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EDGE/CLOUD VIRTUALIZATION TECHNIQUES AND RESOURCE ALLOCATION ALGORITHMS FOR IOT-BASED SMART ENERGY APPLICATIONS

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Abstract

Nowadays, the installation of residential battery energy storages (BES) has increased as a consequence of the decrease in the cost of batteries. The coupling of small-scale energy generation (residential PV) and residential BES promotes the integration of microgrids (MG), i.e., clusters of local energy sources, energy storages, and customers which are represented as a single controllable entity. The operations between multiple grid-connected MGs and the distribution network can be coordinated by controlling the power exchange; however, in order to achieve this level of coordination, a control and communication MG interface should be developed as an add-on DMS (Distribution Management System) functionality to integrate the MG energy scheduling with the network optimal power flow.

This thesis proposes an edge-cloud architecture that is able to integrate the microgrid energy scheduling method with the grid constrained power flow, as well as providing tools for controlling and monitoring edge devices. As a specific case study, we consider the problem of determining the energy scheduling (amount extracted/stored from/in batteries) for each prosumer in a microgrid with a certain global objective (e.g. to make as few energy exchanges as possible with the main grid).

The results show that, in order to have a better optimization of the BES scheduling, it is necessary to evaluate the composition of a microgrid in such a way as to have balanced deficits and surpluses, which can be performed with Machine Learning (ML) techniques based on past production and consumption data for each prosumer.

Keywords

Battery Energy Storage, Edge-cloud computing, Energy management system, Energy scheduling, Energy sources, Energy trading, Internet of Things, Message broker, Photovoltaic, Renewable Energy Source, Smart energy, Smart grid, Time series.

Sommario

Oggigiorno, in seguito alla diminuzione del costo delle batterie, l'installazione di accumulatori di energia (BES) residenziali è aumentata. La combinazione tra produzione di energia su piccola scala (PV residenziale) e BES residenziali promuove lo sviluppo delle microgrids, cioè cluster di fonti locali, accumulatori e consumatori di energia rappresentati come una singola entità controllabile. Le operazioni tra più MG connesse alla rete e la rete di distribuzione principale possono essere coordinate controllando lo scambio di energia, ma per raggiungere questo livello di coordinamento, dovrebbe essere sviluppata un'interfaccia MG di controllo e comunicazione come funzionalità DMS (Distribution Management System) aggiuntiva per integrare la programmazione energetica della microgrid con il flusso ottimale della rete.

Questa tesi propone un'architettura edge-cloud che è in grado di integrare il metodo di pianificazione energetica della microgrid con il flusso di potenza vincolato della rete, oltre a fornire strumenti per il controllo e il monitoraggio dei dispositivi periferici.
Come caso di studio specifico, consideriamo il problema di determinare lo scheduling dell'energia (quantità estratta/stoccata da/in batterie) per ogni prosumer in una microgrid con un certo obiettivo globale (ad esempio fare meno scambi di energia possibile con la rete principale).

I risultati mostrano che è necessario valutare la composizione di una microgrid in modo da avere deficit e surplus bilanciati per avere un'efficiente ottimizzazione dello scheduling energetico, il che può essere fatto basandosi su tecniche di ML basate su dati di produzione e consumo passati per ogni prosumer.

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Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BAU Business As Usual

BES Battery Energy Storage

DER Distributed Energy Resource

DMS Distribution Management System

DN Distribution Network

DNO Distribution Network Operator

DSO Distribution System Operator

EMS Energy Management System

IoT Internet of Things

MFBP Multi Follower Bi-level Programming

MG Microgrid

MG-EMS Microgrid Energy Management System

MGA Microgrid Aggregator

MGCC Microgrid Central Controller

MGMS Microgrid Management System

MMG multi-MG

PCC Point of Common Coupling

PV Photo-voltaic

RES Renewable-based Energy Sources

RPC Remote Procedure Call

SoE State of Energy

SoS System of Systems

TB ThingsBoard

TSDB Time-series Database

TSO Transmission System Operator

VMG Virtual Microgrid

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Chapter 1

Introduction

In Europe, in the past 100 years, geopolitical strength has depended on access to fossil fuel resources. Nowadays, with the support schemes for renewable energy, the energy system is taking a new course towards greater democratization and decentralization: renewable capacity in the EU has increased by 71 percent between 2005 and 2015, contributing to sustainable development and more local jobs [1].

