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MANAGEMENT OF MICROGRIDS IN SOUTH ALGERIAN : ENGINEERING AND SCIENTIFIC CHALLENGES

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General Abstract of the Thesis

Français

Au cours des dernières décennies, de nombreuses initiatives mondiales ont été mises en place pour promouvoir des systèmes énergétiques renouvelables autonomes et durables. Ces efforts ont conduit au développement de technologies de production capables d'assurer l'autosuffisance énergétique grâce à l'intégration de plusieurs sources renouvelables. Parmi ces systèmes, les **microgrids hybrides** jouent un rôle clé, permettant l'intégration flexible des ressources locales tout en garantissant un approvisionnement électrique stable et fiable, notamment dans les zones éloignées.

En Algérie, et particulièrement dans les régions du sud, le **solaire et l'éolien** constituent les sources les plus abondantes. Le **Sahara algérien**, situé près du tropique du Cancer, se caractérise par des températures très élevées, un ensoleillement intense et un climat aride. Ces conditions font du Sahara un environnement idéal pour le développement de **microgrids hybrides** , adaptés aux besoins des communautés rurales dispersées.

La **conception et la gestion optimales** de ces systèmes restent toutefois un défi. Dans ce cadre, l'intégration de l'**intelligence artificielle (IA)** dans la planification, le contrôle et l'exploitation des microgrids apparaît comme une solution prometteuse. L'IA permet de traiter de grandes quantités de données météorologiques et énergétiques afin d'optimiser en temps réel la production, le stockage et la distribution d'électricité. Les algorithmes de machine learning peuvent prévoir la production solaire et éolienne et ajuster dynamiquement les stratégies de gestion.

L'objectif principal de ce projet est de proposer des architectures intelligentes de microgrids hybrides adaptées aux spécificités climatiques et socio-économiques du Sahara algérien. Une évaluation énergétique, économique et environnementale permettra d'identifier les configurations les plus performantes et durables. Cette étude met également en lumière le rôle des outils d'IA dans la prise de décision, la prévision de production et la gestion intelligente de la demande.

Enfin, ce travail vise à renforcer l'autonomie énergétique des communautés rurales du Sahara algérien par l'intégration de **sources d'énergie renouvelables** et de l'**intelligence artificielle**, ouvrant la voie à un avenir énergétique **résilient, propre et intelligent**.

English

Over the past decades, numerous global initiatives have aimed to promote autonomous and sustainable renewable energy systems. These efforts have led to the development of power generation technologies capable of ensuring energy self-sufficiency through the integration of multiple renewable sources. Among these systems, **hybrid microgrids** play a crucial role, enabling the flexible incorporation of local resources while maintaining a stable and reliable power supply, especially in remote areas.

In Algeria, particularly in the southern regions, **solar and wind energy** are the most abundant resources. The **Algerian Sahara**, located near the Tropic of Cancer, experiences extremely high temperatures, intense sunlight, and arid conditions. These circumstances make the Sahara ideal for deploying **hybrid microgrids** adapted to dispersed rural communities.

The **optimal design and management** of such systems remain challenging. In this context, the integration of **artificial intelligence (AI)** in microgrid planning, control, and operation has emerged as a promising solution. AI allows the analysis of large datasets to optimize electricity generation, storage, and distribution in real time. Machine learning algorithms can predict solar and wind production and dynamically adjust management strategies.

The main objective of this project is to propose intelligent hybrid microgrid architectures tailored to the climatic and socio-economic conditions of the Algerian Sahara. A comprehensive energy, economic, and environmental assessment will determine the most efficient and sustainable configurations. The study also highlights the role of AI tools in decision-making, generation forecasting, and smart demand management.

Ultimately, this work aims to strengthen the **energy autonomy** of rural communities in the Algerian Sahara through the integration of **renewable energy sources** and **artificial intelligence**, paving the way for a more **resilient, clean, and intelligent energy future**.

العربية

على مدى العقود الماضية، تم إطلاق العديد من المبادرات العالمية لتعزيز أنظمة الطاقة المتجددة المستقلة والمستدامة. وقد أسهمت هذه الجهود في تطوير تقنيات توليد الطاقة القادرة على ضمان الاكتفاء الذاتي الطاقوي من خلال دمج مصادر متجددة متعددة. ومن بين هذه الأنظمة، تلعب **الشبكات الصغيرة الهجينة (Hybrid Microgrids)** دوراً محورياً، حيث تمكّن من دمج الموارد المحلية بمرونة مع ضمان إمداد كهربائي مستقر وموثوق، لا سيما في المناطق النائية.

في الجزائر، وخصوصاً في المناطق الجنوبية، تعتبر **الطاقة الشمسية وطاقة الرياح** المصادر الأكثر وفرة. وتتميز **الصحراء الجزائرية** بدرجات حرارة مرتفعة جداً، وأشعة شمس قوية، ومناخ جاف، مما يجعلها بيئة مثالية لتطوير **شبكات هجينة** تلبي احتياجات المجتمعات الريفية المتفرقة.

يظل **التصميم والإدارة المثاليين** لهذه الأنظمة تحدياً كبيراً. في هذا الإطار، ظهر **الذكاء الاصطناعي (AI)** كحل واعد للتخطيط والتحكم وتشغيل الشبكات الصغيرة. يتيح الذكاء الاصطناعي معالجة كميات كبيرة من البيانات لتحسين الإنتاج والتخزين والتوزيع في الوقت الحقيقي. كما يمكن لخوارزميات التعلم الآلي التنبؤ بالإنتاج وضبط استراتيجيات الإدارة بشكل ديناميكي.

الهدف الرئيسي من هذا المشروع هو اقتراح هياكل ذكية للشبكات الهجينة تتوافق مع الخصائص المناخية والاجتماعية والاقتصادية للصحراء الجزائرية. وسيتم إجراء تقييم شامل للطاقة، والاقتصاد، والبيئة لتحديد التشكيلات الأكثر كفاءة واستدامة. كما تسلط الدراسة الضوء على دور أدوات الذكاء الاصطناعي في اتخاذ القرار، وتوقع الإنتاج، وإدارة الطلب بشكل ذكي.

في النهاية، تهدف هذه الدراسة إلى تعزيز **الاستقلالية من ناحية الطاقة** للمجتمعات الريفية في الصحراء الجزائرية من خلال دمج **مصادر الطاقة المتجددة والذكاء الاصطناعي**، مما يمهد الطريق لمستقبل **مستدام، نظيف وذكي**.

General Introduction

The global energy transition has become one of the most pressing challenges of our time. The continuous rise in electricity demand, the obligation to mitigate greenhouse gas emissions, and the growing penetration of renewable energy sources such as solar and wind power are transforming the structure and operation of modern electrical networks. Traditional centralized power systems are increasingly limited, particularly when facing rapid fluctuations in both consumption and renewable production. In this context, microgrids—local, flexible, and increasingly autonomous electrical networks—have emerged as an essential component of future energy systems.

A microgrid must continuously maintain a balance between production, storage, and demand. However, renewable sources are intermittent, user demand varies dynamically, and system stability must be preserved at all times. To ensure reliable operation, a dedicated Energy Management System (EMS) is required. An EMS supervises the microgrid, organizes the available resources, processes large volumes of data, and optimizes the operation of the network to enhance efficiency, stability, and sustainability.

This thesis focuses on the design and development of an EMS tailored to a hybrid microgrid. The objective was to build a functional platform capable of collecting energy data, organizing it through a structured database, and presenting it through an intuitive web interface designed for operational decision support. The project also explores modern approaches that can improve the flexibility and performance of microgrids, such as hydrogen-based energy storage and the future integration of artificial intelligence for predictive energy management.

Furthermore, this work contributes to the digitalization of microgrids by bridging concepts from energy engineering, distributed systems, and modern digital tools. It also highlights the analogy between supply chain management and energy flow organization, illustrating how optimization principles traditionally used in logistics can be adapted to microgrid resource coordination.

Structure of the Thesis

To provide a clear and logical progression, this thesis is structured into six chapters :

Chapter 1: Fundamental Concepts and Theoretical Framework This chapter introduces the fundamental concepts of *Supply Chain Management* (SCM) and demonstrates how its principles can be extended to energy systems. It discusses the evolution of SCM, its main analytical models, and the parallels between material flows in supply chains and energy flows in microgrids.

Chapter 2: Microgrids and Energy Management This chapter presents the state of the art on microgrids. It details their architecture, components, renewable energy sources, storage systems, operational challenges, and the central role of an EMS. This chapter provides the technical foundation necessary for understanding the rest of the work.

Chapter 3: Business Model Canvas and Project Vision This chapter presents the global vision of the project through a *Business Model Canvas*. It identifies the stakeholders, key resources, value propositions, cost structure, expected benefits, and user profiles. It provides an integrated view of the project from both technical and economic perspectives.

Chapter 4: Development of the Energy Management System This chapter describes the technical development of the EMS. It details the tools and technologies used (Python, React, MySQL, Docker), the general software architecture, the database structure, the API layer, and the design of the web interface used to visualize and manage microgrid data. It explains how the different components interact to provide a functional monitoring platform.

Chapter 5: MyEMS System Architecture and Implementation This chapter presents the practical implementation of the EMS within the MyEMS platform. It provides detailed descriptions of the system architecture, the data flow pipeline, the functional layers, and the configuration of the interface modules (Space, Meter, Equipment). The chapter also includes the integration of dashboards, time-series visualization, and the structure of the database and REST API. It demonstrates how the EMS can be deployed and operationalized in a microgrid environment.

Chapter 6: Scientific Contribution This chapter highlights the scientific and technical contributions of the work. It describes the creation of a structured microgrid data model, the development of a virtual measurement environment for testing the EMS, the deployment and adaptation of MyEMS for hybrid microgrid monitoring, and the methodological framework linking EMS design with microgrid engineering. It also presents potential improvements and future enhancements such as predictive algorithms, hydrogen storage integration, cybersecurity reinforcements, and multi-microgrid coordination.

In summary, this thesis proposes a complete and evolvable solution for the management of hybrid microgrids by combining modern digital tools, structured engineering methods, and innovative approaches inspired by optimization and supply chain concepts. The ultimate goal is to contribute to the emergence of more autonomous, more intelligent, and more efficient energy systems capable of responding to the technical and environmental challenges of the coming decades.

Dedication

To our beloved families, whose unwavering support, love, and encouragement have been our foundation throughout this journey.

To our parents, who instilled in us the values of perseverance, hard work, and sincerity. Your sacrifices and constant prayers have illuminated our path to success.

To our dear friends **— Sedoud Aimane, Bensari Ayoub, Chadouli Houssem, Abdel-Karim, Kouadri Yahia, and Sahnoue —** thank you for your friendship, your presence, and your continuous encouragement. Your support, motivation, and shared moments made this journey richer and more meaningful.

And to everyone who believed in us, this work is wholeheartedly dedicated to you.

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Finally, we would like to thank all the teachers, colleagues, classmates, and family members who supported us morally, academically, or personally. Their encouragement and belief in our abilities helped us persevere through the challenges of this journey.

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Abbreviations

IE	Industrial Engineering
AI	Artificial Intelligence
API	Application Programming Interface
BESS	Battery Energy Storage Systems
BMC	Business Model Canvas
CI/CD	Continuous Integration / Continuous Deployment
CO_2	Carbon Dioxide
CSS	Cascading Style Sheets
DER	Distributed Energy Resources
DERs	Distributed Energy Resources
DSM	Demand-Side Management
Docker	Containerization Platform for Deployment and Isolation
EMS	Energy Management System
ERP	Enterprise Resource Planning
EV	Electric Vehicle
ESS	Energy Storage Systems
GHG	Greenhouse Gas
HTML	HyperText Markup Language
HRES	Hybrid Renewable Energy Systems
IoT	Internet of Things
JIT	Just-In-Time
ML	Machine Learning
MySQL	My Structured Query Language (Relational Database Management System)
NGO	Non-Governmental Organization
PV	Photovoltaic
R&D	Research and Development
RBV	Resource-Based View
ROI	Return on Investment
SCM	Supply Chain Management
SDGs	Sustainable Development Goals
SIE	Sustainable Industrial Engineering
SSCM	Sustainable Supply Chain Management
VS Code	Visual Studio Code

Chapitre 1

Supply Chain Management in Energy Systems

Supply chain management (SCM) is traditionally associated with the efficient coordination of material, information, and financial flows from raw material suppliers to final consumers. In recent decades, however, the concept has been increasingly applied to complex systems beyond traditional manufacturing, including the energy sector. SCM provides a systematic framework to optimize resource flows, reduce inefficiencies, and ensure reliability in energy production, distribution, and consumption [1].

In the context of microgrids, SCM principles are crucial for managing the lifecycle of energy resources, from generation and storage to distribution and end-use. Unlike conventional supply chains, energy supply chains are characterized by unique constraints such as the perishability of electricity, the intermittency of renewable sources, and the critical importance of balancing supply and demand in real time [2]. These challenges necessitate the integration of digital technologies, predictive analytics, and smart management strategies that align with the broader goals of sustainability and resilience [3].

1.1 Theoretical Foundations of SCM

SCM is defined as "the systemic, strategic coordination of traditional business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole" [1]. It encompasses procurement, production, logistics, and customer relationship management. Within industrial engineering, SCM provides methods to optimize flows, minimize costs, and maximize value creation [4].

Supply Chain Management (SCM) has evolved from the integration of logistics, operations management, and systems theory into a multidisciplinary field that emphasizes the end-to-end coordination of material, information, and financial flows [1]. SCM is built upon theoretical models that explain how networks of firms cooperate, compete, and adapt to changing environments. These foundations not only define SCM's scope but also provide frameworks for its application in diverse sectors such as manufacturing, healthcare, and energy systems.

1.1.1 Systems Theory in SCM

One of the primary theoretical underpinnings of SCM is **systems theory**, which views the supply chain as a complex, interconnected system where the performance of the whole is greater than the sum of its parts [5]. This perspective emphasizes feedback loops, interdependencies, and the importance of balancing efficiency with adaptability. In practice, systems theory supports the idea that disruptions in one part of the supply chain (e.g., raw material shortages) propagate throughout the entire network, highlighting the need for resilience and holistic management [3].

1.1.2 Transaction Cost Economics (TCE)

Another important theoretical foundation is transaction cost economics, which explains why firms choose between market-based transactions, hybrid arrangements (e.g., partnerships), or vertical integration [6]. Applied to SCM, TCE suggests that companies structure their supply chains to minimize the costs of contracting, monitoring, and enforcing agreements. This theory underpins the move toward strategic supplier partnerships, where long-term collaborations reduce uncertainty and transaction costs compared to purely market-based procurement [7].

1.1.3 Resource-Based View (RBV)

The **resource-based view** (RBV) argues that a firm's competitive advantage stems from its unique resources and capabilities [8]. In SCM, this perspective translates into leveraging supplier relationships, logistics capabilities, and digital technologies as strategic resources that are difficult for competitors to imitate. For example, Amazon's superior distribution network exemplifies how supply chain capabilities can create sustained competitive advantage [9].

1.1.4 Network Theory

SCM is also informed by **network theory**, which conceptualizes supply chains as networks of interconnected actors (suppliers, manufacturers, distributors, and customers) [10]. Network theory emphasizes relational ties, power structures, and the importance of trust in facilitating cooperation across the chain. It is particularly relevant in global supply chains where cultural, geographical, and technological barriers complicate coordination [11]. In microgrids, network theory helps explain how diverse stakeholders (energy producers, consumers, regulators) interact within local energy ecosystems.

1.1.5 Lean and Agile Paradigms

The lean paradigm, derived from the Toyota Production System, focuses on **eliminating waste**, **reducing lead times**, and **improving efficiency** [12]. Agile supply chains, in contrast, emphasize flexibility, responsiveness, and adaptability to volatile markets [13]. Modern SCM integrates both paradigms into a "leagile" approach, balancing cost efficiency with responsiveness. In energy systems, lean principles reduce waste in production and distribution, while agility enables quick adaptation to demand fluctuations and renewable intermittency.

1.1.6 Sustainable and Resilient Supply Chain Theories

Contemporary SCM incorporates **sustainability** and **resilience** as key theoretical pillars. Sustainable supply chain management (SSCM) integrates environmental and social considerations alongside economic efficiency [7]. Resilient supply chains focus on robustness and recovery from disruptions, drawing from risk management and complexity science [14]. These perspectives are highly relevant for microgrids, where uncertainty in renewable generation and extreme weather events require adaptive, sustainable supply chain strategies.

1.1.7 Summary

The theoretical foundations of SCM draw from multiple disciplines, including systems theory, economics, strategic management, and operations research. These perspectives provide the conceptual tools to understand supply chains not just as linear flows of goods, but as dynamic, adaptive networks. By applying these theories to energy systems, particularly microgrids, researchers and practitioners can design supply chains that are not only efficient but also sustainable, resilient, and adaptive to global energy transitions.

