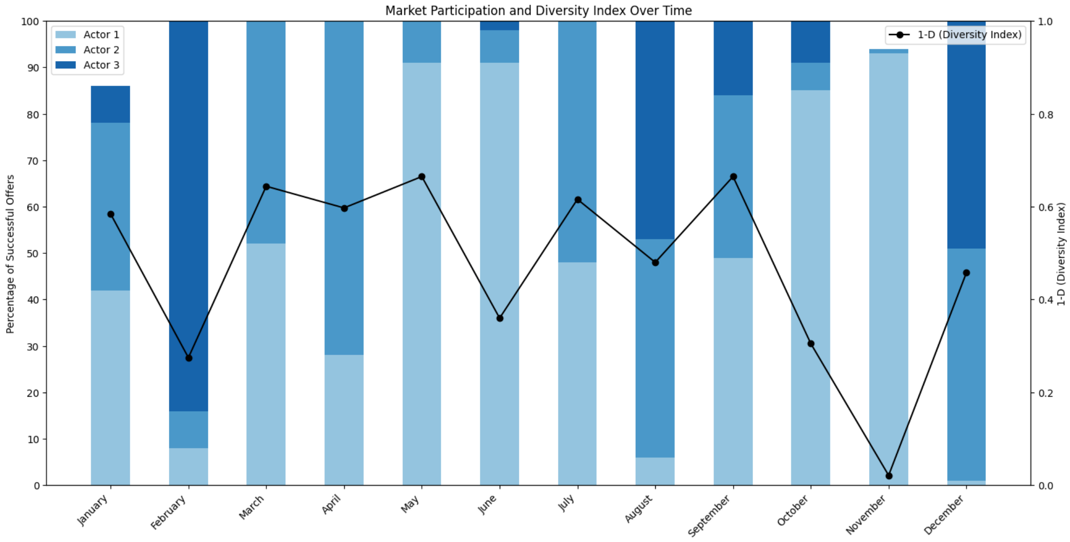


Fig. 5.28.: Applicability of the *Simpsons Index of Diversity*

Legal/ Policy Indicators:

The Energy Security Indicator (ESI) is proposed to evaluate the direct dependency of energy imports based on primary energy [MDA18]. In this thesis, this indicator is modified to evaluate only electricity national production and imports. Therefore, the formulation is modified. The new resulting indicator supports the security of supply assessment and dependency of electricity imports. This modification is of utmost importance for evaluating the coordination of regional long-term planning and for assessing the possibility of developing regional power plants based on each country's dependency perspective. These aspects are of relevance for the performance evaluation of regional markets such as the Electricity Regional Market of Central America.

To implement the *Electricity Security of Supply and Diversity Indicator (ESSDI)*, it is necessary to take into account the equations of the Energy Security Indicator (ESI), which evaluate the diversity of primary energy sources (such as wind, solar, hydro, coal, etc.) and the extent of dependence on primary energy imports from other countries [MDA18]. The *country risk* between the exporter and importer countries can also be considered. By applying the diversity equation for various energy types and evaluating it for electricity, the following formulations are derived:

$$\text{ESI} = -\sum_{i=1}^{N} c_i p_i \ln(p_i) \tag{5.3}$$

$$c_i = \left(1 - \text{dm}_i \left(1 - \frac{\text{IM}_i^m}{\text{IM}_i^{\max}}\right)\right) \tag{5.4}$$

Where:

- i denotes types of primary energy,
- p_i is the share of primary energy i,
- N is the number of primary energy types,
- IM denotes the number of origins of primary energy imports (this differs by country and by energy source). It depends on the origins of primary energy imports, the share of imports of primary energy and the the risk indicator from each country that supplies energy to the country under evaluation.

Therefore, by considering only electricity without taking into account the production source of the electricity imports, the equations for the ESI can be used to elaborate the ESSDI, where the coefficient c accounts for the diversity of imports and the risk of the countries associated with those imports. Additionally, the risk of the country under evaluation is added. Subsequently, the coefficient and its dependent variables are calculated as follows:

$$\text{ESSDI}_e = -c \cdot p_e \cdot \ln(p_e) \tag{5.5}$$

$$\text{ESSDI} = (1 - \text{risk}_R) \cdot p_e - c \cdot \text{dm} \cdot \ln(\text{dm}) \tag{5.6}$$

$$c = 1 - \left(1 - \frac{\text{IM}^m}{\text{IM}^{\max}}\right)(1 - \text{risk}_R) \tag{5.7}$$

$$\text{IM}^m = -\sum_{j=1}^{M} A_j \cdot m_j \cdot \ln(m_j) \tag{5.8}$$

$$\text{IM}^{\max} = \ln(M) \tag{5.9}$$

$$A_j = \frac{r_j}{\text{max}(r_j)} \tag{5.10}$$

Where:

- p_e: Proportion of electricity produced domestically
- dm: Proportion of electricity that is imported (1 - p_e)
- m_j: Proportion of electricity imported from country j. This is used to calculate the weighted diversity of electricity imports. High dependence on a single country can increase vulnerability, especially if that country has a high-risk indicator
- r_j: Risk indicator for country j
- risk$_R$: Risk indicator for domestic production
- M: Number of countries from which electricity is imported
- IM^m Diversity of Imports
- IM$^{\max}$ Maximum Diversity

- A_j Risk Adjustment

The implementation of the *Electricity Security of Supply Diversification Index (ESSDI)* and the $ESSDI_e$ which uses both the entropy-based negative equation and the alternative formulation provides a comprehensive analysis of the security of electricity supply. The negative entropy-based equation formulated in 5.5 effectively penalizes high concentrations in domestic production and promotes diversification by leveraging principles from information theory. This approach underscores the importance of a diversified energy portfolio, where a more negative ESI_e indicates lower security due to high dependency on a single source.

In contrast, the alternative formulation, presented in 5.6, incorporates a balance between the proportion of domestic production and the diversification of imports, adjusting for associated risks as well. This equation allows for both positive and negative values, providing a nuanced view of the energy security landscape where higher positive values indicate greater security. The graphical representation of these indices, where import shares and risk levels are color-coded, highlights the dynamic interplay between domestic production, import diversification, and associated risks, offering valuable insights for policymakers and energy analysts.

The dual-approach implementation of the ESSDI is expected to provide a robust framework for evaluating and enhancing the reliability of electricity imports. The entropy-based negative ESSDI equation is particularly useful for identifying vulnerabilities in energy systems with low diversification, as it quantitatively captures the entropy or unpredictability in energy supply sources. This measure is crucial for countries aiming to mitigate risks associated with over-dependence on singular energy sources. Conversely, the second equation, with its balanced consideration of domestic production and import diversification, offers a practical tool for countries with varied energy portfolios, enabling them to assess and optimize their energy security strategies. This comprehensive approach not only aids in immediate policy formulation but also in long-term strategic planning, making it indispensable for achieving sustainable and secure power systems.

Figure 5.29, which supports equation 5.5, corresponds to an entropy-based formulation. This figure shows that that higher $ESSDI_e$ values are related to lower own-country risks and more balanced import dependencies. This supports the theory that diversification plays a crucial role in enhancing the security of supply in this approach. Moreover, the entropy-based $ESSDI_e$ shows lower values for high own-production shares even at low risks, since it penalizes the dependency on a single supply source. The distinct colors represent own country's risk levels.

Figure 5.30, that supports equation 5.6 depicts that the security of supply is achieved under conditions of high domestic production and minimal associated risks. This graph also reveals the vulnerabilities inherent in scenarios with high import dependencies and elevated risks, where lower ESSDI values indicate significant exposure to supply disruptions. These extreme conditions underscore the importance of both minimizing import dependency and managing associated risks to optimize the security of supply.

By contrasting both formulations, it can be inferred that diversification is pivotal in the entropy-based approach and that the ESSI approach offers the possibility to evaluate positive and negative impacts on the security of supply. The combination and usability of both indicators provide a robust framework for assessing energy security strategies, particularly under varying levels of domestic production and import risk scenarios.