The spread of renewable energy means a switch from a few large power plants to many smaller sources and digitalization is the answer for integrating millions of solar panel and wind turbines into a reliable system that balances out supply and demand in real time (as the capacity of power lines is a scarce resource) [11].

Despite progress with renewables, the European Union is still energy dependent from other countries. A solution lies in improving energy efficiency and developing renewables so as to reduce dependency on imports, for example with a distributed energy system: electricity produced by a large number of small generators (solar roofs, wind turbines, etc.), opposed to a centralized power supply based on large power stations (nuclear and fossil-fuel plants, utility-scale photovoltaic power plants and large wind farms).

In the energy system, the growing phenomenon of decentralized community energy has led to ordinary citizens becoming prosumers: they both produce and consume electricity, especially solar. Prosumers may generate large

amounts of renewable energy, and in doing so may disrupt the centralized energy system [12].

1.1 Thesis Objective

The objective of this thesis is to illustrate an IoT architecture for the monitoring, managing and exchanging energy resources in microgrids.
In addition to this, the theoretical basis for understanding how this mechanism works are provided and the current level of digitalization in the energy sector is illustrated.
Finally, by comparing the different exchange optimisation strategies developed, the characteristics identified as crucial for successful optimisation are shown.

1.2 Project Goals

The goal of the thesis project is to develop an edge-cloud architecture capable of optimising the exchange of energy resources between the various prosumers that make up a microgrid, making the latter "smart". Prosumers are users who produce the energy they use, store it and exchange it with the local and central grid, thus reducing the cost of buying it and the pollution involved in transporting and storing it.

1.3 Ethics and Sustainability

With reference to economic sustainability, this project aims at a more sustainable energy exchange between prosumers (consumers who also produce energy, e.g. with photovoltaic panel installations) within a smart energy grid, thanks to so-called microgrids.
The objective of smart energy grids is a more efficient exchange of energy between different consumers using renewable energy production within the microgrid, so that they do not need as much energy from the main grid

(which only produces parts of it with renewable resources).
In regard to the scope of this thesis, there are no ethical concerns.

1.4 Outline

This thesis is structured as follows. The first Chapter describes the current situation in Europe regarding the transition to renewable energy sources and the "smart" energy evolution; the concepts underlying this thesis project such as smart grids, microgrids and IoT, as the leading technology in this field, are then presented.
In Chapter 3, a technology-independent system architecture is illustrated, which is therefore more generic and focuses only on the objective of the architecture; the data sources and their refinement are then presented, and the solutions designed for energy scheduling problems are illustrated in theoretical terms. Chapter 4 explains how each component of the actually implemented architecture works, also mentioning the technologies used, and how data is processed at each step.
In Chapter 6 we assess the actual performance of the finished product, evaluating and comparing in different scenarios the effectiveness of algorithms for optimising energy exchanges between citizens and/or commercial activities. Chapter 7 draws conclusions and discusses some ideas for possible future developments.

Chapter 2

State of the art

This chapter aims at providing foundations for understanding, albeit in a rather general way, the themes underlying this work, i.e. from Smart Energy to IoT; subsequently some solutions on the market, similar to some components of the conceived system, are analyzed, and finally we review the literature which has been used as a starting point for the interaction models between the agents involved in the smart grid.

2.1 Background

2.1.1 The Europe's energetic transition

In the past, Europe was supplied largely by a small number of big energy companies, but its future lies increasingly in the hands of cities and municipalities, and millions of ordinary citizens across Europe.
The energy transition is already well underway, but it is happening at different speeds across the continent (as shown in Fig. 2.1).