1.2 Core Components of Supply Chain Management

Supply chain management (SCM) can be understood as the orchestration of a set of interconnected processes designed to ensure the efficient flow of goods, services, information, and finances from raw material acquisition to final customer delivery [1], [2]. These processes are typically structured around five key components : **planning, sourcing, production, distribution, and returns,** each of which plays a critical role in ensuring end-to-end efficiency and responsiveness [3], [15].

1.2.1 Planning

Planning is the foundational stage of SCM, focusing on demand forecasting, capacity management, and aligning supply with customer demand [16]. Effective planning involves integrating forecasting models, inventory strategies, and network design to balance cost, service level, and flexibility [2]. Increasingly, advanced analytics and digital tools are used to improve accuracy in demand forecasting, contributing to leaner and more adaptive supply chains [17].

1.2.2 Sourcing

Sourcing refers to the process of identifying, evaluating, and managing suppliers to ensure the consistent availability of high-quality materials at competitive costs [18]. Strategic sourcing has evolved beyond simple procurement to include supplier collaboration, risk management, and sustainability considerations [3], [19]. In modern supply chains, sourcing is often global, requiring careful attention to geopolitical risks, transportation reliability, and ethical standards [20].

1.2.3 Production

Production involves the transformation of raw materials into finished goods, encompassing process design, scheduling, and quality management [21]. The goal is to optimize throughput while minimizing waste and maintaining flexibility to meet variable demand [12]. Concepts such as lean manufacturing, just-in-time (JIT), and Industry 4.0 technologies (IoT-enabled factories, automation, and digital twins) have revolutionized production management in recent decades [22], [23].

1.2.4 Distribution and Logistics

Distribution ensures that finished goods reach customers efficiently and reliably. This component integrates warehousing, inventory positioning, and transportation management [24]. Logistics is increasingly supported by advanced technologies such as warehouse automation, last-mile delivery optimization, and real-time tracking systems [25]. An effective distribution system is essential for maintaining customer satisfaction while balancing costs and environmental considerations [3].

1.2.5 Returns and Reverse Logistics

The final core component is reverse logistics, which manages product returns, recycling, refurbishing, and disposal [26]. This stage has gained prominence due to the rise of e-commerce, stricter environmental regulations, and the increasing focus on circular economy principles [27]. Effective returns management not only reduces waste and environmental impact but also enhances customer trust and brand reputation [28].

In summary, the five core components of SCM form a comprehensive framework for managing the flow of goods and services across the value chain. Each component must be coordinated with the others to achieve resilience, sustainability, and customer-centric performance, particularly in complex global environments [2], [3].

1.3 Energy as a Supply Chain

The energy sector can be conceptualized as a supply chain where raw materials (such as solar radiation, wind, or natural gas) are transformed into usable energy products (electricity, hydrogen, or heat) and delivered to end-users [29]. The chain also involves intermediate stages, including energy conversion, transmission, storage, and distribution. By applying SCM principles, stakeholders can design resilient energy systems capable of addressing uncertainties in supply (e.g., variability of renewables) and demand (e.g., peak loads) [28].

The supply chain perspective has traditionally been applied to tangible goods, but in recent years, researchers have increasingly conceptualized energy as a supply chain. This approach recognizes that energy, like physical products, follows a series of interconnected stages involving sourcing, transformation, distribution, and final consumption [30], [31]. Treating energy flows as a supply chain enables the application of well-established principles from industrial engineering—such as optimization, risk management, and sustainability—to the domain of energy systems.

At the upstream level, the energy supply chain begins with raw energy sources, which may include fossil fuels (coal, oil, natural gas) or renewable resources (solar irradiation, wind currents, biomass, hydro potential). These inputs undergo transformation processes—such as combustion, refining, or electrolysis—that convert them into usable forms of energy like electricity, heat, or hydrogen fuel [32], [33].

The midstream stage involves the storage and transmission of energy. In traditional fossil fuel systems, this includes pipelines, refineries, and large-scale distribution networks. In electricity systems, it refers to the high-voltage grid, substations, and increasingly, energy storage technologies such as batteries or hydrogen tanks [34], [35]. Effective management of this stage is critical for balancing supply and demand, minimizing losses, and ensuring reliability.

The downstream stage covers the distribution and delivery of energy to end-users—households, industries, and transport systems. Here, the challenges resemble those of conventional product distribution : ensuring quality, timeliness(proper timing), and cost-efficiency. However, energy supply chains are unique in that electricity cannot be easily stockpiled(stored), requiring real-time balancing between production and consumption [30], [36].

Moreover, the energy supply chain has increasingly incorporated sustainability and circular economy principles. The shift from fossil fuels to renewables has transformed the supply chain landscape, creating new flows (e.g., decentralized solar production, prosumer (a consumer who becomes involved with designing or customizing products for their own needs.)models, hydrogen logistics) and requiring digital tools for tracking, forecasting, and optimization [37], [38]. Smart grids and microgrids exemplify this transformation, embedding(combining with) advanced monitoring and management systems into the energy chain to improve resilience and reduce environmental impact [39], [40].

Thus, considering energy as a supply chain allows for a holistic(all-inclusive) view of energy systems, where each stage—sourcing, transformation, transmission, storage, and consumption—can be optimized using industrial engineering and supply chain management techniques. This perspective provides a strong foundation for the subsequent exploration of energy supply chains in microgrid contexts, where integration, flexibility, and sustainability are important.

1.4 Microgrids and SCM Integration

The concept of microgrids has emerged as a promising solution for enhancing the resilience, flexibility, and sustainability of modern power systems. A microgrid can be defined as a localized energy system that integrates distributed energy resources (DERs)—such as solar photovoltaic panels, wind turbines, microturbines, fuel cells, and energy storage units—with controllable loads, capable of operating both in grid-connected and islanded modes [39], [41]. By organizing the production, storage, and distribution of energy within a confined network, microgrids exhibit striking similarities to traditional supply chains, where flows must be managed across different actors and stages.

From a supply chain management (SCM) perspective, microgrids can be conceptualized as energy supply chains in miniature, where electricity and energy carriers flow instead of physical goods [30], [34]. The upstream component involves sourcing renewable resources (e.g., solar irradiation, wind currents, biomass) or grid electricity. Midstream processes include conversion, storage, and control systems that act as transformation and inventory stages, ensuring energy is available when required. The downstream component is the delivery of reliable electricity to end-users, which may include households, industries, or critical facilities such as hospitals and data centers [40], [42].

Applying SCM principles to microgrids emphasizes several key dimensions :

1. **Visibility and Traceability :**Just as supply chains benefit from real-time tracking of materials, microgrids require continuous monitoring of energy flows, enabled by smart meters, IoT devices, and advanced data analytics [43], [44].
2. **Optimization of Flows :**SCM seeks to minimize costs and delays while maximizing efficiency. In microgrids, this translates into optimizing **generation–storage–consumption balances**, minimizing transmission

losses, and maximizing renewable energy penetration [39], [45].

3. **Flexibility and Resilience :**Traditional supply chains are vulnerable to disruptions, requiring robust design. Similarly, microgrids must withstand uncertainties such as fluctuating renewable generation, demand variations, and grid outages. SCM methodologies such as **risk management, scenario planning, and resilience modeling** are increasingly applied to microgrid operations [46], [47].
4. **Sustainability and Circularity :**In line with green supply chain management, microgrids contribute to sustainability by integrating renewable sources, reducing emissions, and enabling circular models such as using surplus energy for **hydrogen production via electrolysis** to store energy for future use [34], [38].
5. **Coordination and Stakeholder Management :**Supply chains rely on effective coordination across suppliers, manufacturers, and distributors. Microgrids similarly involve multiple stakeholders, including prosumers, utility operators, regulators, and technology providers. Proper governance structures and contractual arrangements are necessary to ensure efficiency and fairness [48], [49].

By integrating SCM frameworks with microgrid operations, researchers and practitioners gain a powerful lens for addressing technical, economic, and environmental challenges. This approach enables **holistic decision-making**, balancing cost efficiency with reliability and sustainability. Furthermore, it aligns with the **Industry 4.0 paradigm**, where digital technologies such as blockchain, AI, and digital twins provide advanced tools for supply chain-style optimization of microgrid systems [40], [50].

Thus, microgrids are not merely an engineering innovation but also a **supply chain management system for energy flows**. This integrated perspective lays the foundation for the development of advanced **Energy Management Systems (EMS)**, which act as the orchestrators of the microgrid supply chain, ensuring optimal allocation of resources while meeting user demands and sustainability objectives.

1.5 Digital Tools in SCM for Energy Systems

The deployment of digital platforms and management systems strengthens the role of SCM in microgrids. Tools such as Enterprise Resource Planning (ERP), Internet of Things (IoT), and Artificial Intelligence (AI) support real-time tracking, forecasting, and optimization [23]. In our project, the development of a web-based Energy Management System (EMS) directly supports SCM goals by monitoring energy flows, enabling proactive decision-making, and ensuring that the right amount of energy is available at the right place and time.

Digital transformation has fundamentally reshaped supply chain management (SCM), enabling higher levels of visibility, automation, and decision-making accuracy. In the context of energy systems and microgrids, digital tools act as the backbone of modern management strategies, ensuring real-time monitoring, optimization, and coordination across the entire energy supply chain. These technologies integrate data-driven insights with advanced computational models, aligning with the goals of sustainability, resilience, and efficiency in energy systems [23], [51].

Enterprise Resource Planning (ERP) Systems

ERP systems serve as centralized platforms that integrate core business processes—procurement, logistics, asset management, and financial flows—into a unified framework. In energy supply chains, ERP systems facilitate end-to-end visibility of energy resources, inventory management (e.g., fuel reserves or spare parts for renewable installations), and financial planning for infrastructure investments [3], [52]. By synchronizing data across stakeholders, ERP systems enhance coordination and reduce information silos(storage), which is crucial for microgrid projects involving multiple actors.

1.5.1 Internet of Things (IoT) and Smart Sensors

The deployment of IoT devices and smart meters enables real-time data collection on energy generation, consumption, and grid conditions. These devices act as digital nodes within the energy supply chain, improving traceability and responsiveness [44], [53]. In microgrids, IoT sensors provide granular(precise) data on renewable energy production, storage state-of-charge, and load variations, which can be used to optimize scheduling and reduce losses. Furthermore, IoT enhances predictive maintenance of distributed assets, minimizing downtime and ensuring supply chain reliability [54].

1.5.2 Artificial Intelligence (AI) and Machine Learning

AI and machine learning algorithms are increasingly applied to optimize supply chain processes, from demand forecasting to predictive maintenance. In energy systems, AI supports load forecasting, renewable energy prediction, and dynamic energy pricing [55], [56]. These capabilities allow microgrids to balance supply and demand effectively, integrate intermittent(discontinuous) renewable sources, and minimize reliance on costly backup systems. Reinforcement learning approaches have shown particular promise in optimizing distributed energy resource scheduling under uncertainty [57].

1.5.3 Blockchain and Distributed Ledger Technologies (DLT)

Blockchain technology provides decentralized and tamper-proof mechanisms for recording transactions across supply chains. In the energy sector, blockchain has been applied to peer-to-peer energy trading, renewable energy certification, and contract automation [50]. For microgrids, blockchain enhances transparency and trust among prosumers and consumers, reducing the transaction costs of local energy markets. The Brooklyn Microgrid, for instance, demonstrated how blockchain can facilitate community-based energy exchanges, reinforcing the SCM principles of visibility and coordination [58].

1.5.4 Digital Twins and Simulation Platforms

Digital twin technology creates a virtual replica of physical systems, enabling real-time simulation, monitoring, and optimization. In energy SCM, digital twins model the behavior of power systems, predict disruptions, and evaluate alternative management strategies before implementation [59]. For microgrids, digital twins can simulate renewable intermittency, storage dynamics, and consumer demand, providing valuable insights for robust and resilient system design.

1.5.5 Energy Management Systems (EMS) as SCM Platforms

At the core of digital transformation in energy SCM lies the Energy Management System (EMS). EMS platforms act as the “control tower” of energy supply chains, integrating IoT data, AI analytics, and optimization models into a decision-support environment [39], [45]. They enable operators to monitor distributed resources, forecast demand, optimize storage utilization, and balance local energy flows with external grid interactions. In essence, EMS operationalizes SCM principles—visibility, optimization, and coordination—within energy systems, particularly in microgrid environments.

1.5.6 Summary

Digital tools are indispensable enablers of SCM in energy systems, transforming traditional supply chains into intelligent, adaptive, and resilient networks. By leveraging ERP systems, IoT, AI, blockchain, and EMS platforms, energy stakeholders can optimize resource utilization, improve sustainability, and enhance system reliability. The convergence of these tools with SCM theories underscores the growing role of industrial engineering and digital innovation in shaping the future of energy supply chains.

1.6 Sustainability and Circular Supply Chains

SCM in energy systems is not limited to efficiency; it is also closely linked to sustainability. Circular supply chains promote the reuse, recycling, and repurposing of materials and components, aligning with the principles of the circular economy [60]. In microgrids, this translates to reusing batteries, optimizing hydrogen cycles, and ensuring minimal environmental impact from infrastructure development. Such practices enhance resilience while reducing the carbon footprint of energy supply chains.

The increasing urgency of climate change and resource depletion(consumption) has driven the global shift toward sustainable development, making **sustainability a central theme in modern Supply Chain Management (SCM)**. Sustainability in SCM encompasses(surrounds) the triple bottom line—environmental protection, social responsibility, and economic viability(sustainability)—ensuring that supply chains minimize negative ecological impacts while remaining resilient and cost-effective [61]. Within energy systems, sustainable SCM is particularly critical, as the sector is both a major contributor to greenhouse gas emissions and a pivotal enabler of decarbonization.

1.6.1 Sustainability in Energy Supply Chains

In energy-focused SCM, sustainability efforts prioritize the integration of renewable energy sources, efficient use of natural resources, and the reduction of carbon footprints. According to Seuring and Müller [62], sustainable SCM emphasizes collaboration across stakeholders to balance environmental concerns with operational efficiency. Within microgrids, these practices are evident in strategies such as demand-side management, lifecycle planning of equipment, and optimization of energy mix to reduce dependency on fossil fuels [63].

Social sustainability is equally important, as energy systems directly affect communities by improving energy access, creating jobs, and ensuring affordability. In regions with unreliable national grids, microgrids enhance social equity by providing cleaner and more reliable electricity [64]. Economic sustainability, meanwhile, involves the efficient allocation of resources, lowering costs through localized energy production, and ensuring long-term financial viability of microgrid projects.

1.6.2 Circular Supply Chains

A circular supply chain (CSC) is an advanced approach that extends sustainability principles by embedding the circular economy model into SCM. Unlike traditional linear models of ”take–make–dispose,” CSCs aim to design products and systems that facilitate reuse, recycling, and repurposing of resources [60].

In the energy sector, CSC principles manifest through practices such as battery recycling, repurposing end-of-life photovoltaic panels, and integrating hydrogen storage from surplus renewable energy [65]. These practices reduce waste, optimize resource use, and lower the carbon intensity of energy systems. In microgrids, CSCs contribute to closing energy loops, where surplus renewable energy is either stored, repurposed, or fed back into the system for maximum efficiency.

1.6.3 Applications in Microgrids

The synergy(coordination) between sustainability and CSC principles is particularly strong in microgrid management systems. For example, renewable energy integration in microgrids reduces reliance on fossil fuels, while circular practices such as recycling storage components extend the lifecycle of critical assets [66]. Moreover, integrating CSCs enhances system resilience, as localized recycling and repurposing of resources reduce dependence on global supply chain vulnerabilities.

Digital technologies, such as blockchain and IoT (discussed in Section 1.5), further enable CSC adoption by providing traceability, monitoring, and optimization of material flows in energy systems [67]. This creates a transparent ecosystem where resources are efficiently utilized and continuously circulated.

1.6.4 Challenges and Future Trends

Despite their potential, implementing sustainability and CSCs faces challenges. These include high initial costs, technological limitations, lack of standardization, and regulatory barriers [68]. Furthermore, achieving social acceptance and stakeholder collaboration is crucial to transitioning from linear to circular models.

Future trends point toward the integration of Industry 4.0 technologies such as AI, big data, and blockchain to facilitate CSC implementation. Additionally, global sustainability agendas, such as the United Nations Sustainable Development Goals (SDGs), will continue to shape the evolution of circular and sustainable SCM practices in energy systems [69].

Summary

Sustainability and circular supply chains represent a transformative approach to modern SCM, particularly in the energy sector. By aligning environmental, economic, and social objectives, and embedding circular principles into microgrid design and operation, energy systems can achieve both resilience and efficiency. The convergence of digital tools and sustainability-focused SCM will ultimately play a vital role in advancing the global energy transition.