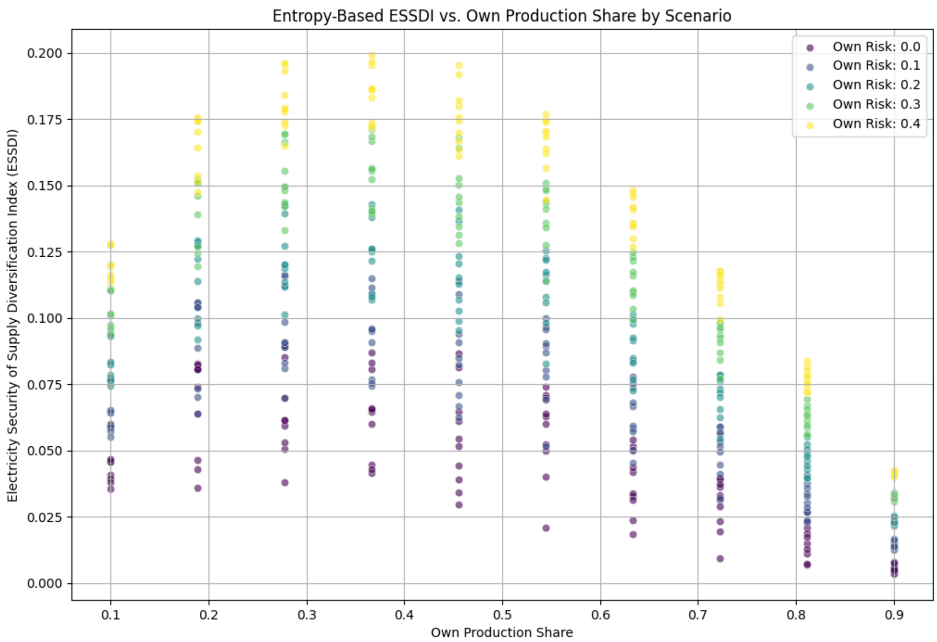


Fig. 5.29.: Entropy-based ESSDI vs. own production share by scenario

Electricity Dependency and country risk factor: A high country risk factor makes investors less willing to invest, underscoring the need for policies that ensure long-term

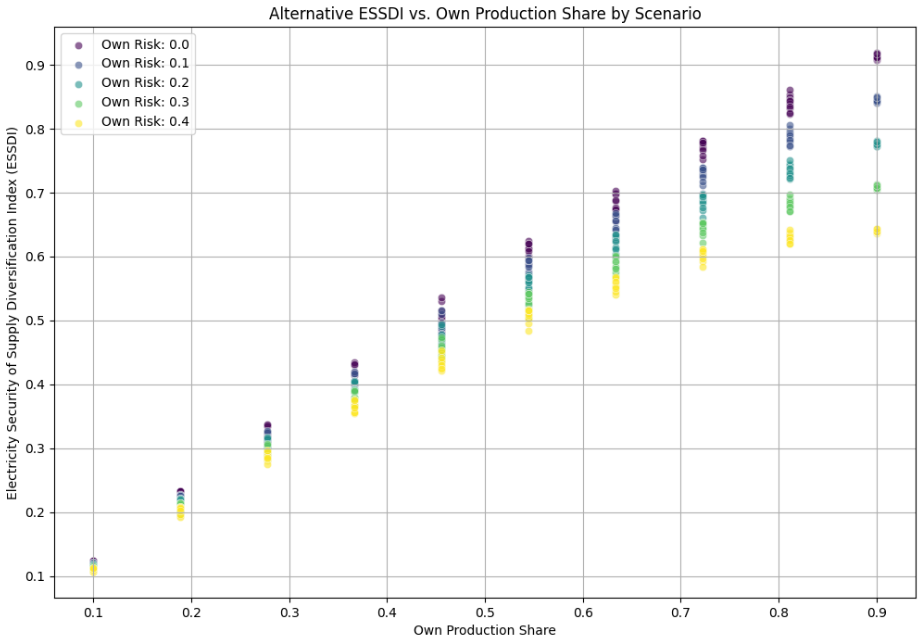


Fig. 5.30.: Alternative ESSDI vs. own production share by scenario

supply. Regarding dependency, it is necessary to consider the potential establishment of policies that can both reduce the dependency risk and simultaneously facilitate the integration of a common market. In the case of European countries, the indicator estimates the dependency on non-EU countries. Therefore, the applicability of this indicator depends on the specific region being evaluated.

Customers and actors' participation: These indicators have a strong connotation with benefits and customer inclusions. They can be used to assess not only customer participation within the market, such as in local markets or offering flexibility through demand response and active/reactive power, but also to evaluate communication among customers and actors within the system. Some indicators also consider the improvement in the system by citizen feedback and the customers-provider exchange rate. Furthermore, to evaluate the system's response to a specific policy, it is proposed also to use the *Margalef Index*to assess the diversity of actors offering a particular service to the grid. The *Margalef index* is defined as:

$$I = \frac{S - 1}{\ln N} \tag{5.11}$$

In equation 5.11, the S represents the number of customers associated with a market out of the total number of customers, N.

Regarding environmental indicators, it is observed the need for the generation diversity influenced by seasonal factors. This indicator is included to evaluate the weather externalities of the system and the availability of natural resources in the generation of clean energy. This is crucial in regions with extreme weather and seasonal variability.

Additional KPIs for supporting the legal dimension or the efficiency of a market implementation are contingent upon the existence of various factors, including renewable energy policies or goals, stringent power quality policies, prosumers and customer inclusion policy, and the presence of flexibility, local or capacity markets. The indicators for estimating the coordination capabilities are closely tied to the transparency data access sharing policy. Many of these functions are already in place in European countries. However, it is crucial to emphasize the need for ongoing monitoring and evaluation.

5.5 Conclusion

In this chapter, the evaluation process based on interviews is presented. The corpus of the interviews is processed with text mining tools to transform unstructured text into a more intermediate form to support the knowledge creation. Moreover, to find patterns between concepts, the interconnectedness of topics mentioned by each interviewee is coded and organized in mind maps.

The main concepts and clusters of topics extracted from each interview are analyzed to find relationships among them, with consideration of different sustainability aspects and their implications in several market mechanisms. It is observed that the interviewees demonstrated expertise in assessing market changes and highlighted the potential of smart grid capabilities embedded in power systems. The applicability of those market mechanisms on trading new market products such as flexibility is considered part of the assessment process. It is emphasized that the overarching objective behind the implementation of market changes is key to the final assessment.

Based on the interviews, several indicators are related to the needs of the stakeholders in the evaluation of changes in the electricity market regulatory framework. Other indicators are not explicitly mentioned by the stakeholders. However, they are proposed based on the urgency of satisfying specific needs. This is the case of the electricity security of supply indicators and the diversity of actors actively participating in different markets.

This chapter additionally provided valuable insights into the dynamics of electricity supply security, highlighting the critical role of diversification and the impact of associated risks.

6 Evaluation and Discussion: Key Performance Indicators for the Evaluation of Smart Grid-Electricity Markets Considering Sustainability Aspects

> *Users do not care about what is inside the box, as long as the box does what they need done.*
>
> — **Jef Raskin**
> about Human-Computer Interfaces

This chapter provides an in-depth evaluation of the methodologies employed in this thesis to assess the performance of smart grid systems, with a particular focus on the impacts of different market mechanisms on the sustainability of the power system. The primary methodologies implemented for this dissertation include the use of morphological boxes, bibliometric analysis, and semi-structured stakeholder interviews, with qualitative assessments.

The evaluation process begins with the usability of the two-layer morphological box, which clearly supports the definition of the main characteristics needed for the market design under analysis. Section 6.1 evaluates and discusses the applicability and limitations of this approach to support the collection of the main data and the objectives behind a possible change in the market.

Section 6.2 evaluates the applicability of bibliometric analysis for identifying smart grid-market related KPIs, contrasted with the needs expressed by stakeholders through the interview analysis. The use case presented in Chapter 4, Section 4.4, which evaluates flexibility in distribution systems, is contrasted with the results from the interview process. Similarly, Section 6.3 presents the implications of evaluating sustainability. These two sections present and contrast the methods for evaluating and comparing different market rules for the same objective.

The integration of these methodologies facilitates a comprehensive analysis of smart grid performance, highlighting the relationships between various market aspects in the achievement of a sustainability outcome. This chapter concludes by discussing the strengths and limitations of the methodologies in use, offering a critical evaluation of their effectiveness in addressing the research questions in Section 6.5. This comprehensive evaluation highlights the importance of integrating quantitative and qualitative approaches to capture the complexity of smart grid systems and their impacts on market mechanisms and sustainability dimensions.

6.1 Usability of the Two-Layer Morphological Box to Define New Market Rules and Its Implications: Evaluation Based on Interviewees' Responses

The application of GMA, as detailed in Chapter 3, captures the primary characteristics of electricity market design and its regulations. The review of the interview responses underscores the evident need for market adaptations. This necessity is apparent not only in markets with a medium to high degree of competition, such as the Panamanian market, but also in highly competitive markets, such as the German market. Both scenarios require the promotion of smart market designs. The intention behind these changes has been increasingly observed in recent years, particularly in the efforts of regulatory bodies.