1.7 Case Studies in Energy SCM

1.7.1 Tesla's Renewable Energy Supply Chain

Tesla provides a notable example of SCM applied in the renewable energy sector. Its supply chain integrates lithium extraction, battery production, renewable energy generation (via solar panels), and energy storage (via Powerwall and Powerpack systems). Tesla's vertically integrated supply chain demonstrates how close coordination of material sourcing, production, and distribution can optimize both efficiency and sustainability [70]. Moreover, Tesla's global distribution of battery storage solutions to microgrids in Puerto Rico after Hurricane Maria illustrated the potential of SCM in rapid disaster recovery [71].

1.7.2 Brooklyn Microgrid (USA)

The Brooklyn Microgrid in New York represents one of the first real-world applications of blockchain technology in managing local energy supply chains. Residents equipped with solar panels can trade excess electricity with their neighbors using blockchain-based peer-to-peer transactions. This model not only enhances local energy autonomy but also ensures traceability, transparency, and trust in the supply chain [58].

1.7.3 Rural Microgrids in India

In rural India, decentralized microgrids powered by solar energy have been implemented to overcome the lack of reliable grid access. These projects require careful SCM design to coordinate the procurement of solar panels, local assembly, maintenance, and distribution of electricity. The success of these microgrids has shown how SCM can improve social equity and economic development by delivering affordable, sustainable energy to underserved populations [72].

1.7.4 Hydrogen Supply Chains in Europe

The European Union has invested heavily in hydrogen supply chains as part of its energy transition strategy. Projects such as the “Hydrogen Backbone” aim to integrate hydrogen production (via electrolysis), storage, transportation, and distribution across member states. These initiatives highlight how SCM principles ensure coordination between diverse stakeholders, optimize logistics, and support the development of sustainable energy infrastructure [73].

1.8 Relation to Industrial Engineering

As an industrial engineering students specializing in SCM, our thesis bridges theoretical knowledge and applied practice. By designing and implementing a digital EMS for microgrid management, you are essentially creating a supply chain monitoring and optimization tool. The EMS functions like a supply chain control tower, providing end-to-end visibility, coordinating distributed assets, and ensuring efficiency in both operational and strategic decision-making [17].

Industrial Engineering (IE) plays a central role in connecting Supply Chain Management (SCM) principles with the practical design, optimization, and operation of energy systems such as microgrids. At its core, IE focuses on improving efficiency, productivity, and resource allocation through the application of analytical, computational, and managerial techniques [74]. These objectives align directly with SCM’s mission to optimize flows of goods, information, and energy across interconnected networks.

1.8.1 Industrial Engineering and SCM

SCM originated as an interdisciplinary field, borrowing heavily from IE methods such as operations research, simulation modeling, systems optimization, and process engineering. For example, IE tools such as linear programming, stochastic modeling, and queuing theory are widely applied to improve logistics, inventory control, and production scheduling in supply chains [75]. These methodologies have evolved into the backbone of modern SCM practices, including those tailored for energy and utility sectors .

1.8.2 Industrial Engineering in Energy Systems

The relevance of IE extends naturally into energy systems. Energy supply chains resemble industrial processes in that they require coordination of material flows (e.g., fuel, renewable resources), technology assets (e.g., turbines, storage), and demand-side consumption patterns. Industrial engineers leverage optimization techniques to design efficient energy distribution networks, enhance grid reliability, and integrate renewable resources in a cost-effective manner [76].

Within microgrids, IE contributes through :

1. Systems modeling for balancing demand and generation.
2. Process optimization for scheduling distributed energy resources (DERs).
3. Reliability engineering to improve resilience in islanded operation.
4. Simulation tools for testing scenarios under uncertainty.

These applications mirror classical IE functions in manufacturing but are recontextualized in energy management systems.

1.8.3 Human Factors and Socio-Technical Integration

Another dimension of IE relevant to energy SCM is human factors engineering. Effective microgrid and EMS deployment requires user-friendly interfaces, decision support systems, and collaboration among stakeholders. IE methodologies in ergonomics and human-system integration ensure that energy management tools are not only technically robust but also accessible, safe, and usable for operators and communities [77]

1.8.4 Toward Sustainable Industrial Engineering

As SCM shifts toward sustainability and circular economy models (Section 1.6), IE has also expanded into Sustainable Industrial Engineering (SIE). This subfield integrates life cycle assessment (LCA), eco-design, and green operations research into industrial systems design [78]. In microgrids, SIE supports long-term sustainability through :

1. Optimized use of renewable resources.
2. Design of closed-loop energy flows.
3. Integration of circular supply chain practices.

This convergence highlights IE as a disciplinary enabler that operationalizes theoretical SCM concepts into practical energy solutions.

1.8.5 Summary

Industrial Engineering provides the methodological foundation and practical tools that enable SCM principles to be applied in energy systems and microgrids. Through systems optimization, reliability analysis, and sustainability-oriented design, IE bridges the gap between theoretical frameworks and real-world implementation. Its contribution ensures that energy supply chains are not only efficient and resilient but also aligned with broader goals of sustainability and digital transformation.

1.9 Conclusion

Supply Chain Management (SCM) provides a comprehensive framework for analyzing and optimizing energy systems, with particular relevance to decentralized structures such as microgrids. By embedding SCM principles, these systems can enhance efficiency, resilience, and sustainability while addressing the dual challenges of rising energy demand and environmental constraints. The integration of digital Energy Management Systems (EMS) reflects the convergence of supply chain thinking with advanced industrial engineering approaches, enabling real-time visibility, predictive decision-making, and system-wide coordination. Case studies—including Tesla's vertically integrated renewable energy supply chain, blockchain-enabled community microgrids, and hydrogen initiatives in Europe—illustrate the transformative potential of SCM in shaping the future of global energy systems and accelerating the transition toward cleaner, smarter, and more resilient infrastructures.

Chapitre 2

State of the Art in Microgrid Management Systems

2.1 Introduction to Microgrids

A **microgrid** is a **small-scale**, **decentralized energy system** that integrates multiple **distributed energy resources (DERs)**, **including solar photovoltaic (PV) panels**, **wind turbines**, **biomass generators**, **hydrogen fuel cells**, and **battery storage systems**.

It is designed to **generate**, **store**, and **distribute** electricity efficiently within a specific area, such as a university campus, industrial zone, military base, hospital, or rural village. By providing localized energy generation, microgrids enhance reliability, reduce transmission losses, and improve energy resilience. They can operate in grid-connected mode, interacting with the main power grid, or in islanded mode, functioning independently during grid failures or planned disconnections

2.1.1 Why Microgrids ?

The global shift towards microgrids is driven by several key challenges in traditional power systems, including :

1. **Aging Infrastructure :** Many power grids worldwide were built decades ago and are not designed for modern energy demands.
2. **Energy Security :** Distributed generation enhances resilience against power outages, natural disasters, and cyber threats
3. **Renewable Energy Integration :** Microgrids can incorporate solar, wind, and hybrid energy sources to reduce dependence on fossil fuels.
4. **Electrification of Remote Areas** : More than 800 million people worldwide lack electricity access, particularly in Africa, Asia, and Latin America.
5. **Environmental Concerns :**The transition to renewable microgrids helps reduce greenhouse gas (GHG) emissions and meet climate change targets.

2.1.2 The Role of Microgrids in Algeria

1. **Geographical Challenge :** The Sahara Desert covers over 82% of Algeria's land, making it difficult to extend the national power grid to remote locations.
2. **Solar energy potential :** Algeria receives an average of 2,500 to 3,500 hours of sunlight per year, making it ideal for photovoltaic (PV) systems.
3. **Wind energy potential :** Coastal and desert regions experience strong winds, suitable for wind power generation.
4. **Hybrid Renewable Energy Solutions :** By combining solar and wind energy with battery storage and hydrogen fuel cells, microgrids can provide stable, reliable power to off-grid areas. [79]

2.2 Microgrid Components and Architecture

A microgrid consists of several interconnected components that work together to ensure reliable, efficient, and stable power distribution. These components include power generation units, energy storage systems, control systems, and load management mechanisms.

The following section presents the general architecture of a Microgrid (Fig. 2.1), highlighting its core components such as renewable energy sources, storage units, and load management systems.

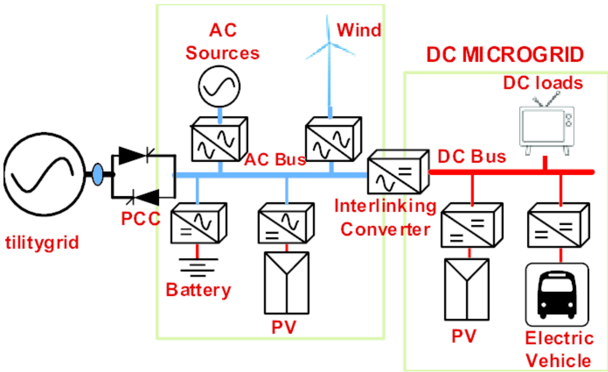

FIG. 2.1: Conventional Microgrid Architecture

Here is a chematic representation showcasing the typical components and layout of a microgrid system, including energy sources, storage, and control systems(Fig. 2.2).

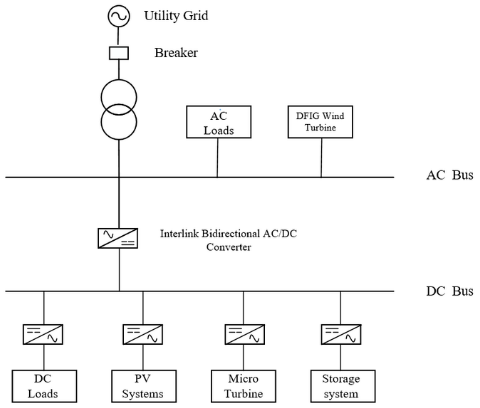

FIG. 2.2: Microgrid Architecture Diagram

2.2.1 Power Generation Sources in Microgrids

Microgrids can use renewable and non-renewable energy sources :

Type	Examples	Advantages	Challenges
Renewable Energy	Solar PV, Wind, Hydro, Biomass	Low emissions, sustainable	Intermittent, storage required
Non-Renewable Energy	Diesel Generators, Gas Turbines	Reliable, high capacity	High fuel costs, emissions

TAB. 2.1: Power Generation Sources in Microgrids

In rural electrification projects, hybrid systems are commonly used, where solar PV and wind turbines are supplemented by backup diesel generators for reliability. [80]

2.2.2 Energy Storage Systems (ESS)

Energy storage is crucial for maintaining a stable energy supply, particularly when using intermittent renewable sources like solar and wind. Common **energy storage technologies** include :

- **Battery Energy Storage Systems (BESS) :**
  - **Lithium-ion :** High efficiency (95%), but expensive.
  - **Lead-acid :** Cost-effective but lower lifespan.
  - **Flow batteries :** Suitable for large-scale storage.
- **Hydrogen Storage & Fuel Cells**
  - Uses **electrolysis** to store excess energy as hydrogen.
  - Can be **converted back into electricity** when needed. [81]

2.2.3 Load Management & Demand Response

Efficient load management is critical for microgrid stability. Some strategies include :

- **Peak shaving :**Reducing demand during high-load periods.

- **Load shifting :**Moving consumption to times when renewable energy is abundant.
- **Demand-side management (DSM) :**Using smart meters and AI-driven algorithms to optimize consumption. [82]

2.3 Classification of Microgrids

Microgrids can be classified based on their operational mode, ownership model, and technology type.

2.3.1 Based on Operation Mode

- **Grid-Connected Microgrid :**Operates while interacting with the national grid.
- **Islanded Microgrid :** Functions autonomously, useful for remote regions.

2.3.2 Based on Ownership Model

- **Utility-Owned Microgrid** (managed by power companies).
- **Community-Owned Microgrid** (local cooperatives).
- **Industrial Microgrid** (factories, mining operations).

2.4 Energy Management System (EMS) in Microgrids

An **Energy Management System (EMS)** is a critical software-based control system that optimizes energy flow and ensures efficient operation.

2.4.1 EMS Functions

- **Real-time Monitoring :**Tracks **generation** , **storage** , and **load** status.
- **Optimization Algorithms :**Uses **AI** and **machine learning** for **decision-making.**
- **Load Forecasting :** Predicts future demand using **historical data.** [83]

2.5 Hybrid Renewable Energy Systems (HRES)

Hybrid energy systems combine multiple renewable sources for greater reliability. Example setups include :

System Type	Example	Advantages
Solar-Diesel	Rural electrification	Reduces fuel consumption
Solar-Wind-Battery	Islanded microgrids	Balances fluctuations

Tab. 2.2: Hybrid Renewable Energy Systems

2.5.1 Case Studies

Microgrid systems have been implemented globally to address energy access challenges, integrate renewable energy, and improve grid resilience. Below are several real-world case studies showcasing successful microgrid deployments in different regions, including their design, challenges, and outcomes.

The following section introduces the Industrial Microgrid Concept Diagram (Fig. 2.3), which illustrates the integration of distributed energy resources, storage systems, and control mechanisms that enable both grid-connected and islanded operation.

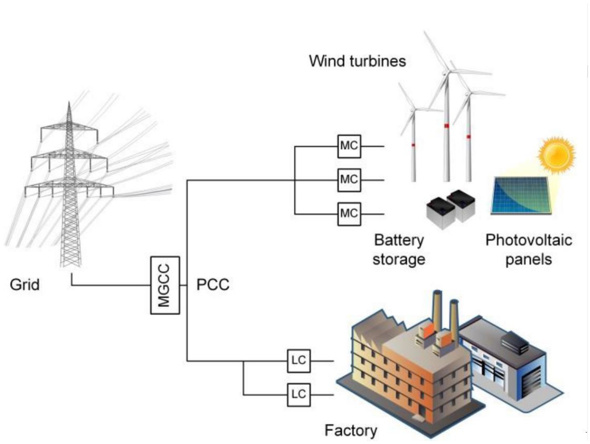

FIG. 2.3: Industrial Microgrid Concept Diagram

Case Study 1: The Ain Guezzam Solar Microgrid, Algeria

One of the most notable microgrid projects in Algeria is the solar-based microgrid installed in **Ain Guezzam** , a remote town in the Sahara Desert. The region was historically dependent on diesel generators, which were expensive and environmentally harmful. The Algerian government, in collaboration with research institutions, introduced a **hybrid solar-diesel microgrid** to provide sustainable electricity to local communities.

Key Aspects of the Project :

- **Energy Sources :**70% solar photovoltaic (PV) + 30% diesel generator backup
- **Storage :**Lithium-ion battery storage for nighttime power supply
- **Challenges :**High desert temperatures affecting PV efficiency, dust accumulation on panels
- **Outcomes :**40% reduction in diesel fuel consumption, improved energy reliability for local businesses and households

This project demonstrates how microgrids can address the energy access problem in rural Algeria while reducing dependence on fossil fuels [84]

Case Study 2: Smart Microgrid for Remote Villages in India

India has a significant rural population that lacks access to reliable electricity. The **Sundarbans Microgrid** Project in West Bengal is an example of how decentralized microgrids can provide stable power to off-grid communities.

Key Features of the Microgrid :

- **Energy Mix :**Solar PV + biomass-based generation
- **Storage System :** Lead-acid batteries for energy backup
- **Demand-Side Management :**Smart meters installed to regulate energy consumption
- **Economic Impact :**Improved agricultural productivity, better lighting for schools, and new business opportunities

A study by **Kumar et al. (2021)** found that similar microgrids in India **increased household income** by 20% due to the introduction of small-scale industries enabled by a reliable power supply [85]

Case Study 3: Hydrogen-Powered Microgrid in Japan

Japan, a leader in clean energy innovation, has been actively developing **hydrogen-based microgrids** as a strategy to decarbonize its energy sector. The **Fukushima Hydrogen Energy Research Field (FH2R)** is one of the world's largest green hydrogen-based microgrid projects.

Project Highlights :

- **Power Source :**Solar PV used for electrolysis to produce hydrogen

- **Energy Storage :**Hydrogen fuel cells store excess solar energy for later use
- **Integration with National Grid :**Can operate in both grid-connected and islanded modes
- **Resilience Feature :**Provides emergency backup power in case of natural disasters

The FH2R project highlights the role of **hydrogen storage** in microgrids, making them viable for long-term sustainability and carbon neutrality [86]

Case Study 4: Community-Managed Microgrids in Sub-Saharan Africa

Many Sub-Saharan African countries have adopted **community-driven microgrid models** to expand rural electrification. In Tanzania, the **JUMEME Microgrid Project** provides **solar-powered electricity** to isolated villages on Lake Victoria's islands.

Notable Features :

- **Solar PV-based power generation** with battery storage
- **Prepaid metering system** for affordable energy access
- **Local job creation** as community members are trained in microgrid maintenance
- **Social Benefits :** Better healthcare services, access to refrigeration for food preservation

A report by the **International Energy Agency (IEA, 2021)** states that decentralized microgrids in Africa could provide electricity to 500 million people by 2030 if investments continue [87]

The following section illustrates a practical example of a Large-Scale Industrial Microgrid Case Study (Fig. 2.4).

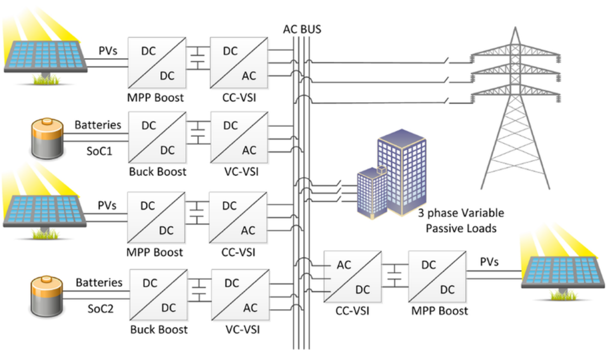

FIG. 2.4: Large-Scale Industrial Microgrid Case Study

Case Study 5: The Brooklyn Microgrid, USA

In developed countries, microgrids are being used to improve grid resilience and enable peer-to-peer energy trading. The **Brooklyn Microgrid Project** in New York is a **blockchain-enabled microgrid** allowing consumers to buy and sell locally produced solar energy.

Key Technologies Used :

- **Blockchain-based energy trading platform**
- **Grid-connected mode** for backup power from the main grid
- **Smart sensors** to monitor energy flow in real-time

This project represents the future of **decentralized energy markets**, showing how **blockchain** can empower consumers to participate in energy trading [88]

A case study detailing the implementation of a solar microgrid at Direct Relief's facility, highlighting its design and resilience benefits.(Fig. 2.5)

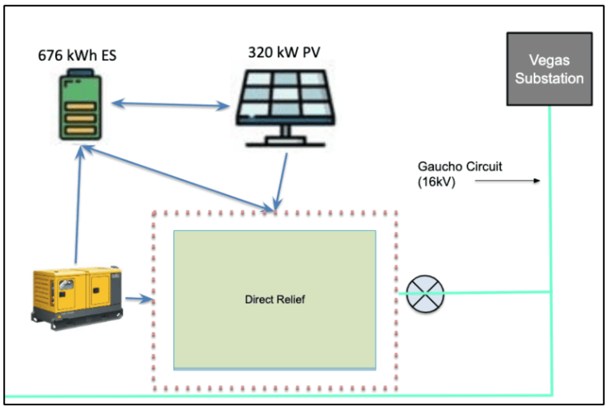

FIG. 2.5: Direct Relief Solar Microgrid Case Study
A case study detailing the implementation of a solar microgrid at Direct Relief's facility, highlighting its design and resilience benefits.

2.6 Challenges and Future Research Directions

2.6.1 Challenges of Microgrid Implementation

Despite their numerous advantages, microgrids face several technical, economic, regulatory, and social challenges that must be addressed to ensure widespread adoption and efficient operation.

Technical Challenges

- **Grid Stability and Power Quality**
  One of the primary technical challenges of microgrids is ensuring stability and maintaining power quality. Due to their reliance on distributed energy resources (DERs), including solar and wind, which are inherently intermittent, voltage and frequency fluctuations can occur. This can lead to issues such as power imbalances, voltage sags, and harmonic distortions, affecting sensitive loads [89]
- **Energy Storage and Management**
  Effective energy storage solutions are essential for mitigating renewable energy intermittency. However, battery technologies, such as lithium-ion and flow batteries, have limitations related to cost, lifespan, and efficiency. The integration of advanced energy management systems (EMS) is necessary to optimize charging and discharging cycles while preventing premature battery degradation [90]
- **Communication and Control Complexity**
  Modern microgrids require sophisticated communication protocols and real-time monitoring to balance loads, manage energy distribution, and interact with the main grid. However, ensuring seamless communication between multiple DERs, sensors, and control units remains a challenge due to cybersecurity risks, interoperability issues, and the need for low-latency response times [91]

Economic and Financial Barriers

- **High Initial Investment Costs**
  Deploying a microgrid, particularly in remote or off-grid locations, involves significant upfront costs, including the installation of renewable energy systems, energy storage, and smart grid technologies. While the long-term operational savings can be substantial, the initial capital investment remains a major deterrent for many stakeholders [92]
- **Return on Investment (ROI) Uncertainty**
  The economic viability of microgrids depends on multiple factors, such as energy tariffs, incentives, and demand-side management strategies. In areas where conventional grid electricity is still relatively cheap, justifying microgrid investment can be challenging without strong policy support [93]
- **Lack of Standardized Business Models**
  Microgrid projects often require unique financing structures, and the lack of standardized business models complicates investment decisions. Models such as community-owned microgrids, private-public partnerships, and third-party energy service providers are still evolving, making it difficult to scale projects efficiently [94]

Regulatory and Policy Constraints

- **Lack of Clear Regulatory Frameworks**
  Many countries lack comprehensive regulatory policies governing microgrid operation, grid interconnection,

and energy trading. This regulatory uncertainty discourages investment and slows the adoption of decentralized energy solutions [95]

- **Grid Interconnection and Tariff Structures**
  In many cases, microgrids must interact with traditional power grids. However, existing tariff structures often do not fairly compensate microgrid operators for supplying excess power to the grid, reducing financial incentives for implementation [96]
- **Cybersecurity Risks**
  The increasing digitization of microgrids makes them susceptible to cyberattacks, potentially leading to unauthorized control, power theft, or operational disruptions. Developing robust cybersecurity protocols and intrusion detection systems is crucial to ensuring secure operations [97]

2.6.2 Future Prospects of Microgrids

Despite these challenges, microgrid development is expected to accelerate due to technological advancements, supportive policies, and the global push toward sustainable energy solutions.

Technological Advancements Driving Microgrid Growth

- **Artificial Intelligence (AI) and Machine Learning (ML) for Energy Optimization**
  AI and ML are playing an increasing role in optimizing energy management, forecasting demand, and enhancing grid resilience. By leveraging real-time data, AI-driven microgrids can self-adjust generation and storage strategies to maximize efficiency [98]
- **Next-Generation Energy Storage Technologies**
  Research is advancing beyond lithium-ion batteries toward alternative storage solutions, such as solid-state batteries, hydrogen storage, and ultra-capacitors. These emerging technologies promise higher efficiency, longer lifespans, and lower environmental impact [99]
- **Blockchain for Decentralized Energy Trading**
  Blockchain technology has the potential to enable peer-to-peer (P2P) energy trading within microgrids, allowing consumers to buy and sell excess power without relying on centralized utilities. This enhances economic efficiency and promotes local energy autonomy[100]

Policy and Market Trends

- **Increased Government Support and Incentives**
  Many governments are introducing subsidies, tax credits, and policy frameworks to encourage microgrid deployment, particularly in rural and off-grid areas. These initiatives aim to enhance energy access while reducing dependence on fossil fuels [92]
- **Integration with Smart Cities and IoT**
  Microgrids are becoming integral to smart city initiatives, where they are used for demand-side management, electric vehicle (EV) charging, and resilience against grid failures. The Internet of Things (IoT) enables seamless connectivity between microgrid components, improving real-time decision-making [101]
- **Expansion of Hybrid Microgrids**
  Future microgrids will increasingly integrate multiple renewable energy sources, such as solar, wind, and biomass, alongside conventional backup generators. This hybrid approach enhances reliability and reduces dependence on a single energy source [90]

Chapitre 3

Business Model Canvas (BMC) Development for the Microgrid Management System

3.1 Introduction to Business Models

A business model represents the **logic and strategy an organization uses to create, deliver, and capture value** in economic, social, or environmental contexts. It outlines how resources are organized, value propositions are delivered to customers, and revenue is generated to sustain operations. Business models are critical for ensuring the sustainability and scalability of innovative projects, particularly in the energy sector where infrastructure costs and operational logistics can be complex.
In recent years, the **Business Model Canvas (BMC)** has emerged as a popular tool for structuring business models, offering a simple yet comprehensive framework that covers all essential operational and strategic elements. The BMC is especially valuable for projects like decentralized energy systems, where multiple stakeholders, variable cost structures, and dynamic customer relationships coexist [102]

This chapter aims to develop a well tailored and detailed business model for the proposed **microgrid management system for rural Algeria**, using the BMC methodology. The model will reflect the unique technical, social, and economic conditions of remote and rural Algerian regions while addressing energy access gaps and deficiencies and promoting environmental sustainability.

3.2 The Business Model Canvas Framework

The **Business Model Canvas (BMC)**, proposed by Alexander Osterwalder, is a visual framework designed to describe, analyze, and innovate business models through nine interconnected building blocks [102]
These are :

1. **Customer Segments** : The target beneficiaries or markets for the product or service. it's about figuring who are our costumers .
2. **Value Propositions** : The unique products or services providing value to customers. in general it's the aspects of the product that separates us from the competition if it exists (from the design , experience ,price , speed

of devilry and service) .

3. **Channels** : Communication and distribution channels to reach customers. generally how the value proposition is communicated and delivered to the costumers , how to increase the awareness of our brand and offerings , how to assist the clients to evaluate the value we bring , what routes can the costumer use to buy or obtain the products and services we provide , and the support offered after sale .
4. **Customer Relationships** : The type of relationships maintained with different customer segments. it's how our organization interacts with each of our costumer segments , this can variate from personal assistance or interaction to dedicated self service or automated experiences .
5. **Key Activities** : The critical tasks and operations required to deliver value. this could be producing a product that meets certain standards , or providing a service that solvs a problem for our clients .
6. **Revenue Streams** : Income sources sustaining the business financially. it's the exploration of the mechanisms used to derive fees from each of the costumer segments , it includes the transactional sales for physical assets or the usage of services , it can also be subscription fees , lease or rental or licensing .
7. **Key Resources** : Assets (human, physical, intellectual, and financial) enabling operations. basically they are the resources that are needed for the model to work and deliver the value proposition .
8. **Key Partners** : The network of suppliers and collaborators essential for project delivery. in summary they represent the entities that are going to be our partners in this project .
9. **Cost Structure** : The major costs incurred while operating the business. they are the costs associated with each of the other elements of the **BMC** .

Its simplicity, flexibility, and holistic view make it suitable for modern, decentralized, and renewable energy projects, especially in developing regions [103] The following section presents the Official Business Model Canvas (BMC) Template (Fig. 3.1), which provides a structured framework for analyzing and developing the key components of a business model.

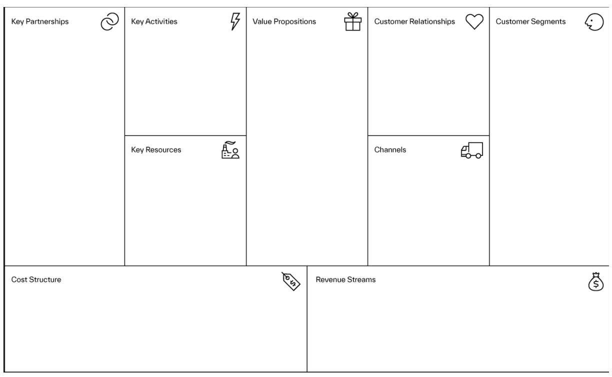

FIG. 3.1: Official BMC Template [102]

3.3 Application of the BMC to the Microgrid Management System

3.3.1 Key Partners

The success of this microgrid project depends on a collaborative network involving :

1. **GISB Electric** as a Social-Economic Partner
2. **Local government authorities** for permits and integration.
3. **Renewable energy suppliers** for solar, wind, and storage components.
4. **nternet providers** for EMS connectivity.
5. **Universities** for R & D and workforce training.
6. **Non-governmental organizations NGOs and humanitarian agencies** for rural development support.

Effective partnerships reduce risk, enhance capacity, and facilitate financing in infrastructure projects [104].

3.3.2 Key Activities

Key operational activities include :

1. EMS software development.
2. Renewable energy system integration.
3. Installation and commissioning of microgrids.
4. User training and local maintenance.
5. Technical support and system upgrades.

Focusing on **localized technical support and community involvement** ensures long-term system sustainability [105].

3.3.3 Key Resources

Essential resources consist of :

1. **Technical staff** (engineers, developers)
2. EMS web infrastructure (servers, IoT devices)
3. Renewable energy equipment (solar panels, wind turbines, batteries)
4. Local logistical resources (vehicles, tools)

Managing both digital and physical resources is critical for successful microgrid deployment in remote environments [106].

3.3.4 Value Propositions

The project offers :

1. Clean, reliable electricity for isolated areas.
2. A customizable, open-source EMS web platform.
3. Job creation and local workforce development.
4. CO_2 emission reduction by replacing diesel generators.
5. Real-time, web-based energy control for isolated communities.

Such localized, modular solutions address critical infrastructure deficits in developing regions [107].

3.3.5 Customer Relationships

Customer engagement is built through :

1. Community workshops.
2. Technical training and system handovers.
3. Feedback channels for EMS improvements.
4. Long-term local maintenance partnerships.

Building trust and participation is essential for acceptance and system longevity [108].

3.3.6 Channels

Service and information delivery channels include :

1. Direct government and NGO projects.
2. University pilot programs.
3. Web-based EMS interface.
4. Public awareness campaigns and local demonstrations.

Multi-channel engagement ensures effective technology transfer and adoption [109].

3.3.7 Customer Segments

Primary beneficiaries include :

1. Isolated rural communities.

2. Agricultural cooperatives.
3. Remote industrial sites.
4. Refugee camps and humanitarian settlements.
5. Universities and research centers.

Targeting multi-sector applications increases the model's resilience and scalability [110].

3.3.8 Cost Structure

Key expenses involve :

1. EMS software development and hosting.
2. Equipment purchase and logistics.
3. Salaries for engineers and support staff.
4. Internet and IoT infrastructure.
5. Community training and maintenance.

Cost management is critical in renewable projects for developing markets [111].

3.3.9 Revenue Streams

Revenue is projected from :

1. Turnkey microgrid project sales.
2. EMS software licenses.
3. Training services.
4. Maintenance contracts.
5. Academic partnerships and R & D grants.
6. Future carbon credit schemes.

Multiple income streams increase financial sustainability for decentralized energy models [112].

The following figure presents the Business Model Canvas (BMC) developed for our project. It provides a structured overview of the different strategic elements surrounding the deployment of our Energy Management System (FIG. 3.2)

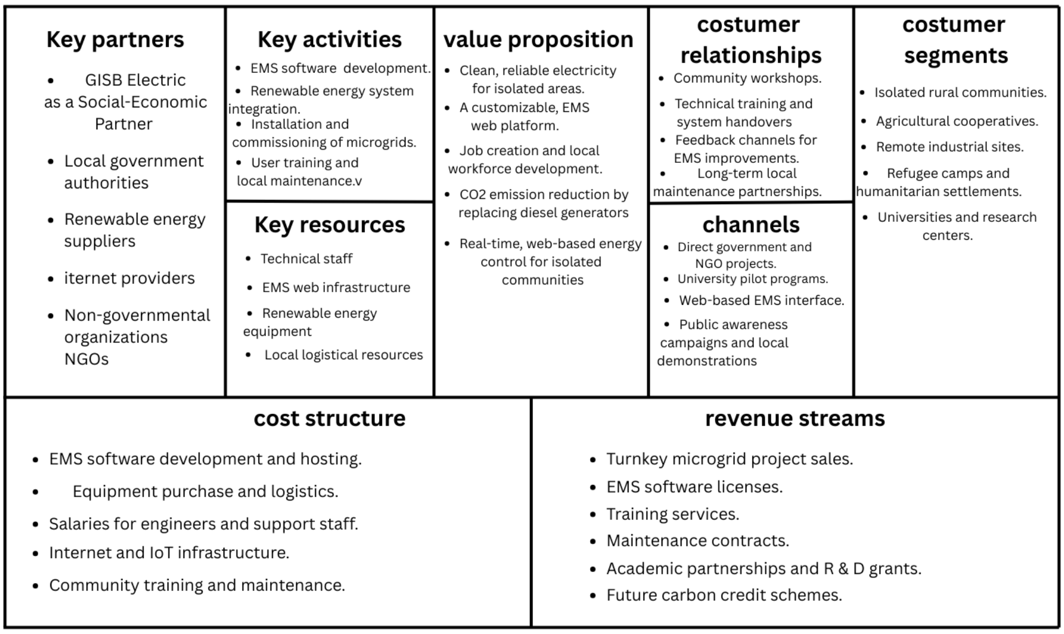

FIG. 3.2: Business Model Canvas for our EMS Microgrid Project

3.4 Innovation and Uniqueness of the Proposed Business Model

Unlike conventional microgrid projects using proprietary EMS solutions, our project features a **fully customizable, student-designed EMS web platform**. This empowers local operators to adapt parameters, manage energy dispatch, and prioritize loads based on real-time needs. Its low-cost, modular, and open-source approach allows for rapid scaling in rural and humanitarian contexts.