The European Commission also proposed and established regulations for adequacy in the European Market, setting guidelines for capacity allocation and congestion management [Com15], and balancing mechanisms [Com17] to address the variability of renewable sources and the need for grid reinforcements. Other reports propose the creation of ancillary service markets [Fra+17], and flexibility markets [VBM18], where not only generation but also demand response programs can interact, as mentioned in Chapter

1, Section 1.1. Nevertheless, some market mechanisms fail to meet sustainability objectives due to insufficient actor participation (low participation) [Kra+19]. Historically, power system changes have often been driven by economic considerations, potentially overshadowing other sustainability dimensions.

The use cases and data collected from semi-structured interviews reveal a clear need for appropriate indicators that enable stakeholders to evaluate sustainability aspects within the power system. As mentioned in the initial chapters of this thesis, such evaluation necessitates consideration of the following points:

1. A comprehensive understanding of the market characteristics under evaluation, the market rules, and the objectives to be achieved. This is crucial before contemplating any change, as it might require a complex legal and regulatory process, especially when transitioning from very different schemes, such as moving from a vertically integrated market to one with a higher degree of competition or changing from cost-based to price mechanisms.

2. An in-depth knowledge of the relationships among key aspects that can trigger different stakeholder behaviors. Interactions among markets, such as parallel markets or regional markets, can result in contingent offering behaviors from different players. Careful consideration is required in systems with varying bidding time frames.

3. An understanding of the internal relationships between achieving a goal and the subsequent impacts on other aspects of the power system. For instance, aiming for a fully renewable electricity system necessitates appropriate capacity mechanisms and flexibility trading to attract investors, especially with low or zero marginal prices.

4. Consideration of externalities and their substantial impacts on the power system. For example, external factors such as war, which affect the security of supply, or the implementation of savings-based versus payment mechanisms to incentivize customers to participate in demand response programs (diversifying actors).

One application of the two-layer morphological box is to support the creation of an electricity market abstraction, advancing towards the development of holistic software capable of evaluating different markets [Mau+23]. The two-layer morphological box facilitates the evaluation of potential markets to identify gaps for new market rules, emphasizing the need for flexibility markets and capacity markets to support the energy transition. Additionally, it allows for the representation of the electricity market by collecting key characteristics and provides a general overview of what, where, and who could be responsible for any new implementation.

Interviewees are shown the morphological box at the end of their interviews to gather their opinions on its usability. Notably, the compact nature of the morphological box allowed interviewees to easily understand the characteristics being collected. They also provided feedback on possible extensions and new rules they considered interesting for analysis.

Most of the interviewees agreed that significant market changes would likely result from implementing system dynamism, either through increased flexibility trades or the introduction of new actors. Indirectly, interviewees relate smart grid technologies to improving the distribution system and providing real-time or near-real-time information to make better decisions. Interviewees 1, 3, and 7 underscore the potential for capacity markets, emphasizing the necessity for clear policy intent in this domain. The proposed version of the morphological box allows for the evaluation of these topics.

All interviewees, particularly interviewees 1, 5, 7, and 6, stress that the objective behind any market change needs to be clearly defined by the regulatory authority or energy ministry. This supports the extraction of the objective when using the morphological box analysis proposed in this dissertation.

One suggestion arising from the interviews is to extend the morphological box to include grid compensation mechanisms. This potential modification, aimed at supporting renewables and flexibility services, involves transitioning from a standard fee system to a dynamic one based on grid usage. Interviewee 7 identifies this as a viable adjustment or as a future consideration as part of the extension of the morphological box. Moreover, since the system utilizes a two-layer morphological box, all prospective new rules can be integrated into the second layer without necessitating substantial alterations to the market design formulated in the first layer.

The current state of the morphological box allows for defining the market design (framework) and identifying possible changes within only one market at a time. The tool has the limitation of not being designed to understand influences among multiple markets. For such cases, each market design should be evaluated independently, creating separate use cases. Later, when performing bibliometric analysis, both use cases should be considered to extract the corresponding indicators. The final evaluations should also aggregate both sets of indicators.

6.2 Merging Bibliometric Analysis with Stakeholders' Needs for the Evaluation of Sustainability Dimensions in Smart Market Applications

The bibliometric analysis explained in Chapter 4 proves to be a rigorous method for identifying KPIs from a vast array of academic literature, technical reports, and journals. This approach ensures a thorough exploration of the KPIs relevant to smart grid technologies and market-driven improvements. The subsequent implementation of co-word analysis reveals significant patterns and trends within the existing body of knowledge. A notable strength of this method is its ability to group identified KPIs into categories pertinent to smart grid capabilities and map them to sustainability dimensions: economic, social, environmental, and legal. This structured framework facilitated a nuanced understanding of the relevance and impact of each KPI. Furthermore, the nature of bibliometric analysis imparted a level of objectivity and replicability to the research findings.

However, bibliometric analysis faced certain limitations. Its effectiveness is inherently constrained by the availability and quality of published data. Given the dynamic nature of smart grid technologies, some relevant KPIs might not have been captured due to the time lag in publication or incomplete reporting. This points to the fact that the method, while not exhaustive in the search for indicators, is designed to be adaptable, allowing continuous updates to maintain its relevance. It offers flexibility, as it can be tailored for specific market considerations, as explained in Section 4.8. However, careful consideration and refinement are needed, as wording differences among researchers could lead to multiple indicators targeting the same objective. This finding supports the need for a standardized *indicator database* to assist researchers in achieving uniformity when evaluating their results.

The applicability of these research-oriented indicators demands alignment with the evaluative requirements of stakeholders to ensure practical usage. This alignment is crucial for bridging the gap between academic research and real-world applications. Stakeholder interviews provided invaluable context-specific insights that complemented the bibliometric findings. For this thesis, linking concepts and extracted indicators is implemented to observe the reliability of the process based on stakeholder requirements.

In addition, the results of the interviews uncovered detailed understandings of market rule implementations, evaluations, and the possible external effects that induce changes in actors' behavior, often absent in purely quantitative analyses. The qualitative data highlighted practical challenges and considerations, offering a multi-sector perspective on the feasibility and applicability of various KPIs in real-world scenarios.

The creation of knowledge concept maps from the coded interview data facilitates the visualization of complex relationships among key topics. Integrating interview topics and concerns with the KPI database supports the evaluation and reliability of the process, ensuring that essential aspects necessary to achieve a sustainable power system are not overlooked. Furthermore, this approach enhances understanding of which indicators are suitable for different aspects. By identifying the links between sustainability dimensions in the context of electricity market concepts, it ensures comprehensive coverage of all critical elements. This connection supports the assessment of specific market implementations, determining whether the objectives behind regulatory changes are achieved.

To evaluate these linkages, each aspect mentioned in the interviews is organized by sustainability dimension. One sustainability dimension, such as the social dimension, is then selected. All concerns regarding this topic are extracted and linked with the indicators derived as part of the use case scenario presented in Chapter 4. Table 6.1 provides an example of the relationships identified between the mind map concepts and the strong indicators related to the social dimension or those that present a socio-technical component.

It is important to mention that the interviews are not specifically focused on a particular market type or implementation. They are open-ended, allowing interviewees to discuss any possible changes and their main concerns. However, the KPIs extracted for the use case specifically target flexibility markets in distribution systems. Therefore, it is understandable that not all the extracted indicators are applicable to every specific aspect.