Our model's adaptability to both **agricultural cooperatives and industrial sites** in isolated regions offers a unique value proposition for Algeria's renewable energy ambitions.

3.5 Expected Economic, Social, and Environmental Impact

1. **Economic** : Boosts local productivity, supports small enterprises, and reduces diesel dependency.
2. **Social** : Improves quality of life, healthcare, and education services in isolated areas.
3. **Environmental** : Reduces CO_2 emissions and local air pollution.

Microgrids have been proven to contribute to rural development and poverty alleviation globally [113].

3.6 Conclusion

This chapter outlined the **Business Model Canvas** for the proposed microgrid management system, demonstrating how it addresses Algeria's rural electrification challenges. The model's emphasis on local partnerships, modular EMS design, and scalable revenue sources ensures both technical viability and socio-economic impact.

Chapitre 4

Tools and Technologies for the EMS Development

4.1 Introduction

The successful implementation of an Energy Management System (EMS) depends critically on the choice of software tools, programming frameworks, and deployment methodologies. These decisions affect maintainability, robustness, reproducibility, performance, and ease of collaboration. In this chapter, we elucidate the principal tools and technologies employed in our EMS architecture : Visual Studio Code (VS Code), Python, React, HTML, CSS, MySQL, and Docker. For each, we describe its role, the rationale for its selection, and its contributions to meeting system-level requirements.

4.2 Development Environment (VS Code)

Visual Studio Code **(VS Code)** was adopted as the principal development environment for all system components—backend, frontend, and deployment configuration. Its role includes editing, debugging, version control integration, and supporting auxiliary tasks (linting, formatting, environment management).

4.2.1 Why VS Code was chosen

1. **Multi-language support** : Since the EMS backend is written in Python and the frontend uses JavaScript/React plus markup (HTML) and style (CSS), VS Code's language server protocol, extension system, and integrated tooling supports all of these consistently.
2. **Extensibility** : Extensions for Python (linting, debugging), JavaScript/React, CSS/HTML, Dockerfile support, and Git are available. This enables enforcing code style, detecting errors early, and improving developer productivity.
3. **Cross-platform and workspace config** : The ability to version workspace settings, configure per-project tasks, and maintain consistent settings across team members reduces drift in development practices.
4. **Integrated debugging and terminal** : Developers can run backend servers, front-end builds, test suites, and Docker commands without switching to separate tools, which reduces context switching.

4.2.2 Contribution to EMS

VS Code served as the hub for :

1. Editing source code (backend modules in **Python**, frontend components in **React**, **HTML**, **CSS**).
2. Managing and viewing **Dockerfile**, **docker-compose**, environment variable files.
3. Debugging across layers (e.g. setting breakpoints in **Python** code, inspecting **API** responses).
4. **Version control with Git** : branching, merging, pull requests, conflict resolution.
5. Ensuring consistency via shared settings (formatters, linting rules) to maintain code quality.

4.3 Backend Technologies (Python)

4.3.1 Definition of Backend

The **backend** is the application's server-side component. In the EMS, it is responsible for data collection, business logic, computational tasks (e.g., forecasting, optimization, scheduling), exposing APIs for data retrieval or control, error handling, logging, security, and interfacing with the database.

4.3.2 Why Python was selected

1. **Rich scientific and numerical libraries** : Python has established packages such as NumPy, Pandas, SciPy, and optimization toolkits which are highly suited to energy data analytics and forecasting.
2. **Rapid prototyping and readability** : Python's syntax and dynamic typing allow swift implementation of complex logic with relatively fewer lines of code, aiding research-driven development.
3. **Web frameworks and REST support** : Frameworks like Flask or FastAPI enable building HTTP API endpoints to serve frontend needs.
4. **Strong community and long-term support**, meaning that security patches, library updates, and tools are available.

4.3.3 Role in the EMS

In our EMS, the Python backend implements :

1. **Data ingestion and processing** : obtaining raw measurement data from sensors or external systems, filtering, aggregating, resampling, etc.
2. **Business rules and control logic** : forecasting consumption/generation, optimizing schedules, enforcing constraints (e.g. limits, thresholds), computing derived metrics.
3. **API layer** : secure endpoints (RESTful) for client applications (frontend) to request data (historical or real-time), issue control commands, query status, etc
4. **Reliability concerns** : logging, error handling, retries, validation.

4.4 Frontend Technologies (React, HTML, CSS)

4.4.1 Definition of Frontend

The **frontend** or client-side component is the part of the system with which users directly interact, typically via a web browser. It displays dashboards, charts, forms ; presents real-time or historical data ; takes user input ; and issues commands or configuration changes to the backend.

4.4.2 Why React, HTML, and CSS were chosen

1. **React** : A JavaScript library for building interactive user interfaces using a component-based architecture. Virtual DOM, declarative UI, and state management make React suitable for complex, dynamic data visualizations.
2. **HTML** : Provides the semantic structure of each page/components ; ensures compatibility with browsers and accessibility.
3. **CSS** : Responsible for layout, styling, responsiveness, theming ; modern CSS techniques (Flexbox, Grid, responsive breakpoints) make the UI adaptive to different device screen sizes.

Additional considerations include performance optimizations for React : avoiding unnecessary re-rendering, lazy loading, splitting bundles, etc., to ensure that the UI remains responsive (see e.g. analyses in "Performance Optimization Techniques in React Applications" [114].

4.4.3 Role in the EMS

The frontend in our EMS is responsible for :

1. Visualizing energy usage, forecasts, control actions, alerts, and historical trends.
2. Interactive elements : filters, zoom on charts, tooltips, user configuration.
3. Form-based user input : settings, control actions, thresholds.
4. Error handling in UI : showing message if backend unresponsive, input invalid
5. Ensuring responsive design so that dashboards work on tablet/desktop.

4.5 Database Layer (MySQL)

The database layer provides persistent storage for measured data, configurations, user accounts, control commands, historical logs, and derived metrics. MySQL was chosen as the relational database management system.

1. ACID compliance (e.g. via InnoDB) ensures transactional integrity
2. Familiarity with MySQL in the team plus mature tooling (query optimizers, backup, replication) made it a low risk, stable choice.
3. Support in Python via official connectors and ORMs allows for safe and efficient interaction.

4.6 Containerization & Deployment (Docker) with CI/CD Pipelines

4.6.1 Role of containerization

Docker is used to package each component of the EMS—backend, frontend, database—as separate containers, encapsulating its dependencies, runtime environment, file structure, and configuration. Containerization reduces discrepancies between development, testing, and production environments, facilitates scalability, isolation, and ease of deployment.

4.6.2 Why Docker was chosen

1. **Environment parity** : Developers, testers, and production servers run the same container images, reducing "it works on my machine" errors.
2. **Modularity and isolation** : Each service (backend, frontend, database) is isolated, which helps in managing dependencies, resource allocation, and potential conflicts.
3. **Portability** : Docker images can be run on many types of infrastructure (local machines, servers, cloud VMs).
4. **Industry support and maturity** : Docker has become a standard in container orchestration and deployment workflows.

4.6.3 CI/CD Pipelines : Definition, Design, and Integration

To ensure frequent, reliable, and automated updates to the EMS, a **Continuous Integration / Continuous Deployment (CI/CD)** pipeline was incorporated into the deployment strategy.

Definitions

1. **Continuous Integration (CI)** : the practice of automatically building, testing, and integrating code changes into a shared repository several times a day, to detect integration issues early.
2. **Continuous Deployment (CD)** : the extension of CI which, upon successful integration and testing, automates the deployment of software to staging or production environments.

Rationale for CI/CD in EMS

1. Rapid assembly of changes : bug fixes, new features, or algorithmic improvements need to be integrated without manual steps
2. Minimizing human errors : automating builds and deployments reduces misconfigurations or missing steps.
3. Ensuring reliability : automated tests (unit, integration) guard against regressions.
4. Faster feedback loops for researchers and developers when system components are changed.

How CI/CD was implemented (or would be implemented) in our EMS

1. **Version control trigger** :Each commit to the main or feature branches triggers the CI pipeline (e.g. via Git hooks or a CI server such as Jenkins, GitLab CI, GitHub Actions).
2. **Build stage** :
   (a) Build the Docker images for backend and frontend using their respective Dockerfile.
   (b) Ensure caching of layers where possible to speed up builds.
   (c) Run static code analysis / linting (Python, JavaScript/React, CSS).
3. **Test stage** :
   (a) Execute unit tests on backend logic (forecasting, optimization, data processing).
   (b) Execute frontend tests (component rendering, state management, UI behavior).
   (c) Integration tests to confirm end-to-end behavior (e.g. API calls, database interactions).
4. **Artifact and image registry** :
   (a) On successful builds/tests, Docker images are tagged (with version or commit hash) and pushed to a container registry (e.g. Docker Hub, private registry).
   (b) This ensures reproducibility and enables rollbacks.
5. **Deployment (CD) stage** :
   (a) Deploy updated containers to staging environment for further evaluation.
   (b) On acceptance, promote the same images to production, ensuring that the image running in production is identical to what was tested.
6. **Monitoring, Rollback, and Notifications** :
   (a) Monitoring services ensure health checks (e.g. via /health endpoints).
   (b) Notifications to developers if build or deployment fails.
   (c) Rollback strategy if production deployment exhibits failures : revert to previous tagged image.

Supporting Research & Best Practice References

1. The importance of Docker in ensuring reproducibility in research and software engineering has been discussed in “Using Docker containers to improve reproducibility in software engineering research” which emphasizes capturing dependencies and configuration to reproduce experiments reliably.
2. Studies such as “Scaling Test Automation in CI/CD Pipelines Using Docker and Kubernetes” illustrate how containerization enables scalable automated testing in complex environments.
3. “Refactoring for Dockerfile Quality : A Dive into Developer Practices and Automation Potential” highlights techniques to reduce build times and image sizes, which become crucial in CI/CD pipelines where frequent builds are expected.

4.6.4 Docker / CI/CD Challenges & Mitigation

TAB. 4.1: Challenges and Mitigation Strategies in Docker/CI/CD Pipelines

Challenge	**Mitigation Strategy**
Long build and test times	Use build cache, optimize Dockerfile layers, parallelize tests, and employ incremental builds.
Dependency version drift	Pin dependency versions in `requirements.txt`, `package.json`, or base images ; maintain stable tagged images in registries.
Environment mismatches	Run identical container images across development, testing, and production ; rely on environment variables instead of hard-coded paths.
Rollback safety	Tag and version Docker images ; use blue/green or canary deployments ; maintain database and container backups.
Security concerns	Regularly scan images for vulnerabilities, adopt minimal base images, and run containers with the least privilege principle.

4.7 Integration of Tools

The EMS architecture integrates all tools as follows :

1. VS Code is used by developers to write backend code, frontend components, Dockerfiles, database schema migrations, and environment configurations.
2. The **backend** (Python) interacts with the database (MySQL), exposes APIs, runs logic, and is containerized for deployment.
3. The **frontend** (React + HTML + CSS) consumes backend APIs, renders data visually, handles user interaction, and is also containerized.
4. **MySQL** persists data ; backup, indexing, schema evolution are managed.
5. Docker brings containerization ; CI/CD pipelines trigger builds, tests, deployments automatically ; all components orchestrated via Docker (and possibly docker-compose or Kubernetes) for both development and production.

This integration ensures a coherent system : reproducible environments, reliable deployments, maintainable codebase, and fast iteration cycles.

4.8 Conclusion

This chapter has provided a detailed account of the technological stack used in building the EMS, including definitions of frontend and backend, explanation of tool choices, and how they were integrated—especially via Docker and CI/CD pipelines. The synergy among tools such as VS Code, Python, React/HTML/CSS, MySQL, and Docker leads to a system that is modular, testable, reproducible, and maintainable.

In future work, you might compare alternate backend languages (e.g. Node.js, Go), alternative databases (e.g. time-series databases), or more advanced orchestration (Kubernetes) and CI/CD practices (blue-green, canary deployments, feature flags). You may also expand benchmarking of build times, test coverage, deployment rollback behavior to further validate system reliability.

Chapitre 5

MyEMS System Architecture and Technical Implementation

5.1 Introduction

This chapter presents the technical architecture and implementation of the MyEMS Energy Management System used throughout this work. The aim is to provide a comprehensive overview of how the system performs data acquisition, standardization, storage, analytics, and visualization for different components of a microgrid.

MyEMS is an extensible and modular EMS platform supporting heterogenous energy sources, hybrid microgrid structures, and multi-granularity data analysis. The following sections provide a detailed explanation of its architecture, functional layers, data life cycle, user interface components, and database/API integration.

5.2 System Architecture Overview

5.2.1 End-to-End Data Processing Pipeline

Figure 5.1 presents the full data life cycle within MyEMS, from raw signal capture to information delivery. This architecture reflects standard EMS engineering principles, including multi-protocol acquisition, temporal aggregation, validation, and multi-level analytics.

The pipeline contains the following stages :

1. **Acquisition Layer :** Physical meters send raw measurements at fixed sampling intervals (1–60 seconds). Data formats include Modbus RTU/TCP registers, BACnet objects, MQTT telemetry, and HTTP JSON packets.
2. **Transport Layer :** Gateways buffer and forward data to the EMS server using secure IP-based transport. Temporal synchronization (NTP) ensures correct timestamp alignment.
3. **Data Preprocessing :**
   - removal of spikes and outliers using threshold-based filtering,
   - interpolation for short-term gaps,

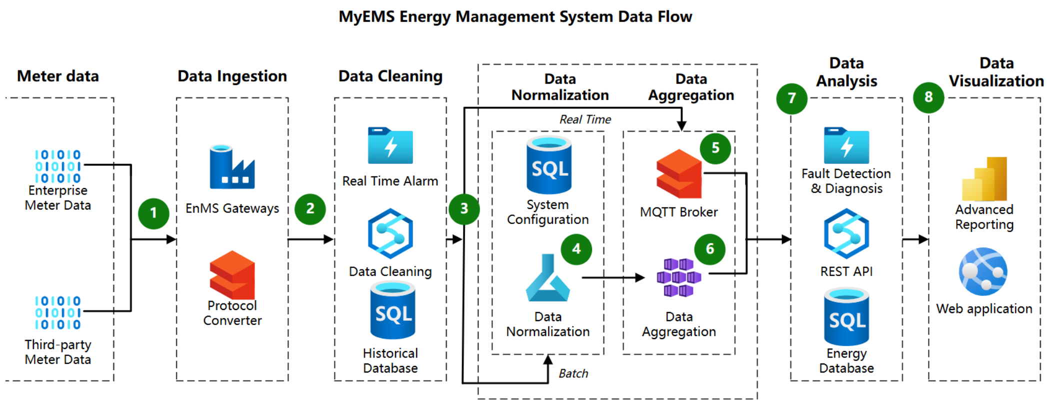

FIG. 5.1: End-to-end MyEMS data flow architecture, illustrating acquisition, transformation, storage, and visualization layers.

- duplicate elimination,
- consistency checks for counters vs. instantaneous values.

4. **Normalization :** All raw values are mapped to unified engineering units (kW, kWh, °C, m^3/h). This ensures comparability across meters and facilitates aggregation.
5. **Aggregation Engine :** Time-series are aggregated into 5-minute, hourly, daily, and monthly profiles using standardized window functions.
6. **Analytics Engine :** The system computes performance metrics such as :
   - load profiles,
   - peak demand,
   - cost allocation,
   - carbon emission factors,
   - equipment efficiency indices.
7. **Visualization Layer :** The processed data is exposed through dashboards, reports, and API endpoints.

5.2.2 Site Architecture and Microgrid Integration

The site-level architecture (Figure 5.2) describes how MyEMS interfaces with physical microgrid components. This includes distributed generation (PV, batteries), loads (irrigation, lighting), sensors, and controllers.

Key features include :

- **Integration with heterogeneous meters** across electricity, water, gas, and thermal systems.
- **Bidirectional communication** enabling potential demand response or equipment control.
- **Scalability** through modular addition of new sensors or subsystems.