Social Aspect from the interview	Indicator ID	Indicator Name	SG Cluster
A1) Demand Management	159	Maximal Social Welfare	Customer benefits and customer inclusion
	97	Customers Aggregation	
	5	Community share of market savings	
	160	Improved flexibility of service delivery	
	185	Number of participants in auctions	Flexibility Markets
	6	Peer-to-Peer closeness index	
G13) Transparency in data and unified sources	80	Hability to share Data customer 2DSO	Transparency Data Access Sharing
	81	Real Time Data Customer to DSO	
	82	Non Real Time Data Customer DSO to TSO	
	83	RT Data DSO to TSO	
G14) Social impact on grid tariff payments	52	Annual Switching Rates – Electricity Retail Markets	System Indicators
A8) Facilitating energy trading for prosumers	168	New energy consumption growth rate	Prosumers trading
	144	Smart Meters Penetration	Smart Asset Management
	151	Consumers being metered	
A) Prosumers and Energy Trading	93	Low entry barriers to provide services	Flexibility Markets
C6) Distribution Grid Challenges	89	Available proper data meter Customer to DSO	Flexibility Markets
	94	Delivery set points to customer	
	95	Interface towards customer device	
	96	Available Customer data DSO to Aggregator	
G17) Evaluating the societal impact of energy projects	46	Benefit–Cost ratio (B–C). Project related	System Indicators
	152	Forecasting reliability of demand/generation	Smart Asset Management
P4) Congestion Issues	84	RT Data DSO to Aggregators	Transparency Data Access Sharing
	85	Non Real Time Data DSO to Aggregators	
	86	Real Time Data Meter to Customer	
	87	Non Real Time Data Meter to Customer	
	88	Data SO to SO	

Tab. 6.1.: Social Aspects and Indicators from Interviews

The primary social concepts are evaluated against the strong social indicators identified in the KPIs database. In this evaluation, 81.2% of the identified strong indicators could be used to assess aspects mentioned by stakeholders. The remaining indicators pertain to socio-technical aspects, which, in this context, directly refer to the market being implemented.

To determine the relationship between interview concepts and each indicator, cosine similarity is employed, as illustrated in Figure 6.1. The Y-axis represents the interview concepts related to social aspects. Each row corresponds to a different concept from the interviews. The X-axis represents the indicator IDs. The list of indicator IDs and their names is additionally published in the Git repository. Each column corresponds to a different indicator. Darker colors denote higher cosine similarity scores, indicating stronger relationships between the interview concepts and the indicators. The heatmap provides a clear visual representation of the relationships between social concepts and indicators. Similarly, the concepts discussed in the interviews can be evaluated against the entire KPIs database. Figure 6.2 depicts the cosine similarity between the same social aspects encountered during the interview process and all of the KPIs. Some aspects present a stronger relationship with specific KPIs. For instance, *Transparency in data and unified sources* demonstrates a strong relationship with certain indicators. Conversely, other topics, such as *Price signal*, show a weaker relationship with specific indicators but influence several of them.

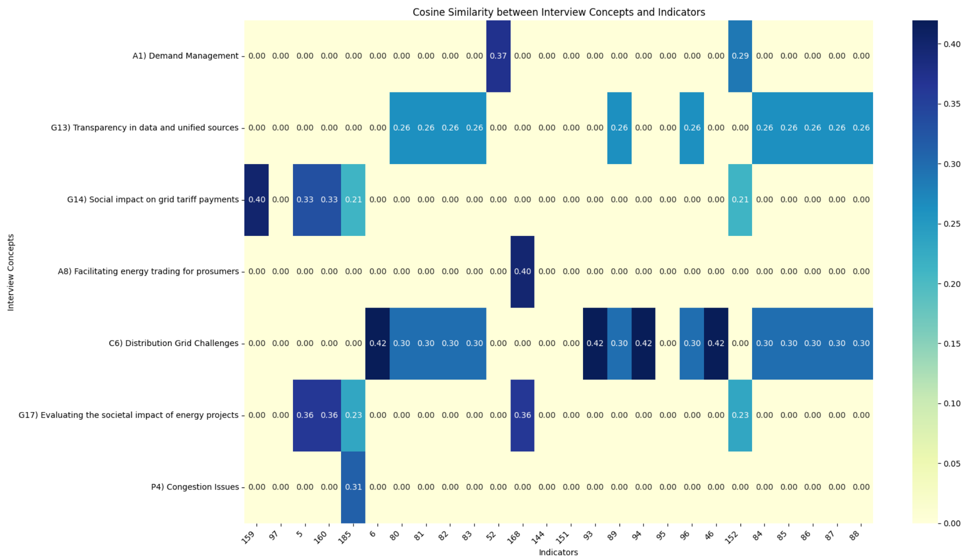


Fig. 6.1.: Cosine similarity of social aspects against the indicators database.

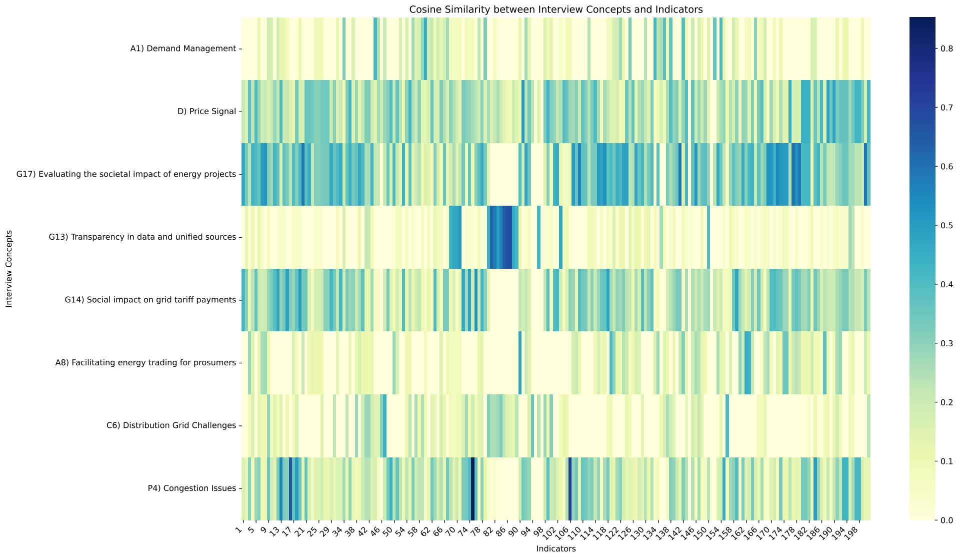


Fig. 6.2.: Cosine similarity between interview concepts and KPI.

If, instead of comparing the detailed interview concepts with the indicators, the comparison is conducted against the general summarized idea behind each sustainability dimension as shown in Figure 5.27, different matching percentages are obtained. This discrepancy arises due to the error introduced when generalizations are made for each concept, resulting in potentially unclear objectives. For instance, if the matching is evaluated based on a generalized idea behind each sustainability dimension rather than the specific insights derived from the interviews, it represents a worst-case scenario for this research. This approach lacks the clarity and specificity needed to achieve precise objectives. Consequently, the matching percentages decrease, since only 76 out of the 145 indicators are matched. This represents a matching percentage of approximately 52.4%. Table 6.2 shows the matching of indicators for the sustainability dimensions.

Sustainability Dimension	**Total Main Aspects**	Total Matching indicators	**Matching Percentage**
Social/Customer	10	17/32	53.13%
Economic	9	33/68	48.53%
Environmental	9	12/20	60%
Legal/Policy	12	14/25	56%

Tab. 6.2.: Matching Percentage of Main Sustainability Aspects with Strong KPIs

The non-directly matching indicators represent more technical aspects that are related to the system properties or to the market mechanisms that are intended to apply.

6.3 Evaluation and Discussion of Smart Market KPIs for Assessing Sustainability

Based on the results, it is possible to infer that specificity and clarity are fundamental characteristics for evaluating sustainability aspects. However, even with very specific indicators belonging to a new market implementation, at least 50% of them can be associated with a sustainable implication as defined in this dissertation. Therefore, each sustainability aspect can be represented by a group of indicators.

Moreover, when implementing a new market rule, it is crucial not to overlook the externalities and implications on other sustainability dimensions. The impact of regulation is evident in the behavior of the electricity market, as "the market follows the regulation." Therefore, a robust mechanism for evaluating the sustainability of the power system involves assessing KPIs from both general and specific market perspectives. This entails introducing detailed KPIs tailored to each market configuration while emphasizing the importance of the intended objectives and market design. The following paragraphs discuss the primary KPIs considerations for each sustainability dimension.

Social Indicators: One of the primary considerations in this discussion pertains to the implications of subsidies, incentives, and taxes in the context of renewable energy integration. It has been severely questioned who has to pay for the integration and variability of renewable energy. Is the current energy policy sending the right incentives to foster the widespread adoption of these technologies? The overarching policy goal is to create a more sustainable power system, which typically involves supporting the expansion of renewable energy. However, this support should not lead to curtailments due to a lack of grid capacity.

[BGG22] investigates the impacts of three alternative policies that subsidize renewable energy production, such as Feed-in tariffs (FITs), tax increases, or exemptions from electricity surcharges, but it is also indicated that the promotion of renewable energies can drive up electricity prices and create an economic burden, especially for low-income households. Therefore, it is also important not only to analyze these impacts in terms of cost, but also in terms of the social benefit to the customers.

Indicators such as the Inequality Index and the Equally Distributed Equivalent Level of Income [Atk+70], not only support the theories outlined in [BGG22], but also provide valuable insights when considering Locational Marginal Pricing (LMP) implementations, since the price might not be the same for all customers. For this reason, expenditure, income, and net welfare effects by other household categories need to be considered within the social aspect.

Furthermore, ensuring transparency in data and access sharing is essential to support markets and also to optimize energy resources. Coordination between aggregators, DOS, TSOs, and other actors is necessary as the effects of different markets overlap and impact each other.

Based on this premises, this thesis proposes using the Margalef Index to represent the number of customers participating in any trading market against the total number of customers, as a measure of the diversity associated with those participating in the retail market. The Margalef Index is particularly useful for understanding the extent of customer engagement and can highlight the inclusivity of market participation. Similarly, the Simpson Index of Diversity $(1 - D)$ is proposed to evaluate the dominance of specific actors in the market. This index is crucial for identifying the concentration of power among market participants, which is especially important in retail markets or markets aimed at resolving grid congestion. By applying these indices, it is possible to gain insights into market dynamics, customer behavior, and the effectiveness of regulatory frameworks in promoting fair and competitive markets. Therefore, these indicators are essential for considering both the social and legal sustainability dimensions, and for evaluating the overall market performance.

Economical Aspects: The electricity price and the market liquidity are the most important indicators to determine if the power system is operating correctly. However, in the literature, most of the key performance indicators are related to economic aspects both directly or indirectly. "The electricity market has not been implemented to support the grid; on the contrary, the grid is there to support the market."

Environmental Aspects: The share of renewable energy seeks to increase the participation of distributed renewable energy in different markets. This allows the participation of higher shares of renewable energy, especially when they are aggregated. But to gain more from the sources, the market interaction (regulation) needs to be in place, allowing the actors to participate in all markets.

Legal/ Policy Aspects: To enhance the transparency of data access and sharing of information, coordination capabilities are needed. However, the efforts should determine whether the market operates in a centralized manner, optimizing resources, or follows a different approach. Since it could lead to investments in technology that can increase the overall assets of the system, a cost-benefit analysis must be implemented to avoid investments that are beneficial for a few actors.

Regulation and policies play a pivotal role in shaping electricity markets because stakeholders react to comply or get benefits from them. Regulations are obligatory, while policies are designed to achieve specific goals, and their impacts depend on the actions of various stakeholders. Policies should not hamper the overarching sustainability objectives. Therefore, it is useful to map the relationships between indicators that reveal the behavior of the system.

6.4 Use Case Application for a Retail Flexibility Market -Panama case and Germany Redispatch scenario

In this section, a use case for implementing a retail flexibility market is explored using a predefined scenario for Panama and drawing on the principles of Germany's *Redispatch 2.0* measure. The German *Redispatch 2.0*, introduced in October 2021, is a measure designed to optimize and manage congestion in the distribution grid by redispatching generation units, including renewable energy sources and storage systems, with capacities above 100 kW. The primary distinction between *Redispatch 2.0* and traditional redispatch lies in the inclusion of DER, as redispatch is typically applied to large power generation units. Notably, *Redispatch 2.0* operates outside of conventional market mechanisms, as its outcomes are driven by decisions made by grid operators to ensure grid optimization, achieve flexible and efficient management of energy resources, prevent congestion, and minimize the need for grid reinforcement.

Therefore, this use case for flexibility markets evaluates two distinct compensation mechanisms: a cost-based approach and a bidding approach. The Panamanian case is previously defined using the two-layer morphological box, with the real considerations of the electricity market in January 2024. Analysis through the morphological box revealed that specific actors and roles, as well as certain legal constraints, must be established to enable the implementation of this type of market. Nevertheless, the methodology proposed in this thesis remains applicable for assessing such an implementation, as its primary objective is to evaluate how the sustainability of the power system can be comparatively analyzed in light of market structure changes.

Flexibility in retail markets, especially involving prosumers and aggregators, presents unique challenges and opportunities for creating different compensation mechanisms. For example, in a cost-based market, the primary focus is on minimizing the costs associated with flexibility services while maintaining grid stability, as seen in Germany's current *Redispatch 2.0* framework. In a bidding mechanism, each actor will try to optimize its price to win the bid, leading to behavior where participants aim to maximize their profits.

The methodology proposed in this thesis is applied to extract and evaluate indicators for the options considered within the second-layer morphological box, specifically for flexibility and capacity markets. For flexibility markets, the main focus is on flexibility in retail markets. The indicators are evaluated to determine whether they represent a cost-based or a price bidding approach.

Both the capacity market indicators and the flexibility market indicators are stored in a database, and each is related to its smart grid cluster functionality. Moreover, each indicator has a weight representing the strength of its relation to each sustainability dimension, as explained in Chapter 4.

To evaluate the behavior of indicators extracted from the database and the considerations in each of those market compensation mechanisms from the interview perspectives, cosine similarity is employed. Cosine similarity is a technique employed in data mining to cluster related texts, identify relevant documents for a query, or construct semantic relationship maps between words, particularly when the magnitude of the data is less relevant than its relational structure. For this reason, this function is used to link key concepts from interviews that support the analysis of changes in the electricity market with corresponding indicators. By using cosine similarity, it becomes possible to identify relationships and patterns among elements represented as vectors in a multidimensional space, where the vectors in this context are the extracted texts.

Figure 6.3 offers a comprehensive visualization of the relationships between identified flexibility indicators and key concepts derived from stakeholder interviews. Capacity market concepts are additionally added for the evaluation in the same figure. The cosine similarity scores, represented by the varying shades of color, indicate the strength of the relationships between each indicator and the respective market concepts. A

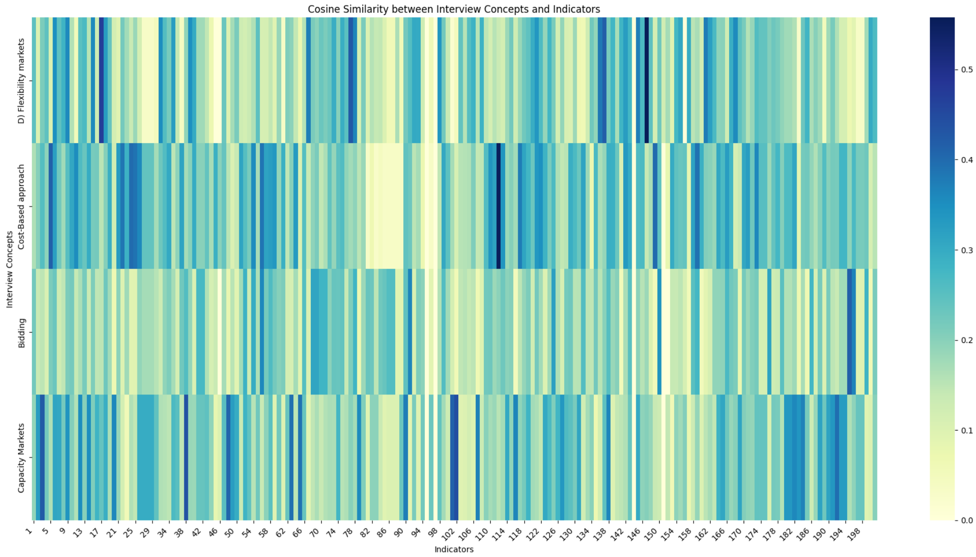


Fig. 6.3.: Cosine Similarity between Interview Concepts and Indicators

deeper analysis of these relationships reveals important insights into the applicability and effectiveness of flexibility indicators in different market scenarios.

Indicators such as "Number of participants in auctions" and "Community share of market savings" demonstrate high cosine similarity scores (darker colors) with concepts like retail market flexibility and demand response management. These indicators are crucial for evaluating the extent of engagement and the financial benefits realized by small-scale actors. For instance, a high number of participants in auctions signifies a robust market where prosumers actively engage in trading their flexibility services, thereby enhancing market liquidity and supporting grid operations.

Moreover, indicators like "Smart Meters Penetration" and "Consumers being metered automatically" are essential in a cost-based market as they provide real-time data critical for optimizing demand response and flexibility services. The presence of advanced metering infrastructure enables more accurate billing, better load forecasting, and enhanced consumer trust, which are pivotal for the success of retail markets with significant prosumer participation.