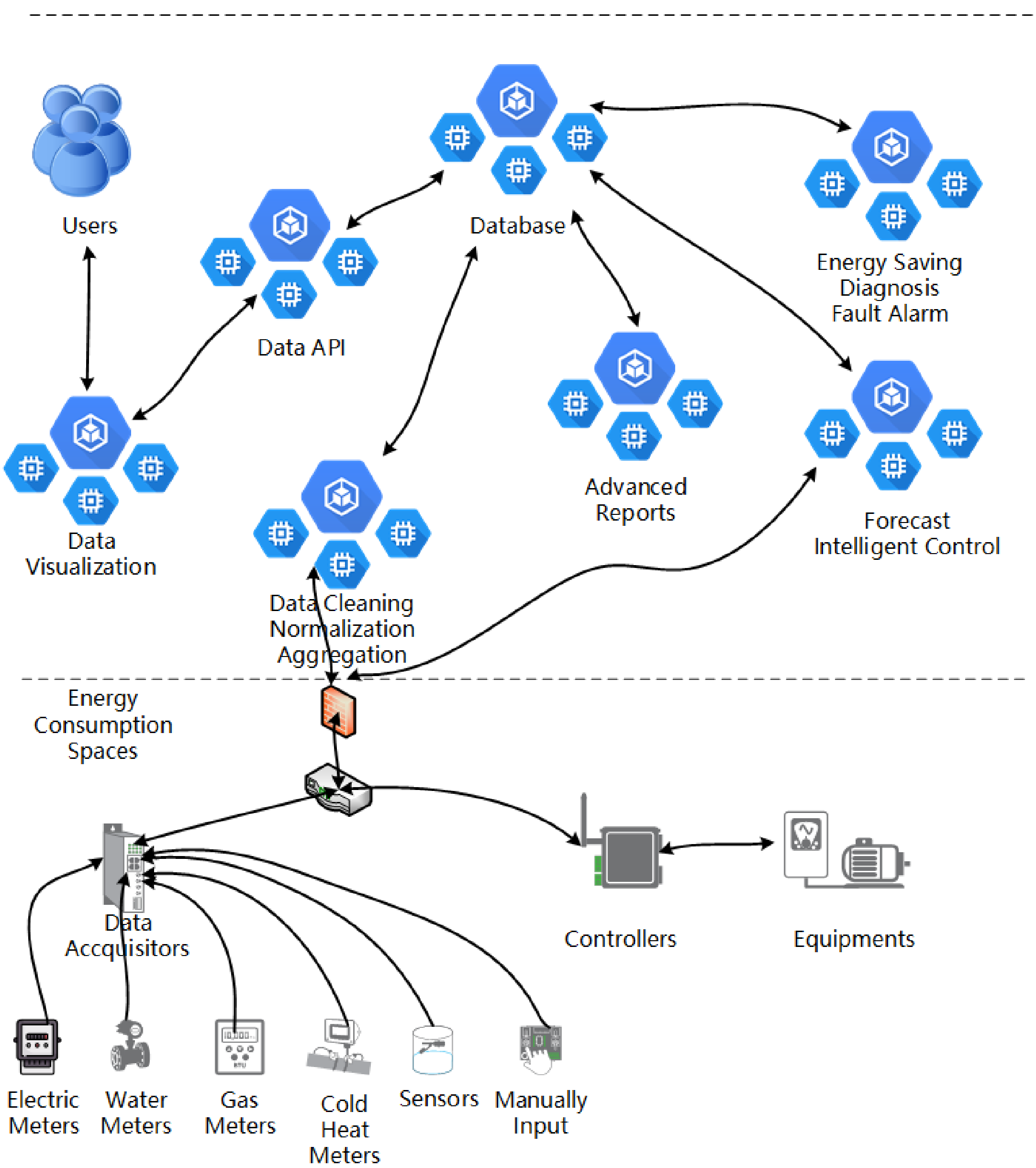

FIG. 5.2: Hierarchical site architecture showing the interaction between field devices and the EMS server.

5.2.3 Functional Layering

The functional architecture (Figure 5.3) follows a classical multi-layer EMS design, enabling separation of concerns and modular upgrades.

The system is composed of :

- **Security Layer :** Access control, user roles, HTTPS/TLS encryption.
- **Data Acquisition Layer :** Drivers for Modbus, BACnet, MQTT, OPC-UA, third-party APIs.
- **Computing Layer :** Data validation, normalization, temporal aggregation.
- **Analytics Layer :** KPI generation, fault detection, advanced reporting.
- **Interface Layer :** Web dashboards, mobile views, external data exports.

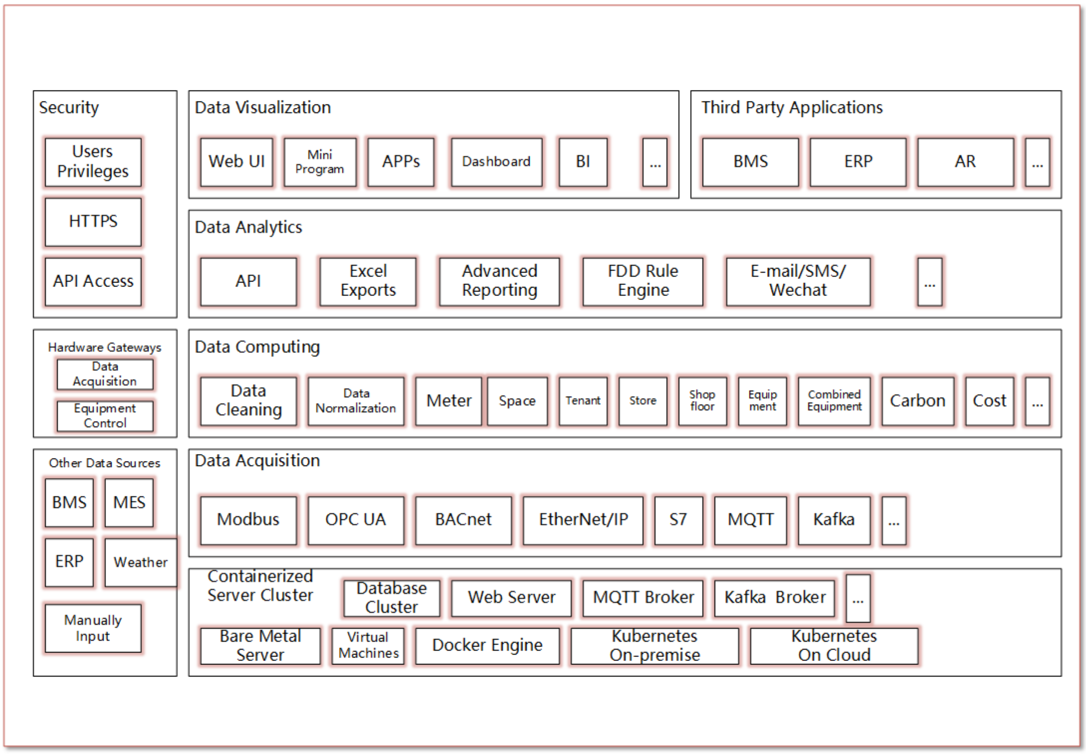

FIG. 5.3: Functional architecture of MyEMS, with explicit separation of acquisition, computation, analytics, and visualization layers.

- **Infrastructure Layer :** Databases, brokers, containerized servers.

5.3 Web User Interface Technical Overview

5.3.1 Navigation Architecture

The navigation structure shown in Figure 5.4 organizes the platform into modules representing functional concerns. This reflects user-centered design and clear domain separation.

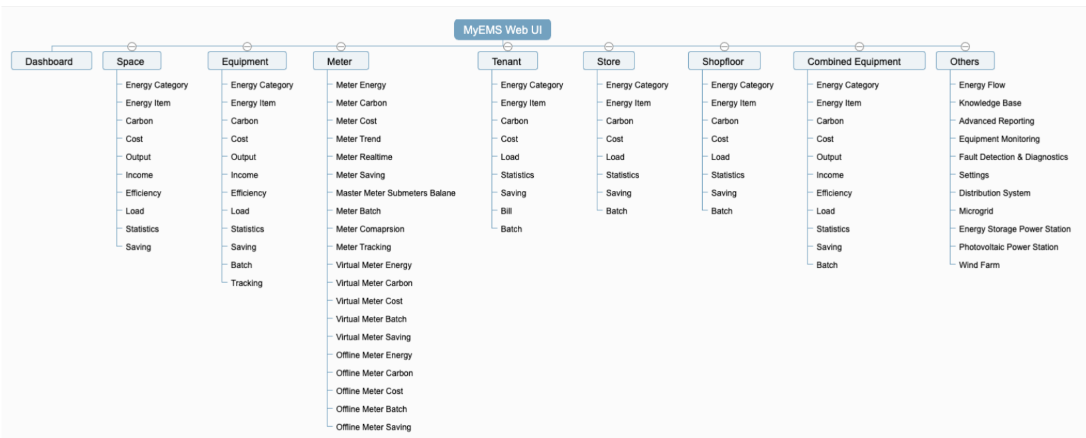

FIG. 5.4: Module-based navigation structure of the MyEMS system.

Modules include :

- high-level dashboards,
- physical-space modeling,
- meter and equipment management,
- tenant/store separation,
- microgrid-specific monitoring panels.

5.3.2 Authentication System

The authentication subsystem handles secure login, CAPTCHA verification, and role-based session management. Figures 5.5 and 5.6 illustrate its interfaces.

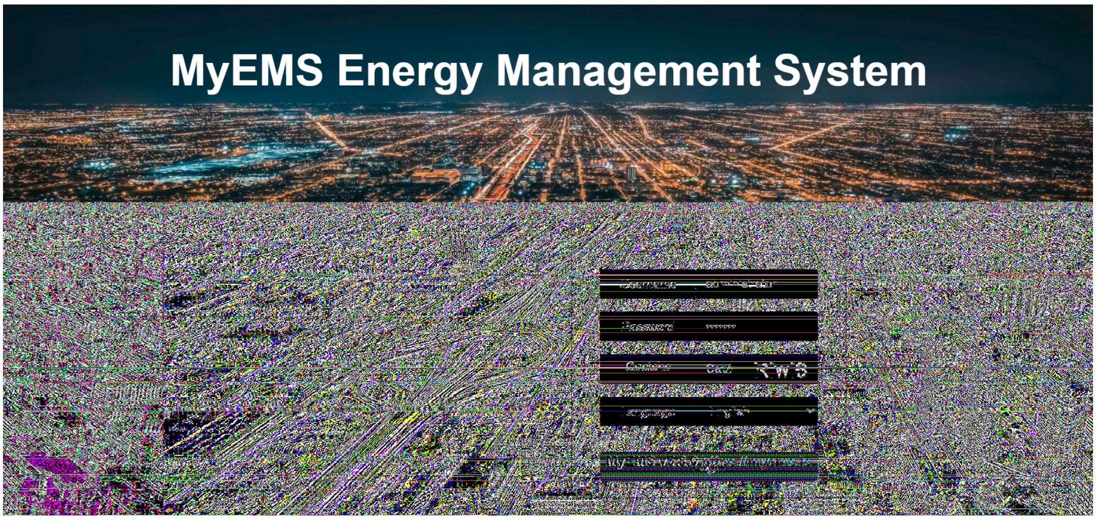

FIG. 5.5: Administrator login interface with role-restricted access.

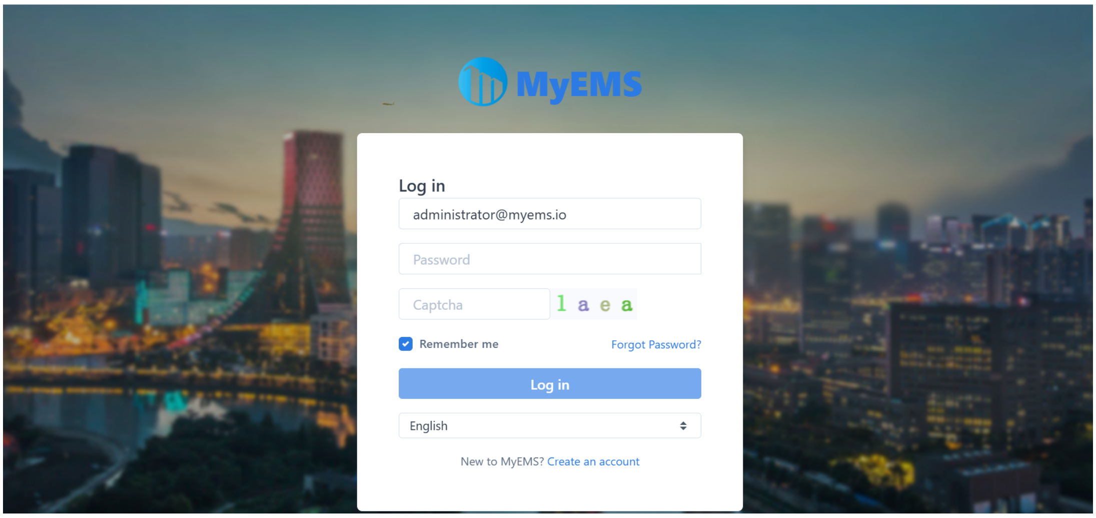

FIG. 5.6: General user login interface with CAPTCHA-based security.

5.3.3 Operational Dashboard

The main dashboard (Figure 5.7) integrates annual and monthly energy indicators, including standardized consumption (TCE), carbon emissions (TCO2E), and cost structures.

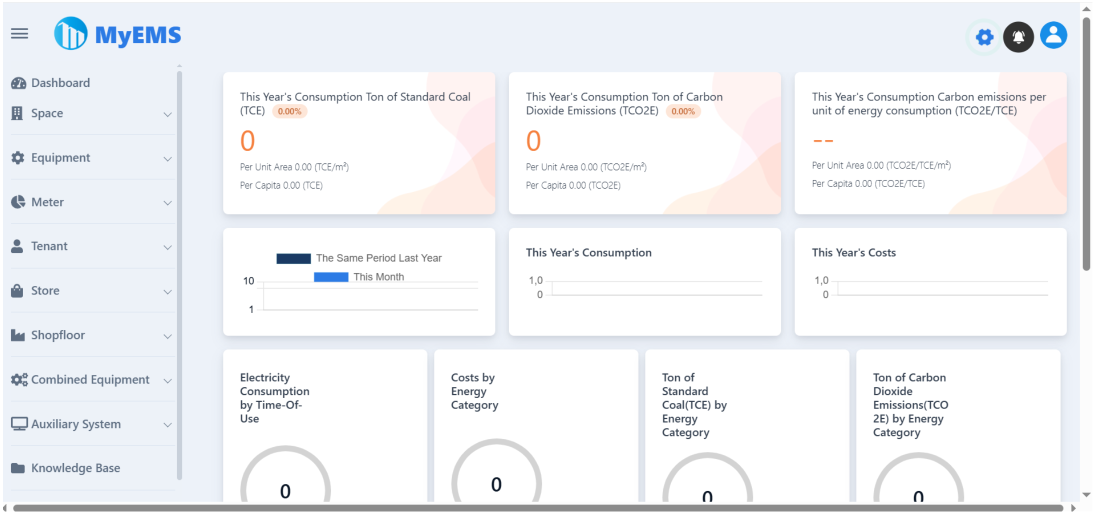

FIG. 5.7: Global operational dashboard showing aggregated energy, carbon, and cost indicators.

This dashboard supports :

- multi-timeframe comparisons,
- energy/cost breakdowns by category,
- early detection of abnormal consumption,
- KPI tracking over long periods.

5.4 Space Modeling and Management

5.4.1 Technical Role of Space Modeling

The Space module enables hierarchical modeling of the physical installation. Spaces function as containers for meters and equipment, enabling aggregated reporting at building, floor, zone, or subsystem level.

5.4.2 Space Energy Dashboard

Figure 5.8 provides the technical interface for energy analysis at space level. It supports comparison methods such as Month-on-Month (MoM), Year-on-Year (YoY), and baseline vs. reporting period analyses.

5.4.3 Hierarchical Structure

Figure 5.9 shows the hierarchical structure of spaces. This structure allows representing a microgrid with all its internal components.

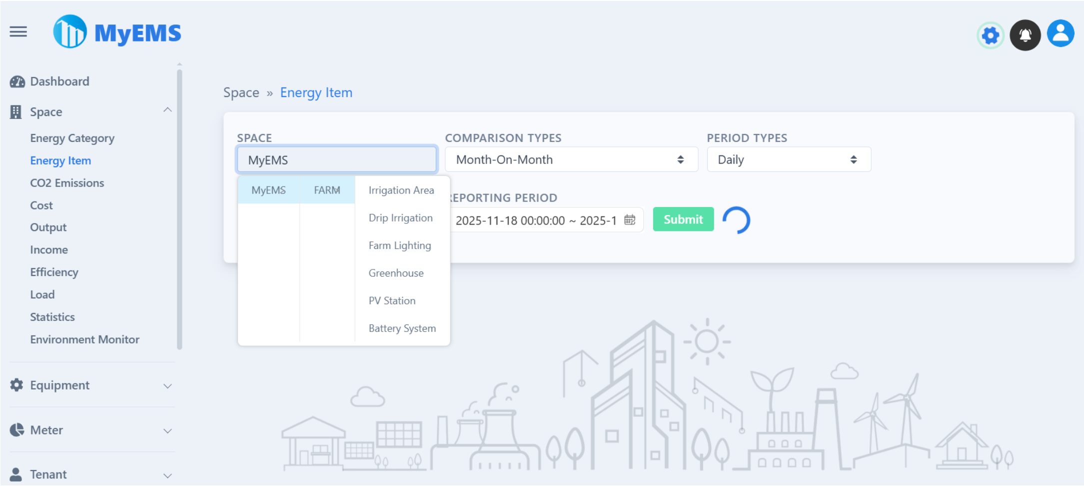

FIG. 5.8: Space-level energy dashboard enabling analytical comparison and time-series visualization.

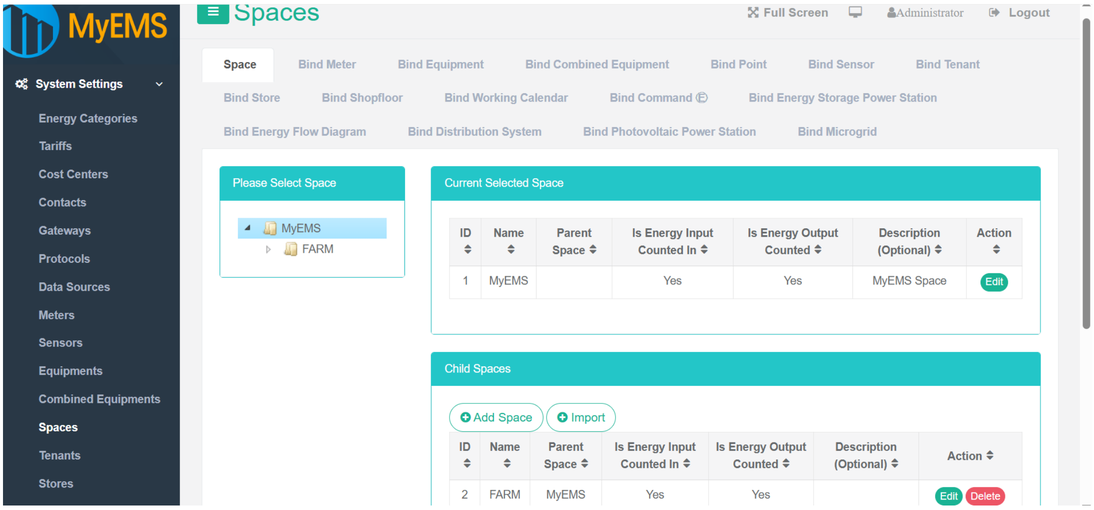

FIG. 5.9: Hierarchical representation of spaces and subspaces within the MyEMS system.

5.4.4 Child Spaces and Subsystems

Figure 5.10 lists the subsystems associated with the FARM microgrid, including :

- irrigation pumps,
- drip irrigation system,
- lighting networks,
- greenhouse loads,
- PV station,
- battery system.

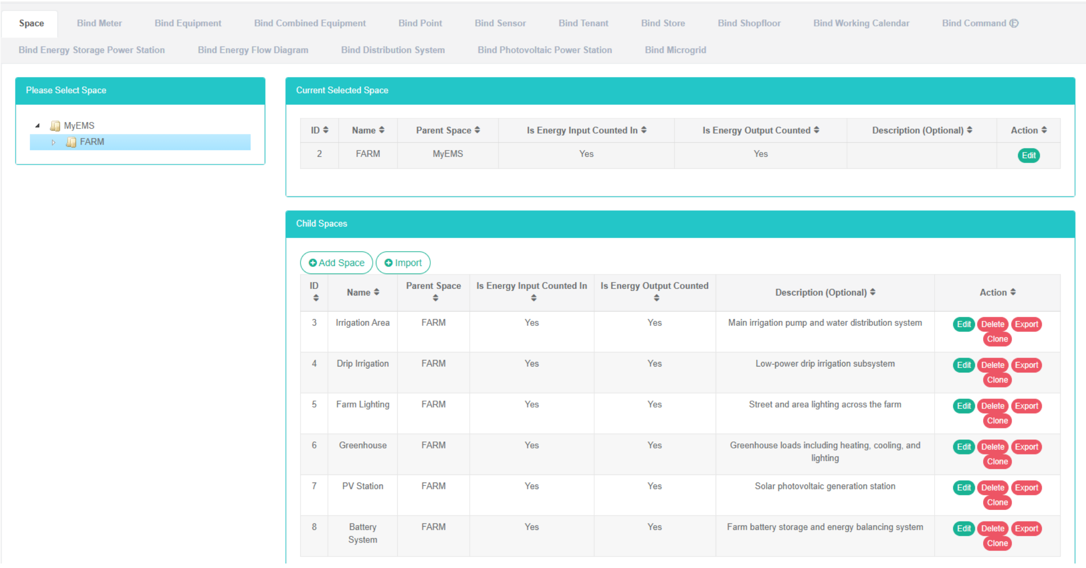

FIG. 5.10: Subsystem-level child spaces representing the FARM microgrid.

5.4.5 Space Configuration Interface

Figure 5.11 shows the configuration window where engineers can assign physical, environmental, and operational attributes to each space.

5.5 Meter Management and Data Integrity

5.5.1 Meter Dashboard and Time-Series Explorer

The technical dashboard in Figure 5.12 supports granular analysis of meter data. It includes :

- dynamic queries over arbitrary time windows,
- period comparison (MoM, YoY),
- multiple period types (hourly, daily, monthly),
- base period selection for error detection.

5.5.2 Meter Inventory

The meter inventory (Figure 5.13) lists all meters and their associated metadata, including energy category, cost center, and master meter relationships.

5.5.3 Meter Configuration

Figure 5.14 illustrates the configuration interface used to enforce data integrity and proper measurement scaling.

5.6 Equipment Performance Analysis

The Equipment module (Figure 5.15) centralizes equipment-level monitoring, enabling engineers to analyze operational efficiency, detect abnormal loads, and perform consumption diagnostics.

5.7 Database and API Infrastructure

5.7.1 Database Structure

The database extract shown in Figure 5.16 reveals the relational model used in MyEMS. Tables include configuration schemas (spaces, tariffs, meters) and time-series repositories.

5.7.2 REST API Layer

The API layer (Figure 5.17) exposes programmatic access to data and configuration parameters using REST conventions. It is used for :

- external system integration,
- mobile applications,
- advanced reporting tools,
- automation scripts.

5.8 Conclusion

This chapter presented a detailed technical overview of the MyEMS platform. Its multi-layered architecture, flexible data acquisition, advanced analytics, and modular user interface make it suitable for microgrid monitoring and industrial energy management. The platform provides the required foundation for future extensions such as forecasting, optimization, and automated control algorithms, which can serve as the basis for future research and system scaling.

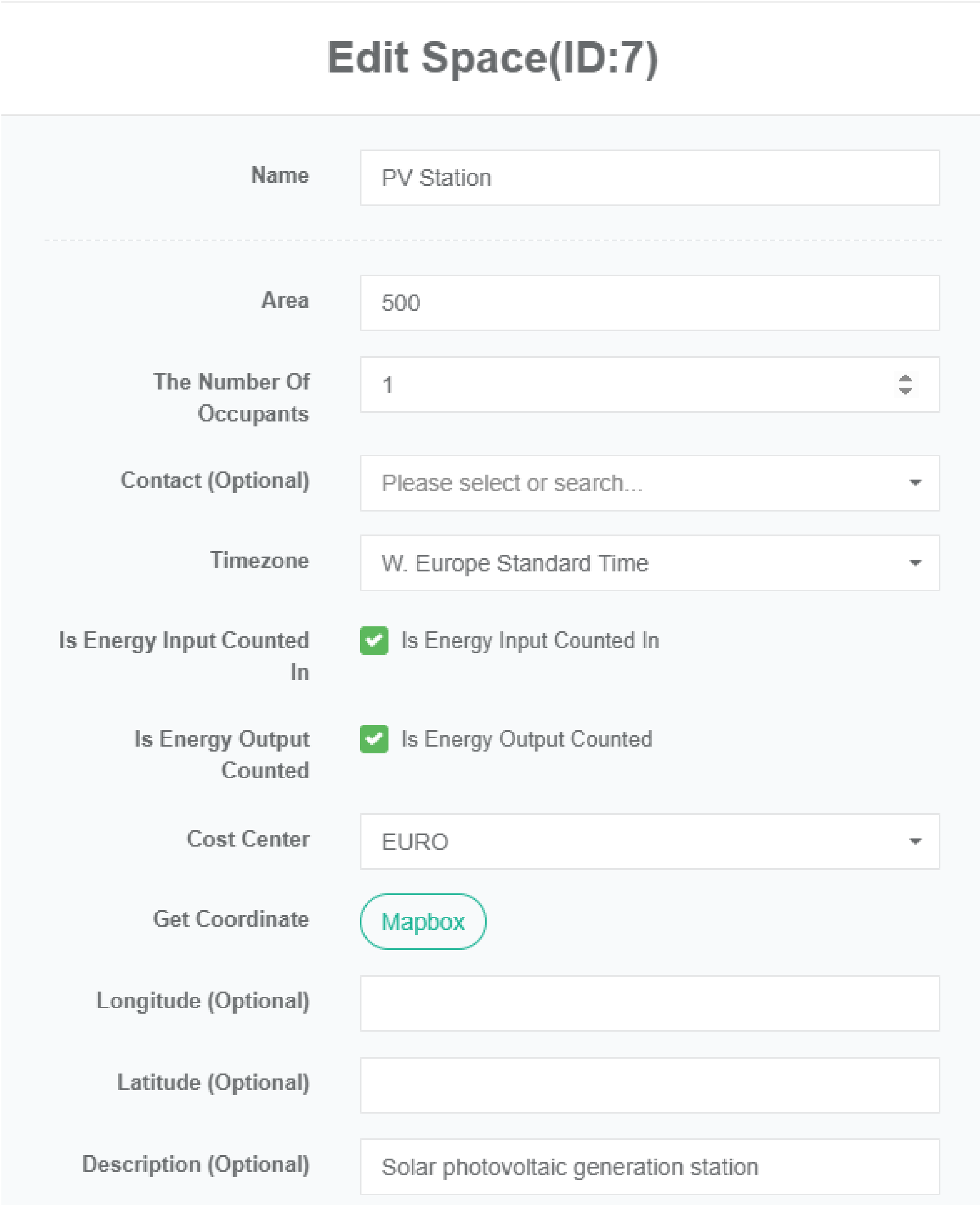

FIG. 5.11: Space configuration parameters including occupancy, area, timezone, and energy boundaries.

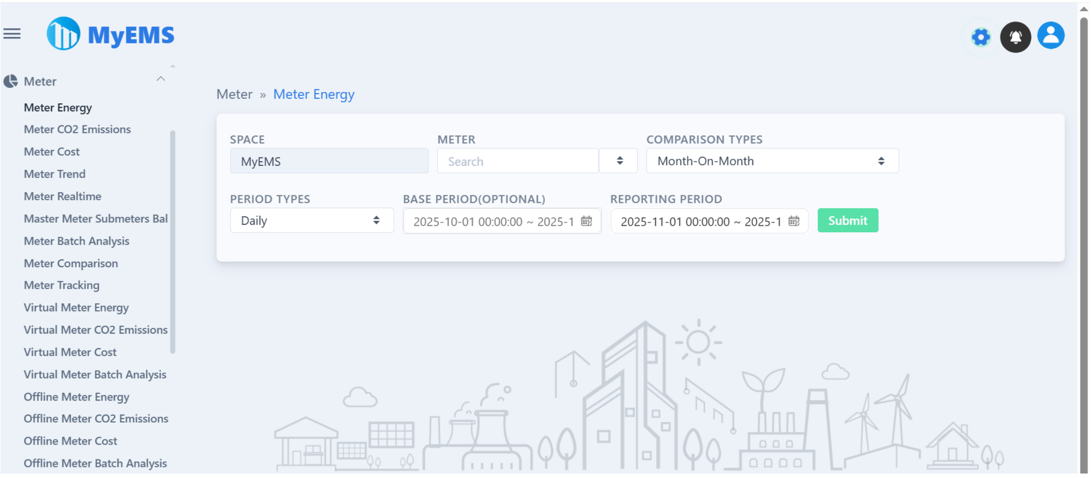

FIG. 5.12: Meter time-series dashboard for consumption pattern analysis.

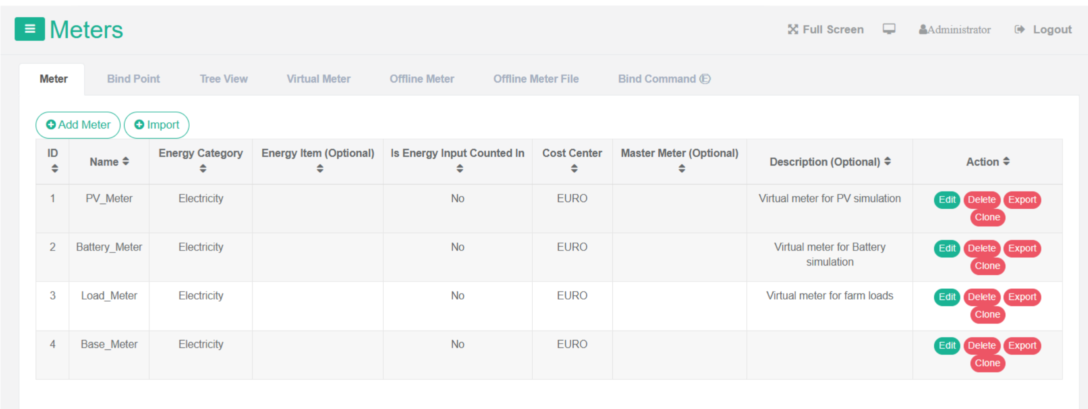

FIG. 5.13: Inventory of configured meters with metadata and hierarchical associations.

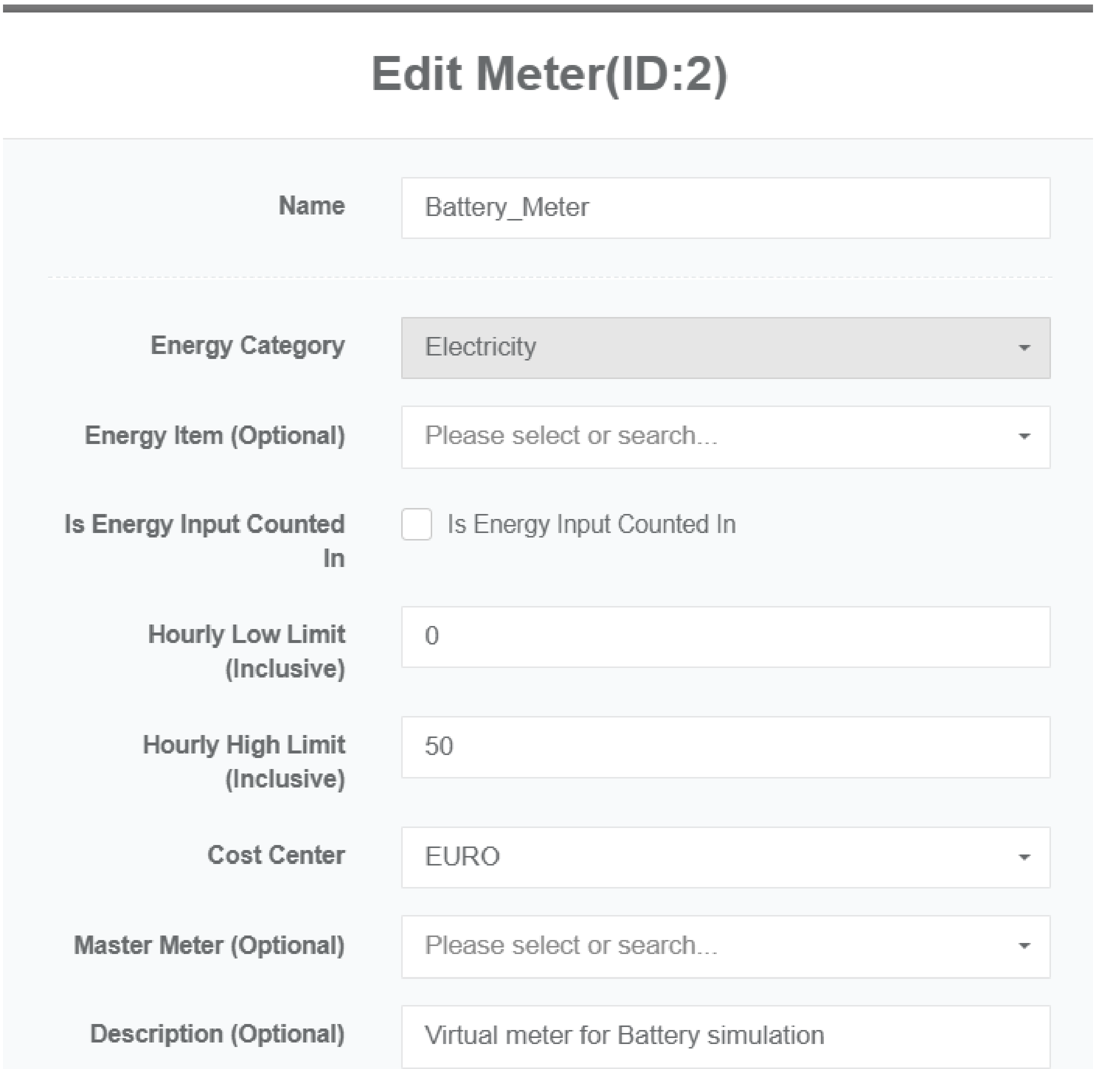

FIG. 5.14: Technical configuration form for meter attributes and operational thresholds.