In contrast, an offer-based market relies heavily on the competitive bidding process to allocate flexibility services. Here, the focus shifts towards the effectiveness of market mechanisms in eliciting the most cost-efficient and reliable flexibility bids. Indicators such as "Price-Based Demand Response" and "Incentive-Based Demand Response" show strong relationships with the concepts of bidding and market efficiency. These indicators help assess how well the market design encourages participants to offer their flexibility at competitive prices, thus ensuring cost-effective grid management.

The heatmap reveals that indicators related to market dynamics, such as "Market Liquidity" and "Retail electricity prices," are closely tied to the concepts of flexibility markets and bidding processes. High cosine similarity scores in these areas suggest that effective bidding mechanisms can significantly influence market liquidity and pricing stability. For example, a well-designed offer-based market can mitigate price volatility and enhance grid reliability by attracting a diverse range of flexibility providers, from large-scale aggregators to individual prosumers. Nevertheless, the key aspect here is to demonstrate the diversity of the offers. This shows the relevance of the Margalef Index and Simpson Index of Diversity.

Other indicators, such as "Demand flexibility" and "Real Time Data Customer to DSO," show significant relevance across both market types, underscoring the critical role of real-time data and flexible demand management in achieving sustainability goals. Therefore, some differences between cost-based and offer-based markets are more noticeable than others. For aspects that might not be that specific, it is necessary to consider the relationships shown in the interview concept maps to understand the interlinking relationships.

Additionally, capacity markets play a crucial role in ensuring the reliability and stability of the power system. Indicators such as "Capacity of reserves" and "Degree of Curtailment" are essential for evaluating the effectiveness of capacity markets. In the figure, those indicators show high cosine similarity scores, underscoring their importance in maintaining a balanced and resilient power grid. The presence of adequate reserves and the management of curtailment are vital for preventing supply shortages and ensuring that the power system can respond effectively to demand fluctuations.

Indicators like "Total quantity of engaged balancing energy in the tertiary regulation" and "Availability of natural resources" further highlight the role of capacity markets in integrating a security mechanism due to the variability of renewable energy sources. For example, well-designed capacity markets can support the integration of renewables by providing the necessary backup and balancing services. This is particularly important in markets with high shares of variable renewable energy, where the ability to balance supply and demand in real-time is critical. Therefore, the additional relationship with smart grid real-time and non-real-time controllability is crucial.

The cosine similarity in these cases supports the visual relationship between indicators and concepts. This relationship demonstrates that the application of flexibility indicators in different market scenarios highlights the importance of tailored market designs to maximize the benefits of smart grid technologies.Cost-based markets benefit from indicators that enhance prosumer engagement and optimize cost management, while offer-based markets leverage competitive bidding processes to drive market efficiency and stability. Capacity markets, on the other hand, ensure system reliability and support renewable integration through adequate reserve management and balancing services. Certainly, the fact that capacity markets are strongly related to balancing services does not mean that other flexibility market pricing mechanisms do not contribute to those services. In this dissertation, and with the support of the KPIs, the stronger relationships and functionalities observed are pointed out without neglecting secondary relationships.

6.5 Conclusion

The methodology for extracting KPIs proposed in this thesis and its relationship to different concepts is not intended to exhaustively identify all KPIs that researchers and decision-makers use. Instead, it seeks to explore the interaction between market concepts and potential methods for assessing new rules without overlooking the sustainability dimensions. The methodology proposes a holistic process that supports the evaluation of smart grid integration in power systems and their capability to support market dynamics.

Engagement with stakeholders from academia, industry, policy-making, and regional consultancy enriched the research with practical perspectives and experiential knowledge. It is observed that more than 80% of the identified indicators with a strong component can effectively measure the impact of regulatory changes and market implementations on sustainability dimensions for detailed concepts and at least 52% for general concepts. This demonstrates the importance of specificity and clarity in evaluating sustainability aspects and highlights the robustness of the proposed KPIs in representing each sustainability dimension.

By applying the Margalef Index and Simpson Index of Diversity, the analysis effectively measures market diversity and dominance, providing a comprehensive view of market dynamics and customer engagement. These indices are essential for considering both social and legal sustainability dimensions and for evaluating overall market performance.

The implications of regulation are evident in the behavior of the electricity market, underscoring the need for mechanisms to evaluate the sustainability of the power system. This involves assessing KPIs from both a general and specific market perspective, introducing detailed KPIs tailored to each market configuration while emphasizing the importance of intended objectives and market design.

The economic aspects emphasize the importance of electricity prices and market liquidity as key indicators of market performance. However, the inclusion of additional KPIs highlights the interconnectedness of economic factors with other sustainability dimensions.

Environmental aspects focus on increasing the share of renewable energy in the market, facilitated by regulatory frameworks that allow broader participation of renewable energy sources. Legal and policy aspects stress the necessity for data transparency, coordination capabilities, and the careful evaluation of investments to avoid benefits limited to a few actors.

The proposed methodology and KPIs offers a comprehensive framework for evaluating the sustainability of electricity markets. By integrating stakeholder insights and considering the multifaceted nature of market dynamics, this research contributes to the development of sustainable and efficient electricity markets that align with regulatory objectives and societal needs.

7 Concluding Remarks and Outlook

The process of implementing Key Performance Indicators (KPIs) for evaluating new markets based on smart grid technologies, while ensuring that sustainability aspects are included, proposes a novel approach involving several critical steps and innovative techniques. This thesis presents a multi-methodological approach combining General Morphological Analysis (GMA), bibliometric analysis, science mapping, semi-structured expert interviews, and NLP analysis of the corpus of the interviews as a systematic method that integrates stakeholder insights, advanced analytical techniques, and the comprehensive understanding of market dynamics aimed at achieving sustainability of the power system.

Defining the scope and objectives is the initial step in this process. This involves understanding the electricity market evaluation and establishing the goals regarding the reasons behind changing the current market dynamics. A two-layer morphological box was implemented to determine the market design and then define the possible new market rules or changes in the trading scheme made possible by smart grid capabilities. Information about the actors allowed in the power system or about those actors interested in implementation was used to identify any missing roles.

The results from defining the market design and possible new market rules allowed for setting feasible market combinations and changes, identifying those that are either mutually exclusive or would require fundamental changes in the market design. This is a crucial consideration for regulators and policymakers who may be reluctant to implement fundamental changes. However, evaluating whether a new market rule or trading scheme can support the energy transition toward a more sustainable and resilient power sector remains challenging. Traditionally, markets have been seen as economic instruments separate from real operational constraints, which was true in highly centralized systems with significant inertia, where load variability was the primary concern. However, with the integration of a high amount of renewable sources, especially in the distribution grid (medium and low voltage levels), and the capabilities to control, operate, heal, and share information through smart grid technologies, grid congestion and variability problems arise.

One solution to this problem has been the implementation of market mechanisms, as "someone has to pay for those services." This involves not only the market capabilities of trading energy but also the interaction of smart grid technologies with platforms for these market implementations. Therefore, it is critical to understand that, after implementing smart grid technologies and DER resources, managing assets becomes essential, particularly with the goal of achieving carbon neutrality. Policymakers need tools and mechanisms to evaluate which new market implementations can effectively support this goal.

To address this problem, this thesis proposes the evaluation of specific indicators that could lead to assessing the performance of the smart grid in achieving a more sustainable power system. The analysis of similarities between different market configurations and their sustainability impacts demonstrated that certain market designs are more conducive to achieving sustainability goals, supporting the evaluation of dimensions beyond just the economic or environmental. For example, markets with high flexibility and integration of renewable energy sources can additionally support the social dimension if customers are incentivized to participate in trading. Therefore, market mechanisms should consider customer involvement, their capability to trade and share information, the liquidity of small actors, and their contribution to market diversity. Consequently, the impact of regulation on market behavior underscores the need for mechanisms that evaluate the sustainability of the power system, involving both general and specific market perspectives.

To reach these conclusions, a database of indicators based on pioneering research was developed. By implementing bibliometric analysis, the most recent open-source publications were used to extract the mechanisms researchers employed in presenting their findings, particularly those related to smart grids and market mechanisms. The bibliometric and content analysis methods for creating a smart grid-market-related database is a novel implementation in this domain. This proposed method forms the foundation of the KPI implementation process. By reviewing existing studies and theoretical frameworks related to smart grid technologies, market dynamics, and sustainability assessments, this research identifies gaps in current knowledge and determines relevant KPIs which address these gaps. Previous approaches to KPIs were limited to literature reviews, neglecting the capabilities that bibliometric analysis offers. The bibliometric analysis supported by content analysis involves more than just selecting and defining KPIs that are specific, clear, and relevant. It sets the basis for understanding these KPIs, their context, and their possible relationships to electricity markets, clustered based on their smart grid capability and weighted based on their implications across the four sustainability dimensions. One indicator can impact several clusters, requiring the evaluation of direct and indirect relationships among clusters to understand potential mapping implications.

Based on the proposed process, each KPI is reviewed to demonstrate its effectiveness in measuring the impacts of new market rules and smart grid technologies on sustainability aspects. The quantitative data from the bibliometric analysis was enriched by the qualitative insights from stakeholder interviews, resulting in a comprehensive and multidimensional understanding of the research questions. The use of multiple methods increased the validity of the findings through triangulation, ensuring a robust and credible set of indicators. This qualitative weighted process was supported by semantic similarities of pre-selected words commonly used to relate the main KPI variables with sustainability aspects.

The proposed methodology allows the evaluation of KPIs for any new market type or regulation that researchers investigate. The KPIs database covers critical aspects across social, economic, environmental, legal and policy, technical, and institutional dimensions, offering a holistic approach to market assessment. However, since research is a continuous process, the methodology will need updates based on technological advances in electricity markets. Additionally, it relies on previous research or open-source scientific documents.

It is important to understand what stakeholders are actually interested in evaluating market changes. Understanding the reasons behind the necessity for change and their foresight about the change is essential for evaluating two parts of the process: the morphological box, which can be extended based on requirements or new market rules, and the smart grid-market-related KPIs database.

A key aspect of the evaluation process was implementing semi-structured interviews with stakeholders. Engaging stakeholders from diverse backgrounds, including academia, industry, policy-making, and regional consultancy, enriched the research with practical perspectives and experiential knowledge, providing insights into the real-world challenges and requirements for implementing KPIs in new markets. Their input about implementing sustainability in the power system, the need for proper evaluation methods, such as regulatory sandboxes, and the concern about balancing social acceptance, price, and environmental commitments allowed for the creation of concept maps. These concept maps served as a knowledge pool supporting the interrelation of power concepts and market implications, connecting concepts to indicators that could address their concerns.

Legal and policy aspects cannot be neglected when discussing electricity markets. While markets can serve as resource optimization tools, their framework is constrained by policymakers. Policymakers and regulatory authorities need to assess changes, sometimes without knowing the possible implications for other aspects. Creating a concept map with detailed discussions about market implications and sustainability aspects opens the possibility to relate market concepts to any database of indicators, presenting a tool for a more holistic evaluation.

Natural Language Processing (NLP) is used to extract and process conversational transcripts from interviews into concept maps that create and relate knowledge. A human factor is also involved, particularly in coding the interviews and reviewing their main applicability concepts. However, this part of the process does not need to be repeated every time a new KPIs dataset is extracted. The concept maps help understand main concerns and bridge the gap between research and real-world applications. The evaluation of KPIs includes assessing their ability to measure intended outcomes effectively, ensuring they provide a quantitative basis for evaluating market performance, environmental concerns, customer behavior, and the effectiveness of regulatory frameworks. Case studies are implemented to validate the KPIs, particularly for the implications of flexibility markets considering a cost-based approach and a bidding approach. The concept maps support the evaluation of these cases by providing concepts necessary for evaluation according to experts.

To overcome the limitations of the indicators, this dissertation proposes using diversity indicators to evaluate the actual capacity of new actors to participate in the market and their potential market power. The findings highlight that specificity and clarity are essential for accurately evaluating sustainability aspects. Utilizing indices such as the *Margalef Index* and the *Simpson Index of Diversity*, this analysis effectively measures market diversity and dominance, providing a comprehensive view of market dynamics and customer engagement. These indices are crucial for considering both social and legal sustainability dimensions and for evaluating overall market performance. Additionally, at least 52% of the strong specific indicators extracted from the bibliometric analysis and associated with sustainable implications demonstrate that they can satisfy some of the interviewees' concerns, showing the robustness of the proposed method in representing each sustainability dimension. However, a sufficient number of indicators per sustainability dimension needs to be implemented to achieve a holistic approach. The concept maps elaborated from the interviews support not overlooking specific interrelated concepts that can cause several impacts.

The evaluation of the indicators shows that, when implementing new market rules, it is crucial to address externalities and implications for other sustainability dimensions. This involves analyzing the broader impacts of regulatory changes on social, economic, and environmental aspects, and ensuring that the KPIs capture these impacts to provide a comprehensive evaluation of market performance. Integrating the KPIs with existing regulatory frameworks ensures that the market follows the regulation and that said regulation promotes sustainability. The innovative approach of using a two-layer morphological box and concept maps for the indicators, combined with the advantages of using Natural Language Processing (NLP) and data mining techniques, facilitates the identification and analysis of relationships among KPIs and market mechanisms. These advanced techniques allow for a more nuanced and detailed understanding of how different market configurations and regulatory changes impact sustainability dimensions.

The proposed methodology and KPIs offer a robust framework for evaluating the sustainability of electricity markets based on smart grid technologies. This holistic approach considers the interaction between market concepts and potential methods for assessing new rules. By integrating stakeholder insights, advanced analytical techniques, and considering the multifaceted nature of market dynamics, this research contributes to the development of sustainable and efficient mechanisms to evaluate electricity markets that align with regulatory objectives and societal needs. This comprehensive approach ensures that new market rules promote sustainability without overlooking the critical aspects of market performance and regulatory impact.

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7.1 Future Work

While this thesis has made substantial contributions to the development of tools for evaluating electricity market rules, it also highlights areas for future research. This dissertation not only presents contributions to the domain of electricity markets and sustainability but also suggests potential directions for future research to enhance other market designs and the possible creation of different use cases. Future work should focus on three main topics:

- A key aspect is the need for a continued exploration of market design innovations and their impacts on sustainability. Further refinement of the KPIs and an extended validation through practical implementations and longitudinal studies is essential. Simulation tools, such as those presented in the use case, should be utilized to evaluate different market designs resulting from the morphological box, with the support of results from various applications targeting a wide spectrum of goals. These simulations can provide valuable insights into the long-term effects of different market configurations and help identify the most effective strategies for integrating smart grid technologies.

- Another issue arises from the limitations of this study related to its dependence on the availability of open-source journals and papers. This limitation can be addressed by strengthening the link between research and open-source databases, which would support the standardization of KPI usage. Establishing a centralized, open-access repository for KPIs would facilitate the sharing of research findings and promote collaboration among researchers, policymakers, and industry stakeholders. This repository could serve as a living document, continuously updated with new KPIs and market designs as they are developed and validated..

- Finally, the evolving nature of Natural Language Processing (NLP) and Artificial Intelligence (AI) techniques presents an opportunity to enhance the methodology proposed in this thesis. Integrating these advanced technologies could automate the entire process, from the publication of open-source journals and papers to the identification and alignment of KPIs based on the concept maps created in this thesis. This automation would not only maintain the reliability of the KPIs database over time but also ensure that the database is consistently updated with the latest research findings. Additionally, AI-driven tools could provide more sophisticated analyses of the relationships between market mechanisms and sustainability indicators, leading to more precise and actionable insights.

These aspects highlight the need for future work to focus on three main areas: exploring innovative market designs, improving the linkage between research and open-source databases, and integrating advanced NLP and AI techniques to automate and enhance the KPI evaluation process. These steps will further solidify the foundation laid by this thesis and contribute to the ongoing development of sustainable and efficient electricity markets.