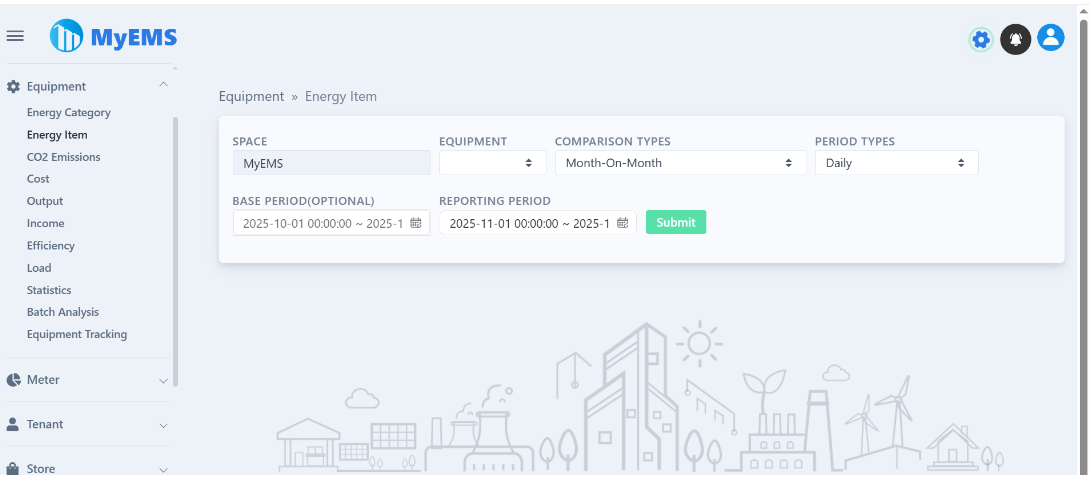

FIG. 5.15: Equipment performance dashboard for operational condition monitoring.

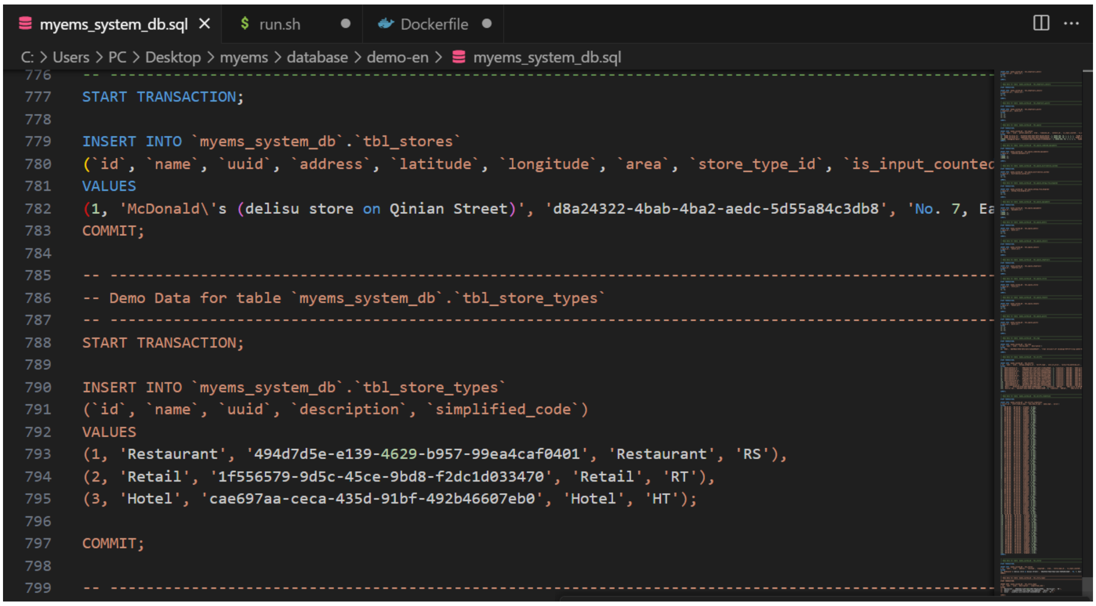

FIG. 5.16: SQL database structure used for configuration and time-series storage.

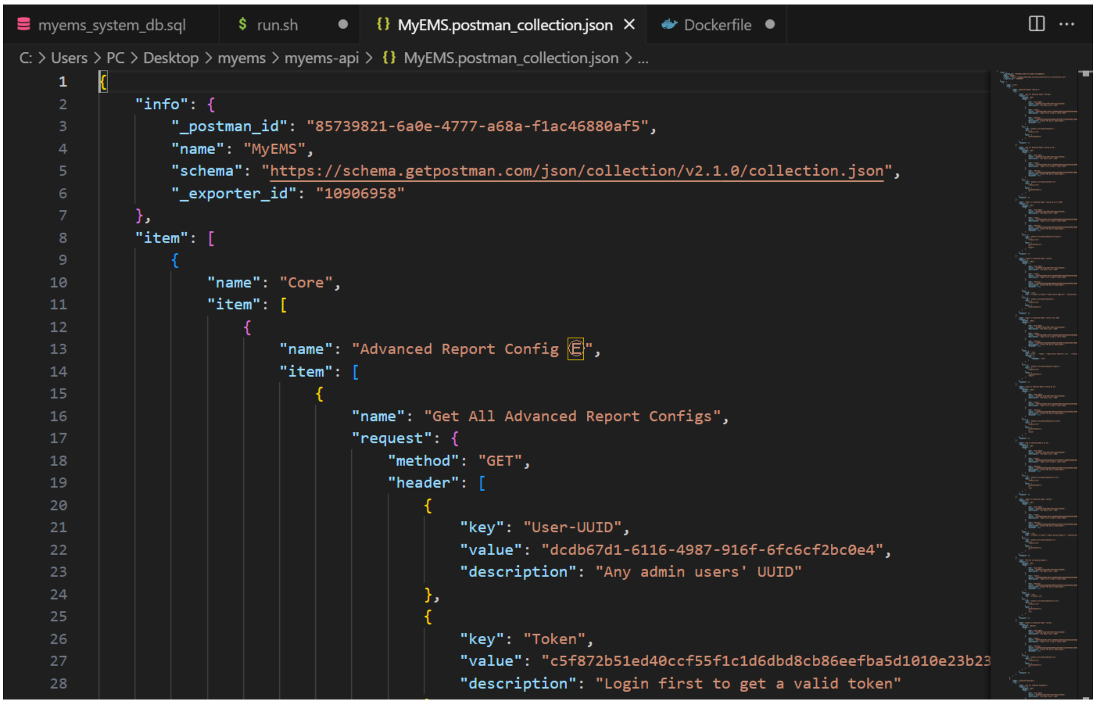

FIG. 5.17: Extract from the REST API collection used for testing, integration, and automation.

Chapitre 6

Scientific Contribution

6.1 Introduction

The objective of this project was to study, deploy, and adapt an Energy Management System to the context of microgrid monitoring and hybrid renewable energy systems, its practical use in microgrid research requires substantial engineering work, including data modeling, system configuration, integration of simulated measurements, and adaptation of the interface to a new use case.

This chapter presents the scientific and technical contributions achieved during this work. They focus on four key aspects :

- the construction of a coherent microgrid data model and hierarchy tailored to a real agricultural energy system ;
- the design of a virtual measurement environment enabling realistic data analysis in the absence of physical sensors ;
- the implementation and adaptation of the MyEMS platform for structured monitoring of a hybrid microgrid ;
- the methodological contribution of bridging EMS concepts with microgrid system engineering.

6.2 Contribution 1: Construction of a Structured Microgrid Data Model

A first contribution of this work is the development of a complete and hierarchical data model for a real-world microgrid scenario. Most EMS platforms require a carefully constructed structure to correctly interpret and aggregate energy data, yet such structures are rarely available for academic or pilot microgrids.

In this project, a detailed hierarchical model was created, consisting of :

- a top-level space representing the global site ;
- a “FARM” subsystem containing multiple operational zones ;
- subspaces representing agricultural processes (irrigation area, drip irrigation, greenhouse, farm lighting) ;
- energy production subsystems (PV station, battery storage) ;

- equipment and meters associated with each functional block.

This structure ensures correct inheritance of parameters (cost centers, energy boundaries, time zones) and provides a realistic testbed for microgrid analysis. The proposed model can be reused for similar agricultural or industrial microgrid applications.

6.3 Contribution 2: Development of a Virtual Measurement Environment

A second major contribution is the creation of a virtual measurement system enabling the EMS to operate without physical hardware. This was essential due to the lack of access to real sensors and meters during the study.

The virtual measurement framework designed in this work includes :

- simulated electrical profiles for solar PV generation, battery charging/discharging and agricultural loads ;
- realistic temporal patterns (daily cycles, seasonal variations) ;
- synthetic noise and fluctuations to emulate real measurement variability ;
- consistent relationships between meters, master meters and sub-meters.

6.4 Contribution 3: Technical Deployment and Adaptation of MyEMS

1. **Database configuration and restructuring** Definition of meters, equipment, tariffs, and energy items adapted to the microgrid use case.
2. **Creation of meter attributes and operational limits** Custom thresholds were set to detect abnormal behavior in virtual loads and batteries.
3. **Full configuration of the Space, Meter and Equipment modules** All entities were linked and validated to reflect real microgrid operation.
4. **Integration of simulated data into the EMS back-end** This required generating valid timestamped data compatible with MyEMS ingestion rules.
5. **Verification of dashboards and reporting tools** Ensuring that the EMS correctly displays consumption, comparisons, trends and statistics.

6.5 Contribution 4: Methodological Bridge Between EMS and Microgrid Engineering

One of the original aspects of this project is the methodological framework used to adapt an EMS to a microgrid environment. This includes :

- **interpreting MyEMS structures in terms of microgrid components** ;
- **mapping distributed energy resources to EMS entities** ;
- **linking EMS indicators (energy, cost, emissions) with microgrid KPIs** ;

- **translating microgrid behavior into EMS-compliant data features**.

This methodological bridge is significant because EMS solutions are traditionally designed for buildings or factories, whereas microgrids have additional constraints such as variability of renewable sources, energy storage behavior, and hybrid load dynamics. The contribution demonstrates how to adapt a general-purpose EMS to a microgrid setting without modifying the core software.

6.6 Contribution 5: Evaluation of EMS Capabilities for Microgrid Monitoring

The final contribution is an evaluation of MyEMS as a research tool for microgrid monitoring. The following capabilities were assessed :

- detection of abnormal consumption patterns,
- visualization of PV generation trends,
- separation of energy use by subsystem,
- estimation of CO_2 emissions using conversion factors,
- cost allocation by energy category or by space.

Limitations were also identified, such as :

- lack of built-in optimization algorithms,
- no native support for real-time power flow control,
- limited modeling of battery/renewable operational constraints.

These limitations open avenues for future research.

6.7 Summary of Scientific Contributions

The scientific and technical contributions of this project can be summarized as follows :

- A complete, hierarchical microgrid data model tailored for EMS integration.
- A virtual meter environment capable of generating realistic synthetic measurements.
- Successful deployment and adaptation of MyEMS for microgrid applications.
- A methodological framework connecting EMS concepts with microgrid engineering.
- A functional evaluation of EMS monitoring capabilities in a hybrid microgrid setting.

These contributions provide a solid foundation for future work in microgrid monitoring, optimization, and intelligent energy management.

General Conclusion

The main objective of this thesis was to design and develop an Energy Management System (EMS) dedicated to a hybrid microgrid integrating renewable energy sources. The work carried out throughout this study required the integration of several disciplines, including energy engineering, distributed resource management, computer science, and modern digital tools.

After defining the Supply Chain Management (SCM) framework, we were particularly interested in applying its principles to the supply chain of electrical energy production. Electricity, although intangible, follows a complete supply chain : generation, storage, distribution, and consumption. Applying SCM concepts to this flow allows us to analyze and optimize the movement of energy in the same way traditional supply chains optimize goods. This perspective was central to our work, because **our problem directly involves microgrids, especially in terms of controlling, monitoring, and ensuring efficient coordination between different components of the energy chain.**

To strengthen the strategic foundation of our work, we **developed a comprehensive Business Model Canvas (BMC)** for the proposed solution. This BMC included all mandatory elements required for structuring an innovative project and preparing it for obtaining a **LABEL** or accreditation. The elements we identified and analyzed in detail are :

- Key Partners : GISB Electric as a Social-Economic Partner, governmental institutions, local authorities, NGOs, technology providers
- Key Activities : energy monitoring, data processing, analytics, system deployment
- Key Resources : MyEMS platform, data models, renewable energy infrastructure
- Value Proposition : reliable, clean, low-cost, and transparent energy management services
- Customer Segments : rural communities, agricultural cooperatives, industrial remote sites
- Channels : on-site deployment, digital dashboards, user training
- Customer Relationship : technical support, training programs, long-term partnership
- Cost Structure : hardware acquisition, system integration, maintenance
- Revenue Streams : service deployment, maintenance contracts, technical support

Through this canvas, we validated the feasibility and innovation potential of our project and ensured that all essential aspects—technical, economic, and operational—were coherently integrated in preparation for obtaining the project LABEL.

Following this strategic framing, our technical work focused on designing a complete microgrid data model, creating a virtual measurement environment, and deploying MyEMS to simulate and manage a hybrid microgrid by the creation of a full functional data-base that linked all the elements of the microgrid. The EMS proved capable of cleaning, processing, aggregating, and visualizing energy data, producing key indicators such as energy consumption, CO_2 emissions, and operating costs. These results demonstrate the central role of EMS platforms in improving the efficiency, stability, and transparency of decentralized energy systems. Beyond the technical achievements, the project also generated significant social and economic value. A reliable EMS improves access to electricity in remote communities, supports agricultural productivity, reduces dependence on diesel, and promotes the development of local technical skills. Thus, the work contributes not only to engineering progress, but also to sustainable development in Southern Algeria.

However, the study has limitations, such as the absence of real sensor data and the lack of automated control features. These limitations open promising avenues for future research, including the integration of AI-based forecasting, real-time control strategies, enhanced cybersecurity, and the deployment of a pilot microgrid in a real environment.

In conclusion, this work represents a meaningful step toward the development of intelligent microgrids tailored to the Algerian context. By combining energy engineering, digital technologies, and socio-economic considerations, we propose a solution that is both technically solid and socially impactful. We hope this work will support future initiatives aiming to build resilient, sustainable, and autonomous energy systems across Algeria.

Perspectives

At the end of this thesis, several directions for improvement and further development can be considered to enrich and extend the proposed system :

- **Integration of artificial intelligence :** develop predictive models to forecast solar or wind production, anticipate energy demand, detect anomalies, and automatically optimize microgrid decision-making.
- **Full microgrid automation :** transition from a monitoring-oriented system to a fully automated control system capable of managing storage, load distribution, source switching, and energy priorities in real time.
- **Deployment of hydrogen storage :** integrate an electrolysis and reconversion model to study the efficiency of seasonal storage and compare its performance with traditional batteries.
- **Multi-microgrid coordination :** extend the system to enable communication and energy exchange between several microgrids, integrating mechanisms for collective optimization and resource sharing.
- **Development of a mobile application :** offer real-time alerts, simplified visualizations, and remote control options for users.
- **Enhancement of the web interface :** add more detailed dashboards, customizable graphs, and advanced energy-flow visualizations to improve analysis capabilities.
- **Integration of a digital twin :** enable real-time simulation of different operational scenarios to test microgrid stability before applying control actions in practice.
- **Reinforcement of cybersecurity :** integrate secure authentication, data encryption, and intrusion detection systems to protect the network from cyber threats.
- **Expansion of the data collection system :** add more environmental sensors (temperature, irradiance, humidity), integrate IoT modules, and enrich the historical database.
- **Real deployment in a microgrid :** test the system in an industrial or academic environment to validate its performance, analyze results, and adapt functionalities to real operational needs.

These perspectives open the door to numerous future developments and demonstrate the strong potential of microgrids when combined with advanced digital solutions. The system designed in this thesis represents a solid first step toward smarter, more autonomous, and more resilient energy networks capable of meeting tomorrow's challenges.

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