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Appendix: Morphological Box for market categorization

A

A.1 Morphological Box

Tab. A.1.: Morphological Box for Electricity Market Configuration (Layer 1)

Morphological Box for Electricity Market Configuration (Layer 1)					
Degree of Competition	Vertically integrated (only one Co)	Only one buyer	Wholesales competition	Wholesale and retail competition	
Market Structure	Central scheduling and central dispatch	Bilateral contract with power exchange	Bilateral contract self-dispatch		
Clearing Mechanisms	Power pool price based	Power pool cost based	Financial bilateral contract	Physical bilateral contract	
Price Formation	Marginal Pricing	Pay as bid			
Pricing mechanisms	Nodal pricing	Zonal pricing			
Market Products	Energy Only Market (EOM)	Energy and power	Firm capacity	Reserve capacity	Ancillary services
Market Timeframe	Forward market (FM)	Day-ahead market (DAM)	Intraday market (IDM)	Balancing market	

A list of the KPIs and the calculated correlation values based on the sustainabilityaspects for specific new markets is presented

A.2 Roles in the Smart Electricity Market

Tab. A.2.: Roles in the Electricity Market

Role	Description
Active demand and supply (ADS) or prosumers	Can consume and produce electricity. There is no size constraint but this actor is not a purely power producer or generator.
Aggregators	Collect and can also manage the power from ADS and prosumers with to aggregated for market purposes. This is a Key role in the flexibility service market.
Supplier or billing agent	Procurement of electricity to customers and commercialization. It has the task of setting the invoice.
Electricity trader	Sells or buys bulk energy.
Balance responsible party (BRP)	Responsible for balancing zones and system imbalances caused by deviations in demand and supply within an area.
Distribution system operator (DSO)	Operates a distribution grid, it can additionally be the owner of it.
Transmission system operator (TSO)	Operates a transmission system grid. It can additionally be the owner of it.
Generators or power producers	Owners of a license to generate and participate in the electricity market.
Grid operator	Third party agent in charge of system operation, grid model, price calculation, congestions, and grid access.
Meter data responsible	Responsible for all the measures and the commercial metering system. In some places this is not an additional actor, it belongs to a rol of the grid operator. However, it is important to distinguish the actor in charge of the meters for smart grid implementations due to the volume of information and sensible data.
Imbalance settlement responsible (ISR)	Establish quantities of energy products for BRPs.
Capacity trader	Participates in the Capacity Market.
Transmission capacity allocator	Allocates and offers transmission capacity to the market.

A.3 Bibliometric Analysis Queries

Tab. A.3.: Queries for bibliometric analysis.

Search Engine	Filter/Query	Year of Publication	No. of Papers
MDPI	"Key performance indicators" **AND** "Electricity markets"	Not limited	98
MDPI	"Key performance indicators" **AND** and "Flexibility markets"	Not limited	15
Scopus	"Electricity markets" **OR** "Flexibility markets" **AND** "Performance" **OR** "Indicators" **OR** "Key performance indicators"	2018-2023	1357
Scopus	"Sustainability" **AND** "Indicators" **AND** "Electricity" **AND** "Market"	Not limited	91
Scopus	"Flexibility markets" **AND** "Performance" **OR** "Electricity indicators" **OR** "Electricity market key performance indicators"	2018-2023	285
Scopus	"Performance" **AND** "Indicator" **AND** "Market" **AND** "Electricity"	Not limited	296
Scopus	"electricity" **AND** markets **AND** smart **AND** grids **AND** key **AND** performance **AND** indicators **AND** PUBYEAR < "2023"	Before 2023	1817
Scopus	"electricity" AND "markets" AND "smart" AND "grids" AND "key" AND "performance" AND "indicators" AND PUBYEAR < 2023 AND (LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "ENGI")) AND (EXCLUDE (DOCTYPE , "no") OR EXCLUDE (DOCTYPE , "tb") OR EXCLUDE (DOCTYPE , "ed")) AND (EXCLUDE (LANGUAGE , "Chinese") OR EXCLUDE (LANGUAGE , "Polish")) AND (LIMIT-TO (EXACTKEYWORD , "Smart Grid") OR LIMIT-TO (EXACTKEYWORD , "Sustainability") OR LIMIT-TO (EXACTKEYWORD , "Power Markets") OR LIMIT-TO (EXACTKEYWORD , "Energy Market") OR LIMIT-TO (EXACTKEYWORD , "Sustainable Energy") OR LIMIT-TO (EXACTKEYWORD , "Smart Grids") OR LIMIT-TO (EXACTKEYWORD , "Energy Flexibility") OR LIMIT-TO (EXACTKEYWORD , "Electric Load Dispatching") OR LIMIT-TO (EXACTKEYWORD , "Electricity-consumption") OR LIMIT-TO (EXACTKEYWORD , "Electric Power Plant Loads") OR LIMIT-TO (EXACTKEYWORD , "Smart Energy Systems") OR LIMIT-TO (EXACTKEYWORD , "Performance") OR LIMIT-TO (EXACTKEYWORD , "Performance Indicators"))	Before 2023	422

A.4 Semantics Code for Sustainability relationships

Tab. A.4.: Semantics used for KPI bibliometric search

Semantics for Mapping		
Sustainable Aspects	**Main word**	**Similar Words and Concepts**
Social Aspects	Actors	actors, amount of actors, role, roles, participant, participants
	Aggregator	aggregators, aggregation
	Capacity payment (power)	capacity payment, capacity remuneration
	Retailer	retailers
	Consumer	consumers, energy users, user, amount of customers, big customers
	Demand response	demand response, demand, users demand, active participation
Economic Aspects	Contracts	contract, contracts, contract market, power purchase agreement, agreement, licitations
	Cost	cost, costs
	Dispatch	dispatch
	Energy markets	energy market, energy markets, energy-only market, energy-only markets, energy
	Price	price
	Lower tarif	lower tarif, lower tarifs
	High tarif	high tarif, higher tarifs
Policy Aspects	Institutionality	institutionality, State, state
	International	international, Germany, Panama, Europe, United States, regional, New Zeland, Finland
	Regional Market failure	regional market, regional markets, integrated markets, regional market failure
	Regulation	regulation, regulations, regular, norm, code
	Subsidies	subsidies, subsidy, government incentive, policy incentive, government incentive
Environmental Aspects	Renewable	renewable, wind, solar, photovoltaic, battery, storage, distributed energy, distributed energy resources, distributed supply
	Resilience	resilience, recover
	Emissions	CO_2 emissions, carbon, CO_2.

A.5 Key Performance Indicators metrics per Cluster for Flexibility Markets

Tab. A.5.: Key Performance Indicators metrics per Cluster.

Cluster	N Direct	N Indirect	Avg.	σ	Reference for each cluster
Active system management	63	48	0.866	0.864	[Bra+22; Har17; Far+21; KGG21; Dom+22; Vit+21; TB20; Zen+18; Con18]
Balance mechanism and responsibility	26	22	N/A	N/A	[Bra+22; Har17; SZ19; Vit+21; Rad+18; Con18; Bhu+22]
Customer benefits and customer inclusion	32	47	0.552	0.754	[Bra+22; Har17; Air+21; Okw+22; SZ19; Dom+22; Vit+21; Com+19; Ang+19; Zen+18; Con18; Bhu+22]
Reliability and quality of supply	43	20	0.527	0.825	[Bra+22; Har17; Far+21; Vit+21; TB20; Ken+21; Rad+18; Con18; Bhu+22]
Market structure					
(Behaviour)	23	18	0.318	0.669	[Bra+22; Sun+22; SZ19; Vit+21; Ang+19; Zen+18; Dun+06; Con18; Bhu+22]
(Biddings)	40	37	0.582	0.803	[Bra+22; Air+21; Sun+22; Hir+19; HA11; KB16; SZ19; Vit+21; Ken+21; Ame04],[Zen+18; Dun+06; Con18; Bhu+22]
Flexibility/Local markets	74	31	0.890	0.915	[Bra+22; Har17; Air+21; Okw+22; SZ19; Dom+22; Vit+21; TB20; Ang+19; Zen+18; Dun+06; Rad+18; Con18; Com+22; Bhu+22]
Prosumers tradings	6	5	0.398	0.735	[Bra+22; Har17; Okw+22; SZ19; Dom+22; Vit+21; Ang+19; Zen+18; Con18]
Renewable energy integration	12	23	0.234	0.548	[Bra+22],[Har17], [Nou18; Vit+21; TB20; Zen+18; Bhu+22]
System indicators					
(Power grid)	98	13	0.552	0.859	[Bra+22],[Har17; Air+21; Sun+22; Far+21], [Nou18; KGG21; VBM18; SZ19; TB20; Ken+21; Com+19; Con18; Zen+18]
(Flexibility)	63	34	0.796	0.891	[Bra+22; Har17; UA15; Sun+22; KGG21; SZ19; Vit+21; Ken+21; Zen+18; Rad+18; Con18; Bhu+22]
Transparency data access sharing	24	31	0.413	0.695	[Bra+22; Vit+21; Rad+18; Con18; Bhu+22]
TSO-DSO coordination capabilities	37	15	0.443	0.786	[Bra+22; SZ19; Rad+18; Con18; Bhu+22; Vit+21; Ang+19]

Declaration

You can put your declaration here, to declare that you have completed your work solely and only with the help of the references you mentioned. A statement that indicates whether the thesis has already been published in part or in full; in this case, a list of publications must be enclosed.

Oldenburg, November 18, 2024

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