Competition from North America and the Far East is pushing Europe to invest further in research and innovation, and to establish conditions where green technologies can flourish: flagship projects are emerging with EU financial support, such as offshore wind-farms in the North Sea and Baltic Sea, the conversion of district heating from fossil fuels to renewable energy, and European corridors for electric mobility.

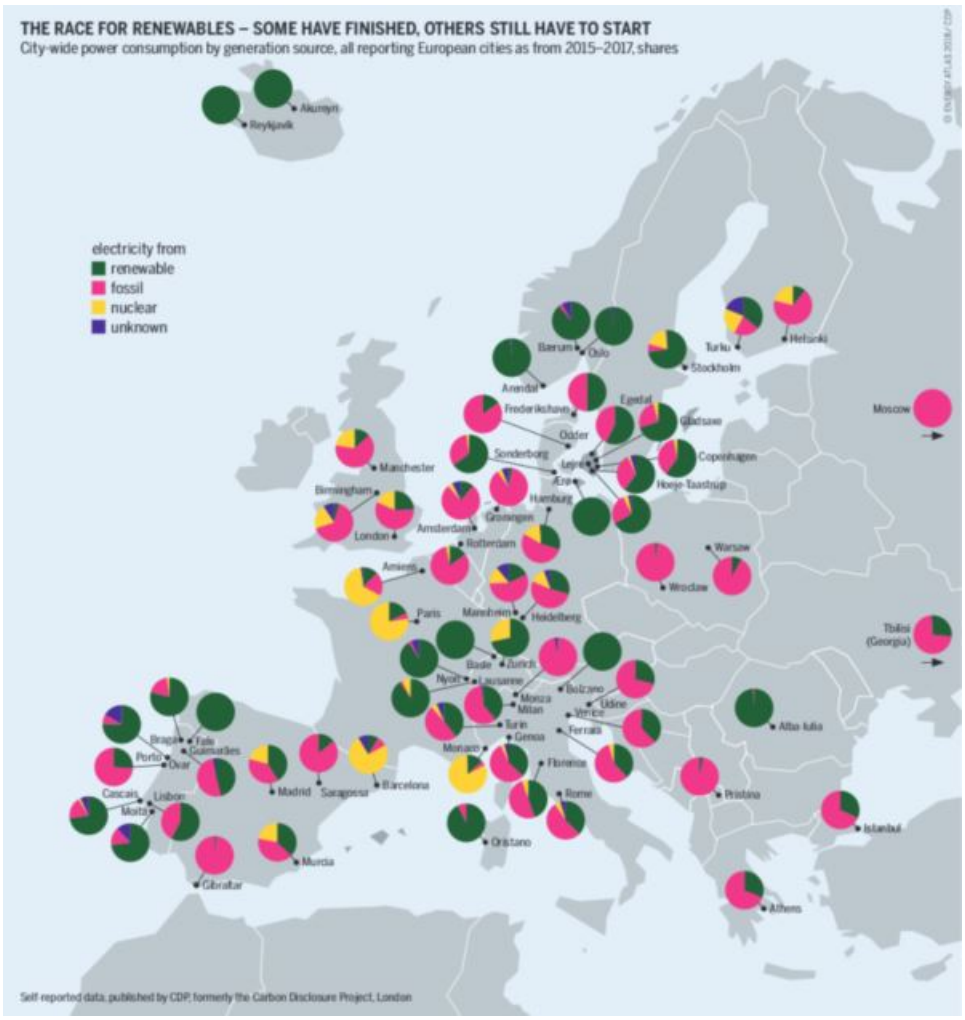


Figure 2.1: City-wide power consumption by generator source [1].

2.1.1.1 Coupling sectors

The next big challenges in Europe's energy transition are the heating and transport sectors, bringing them together with the power sector will allow Europe to reach a 100 percent renewable system with technology that is already available today [13].

So far, strategies to reduce emissions have been implemented independently in the heating, electricity and transport sectors. The potential of sector coupling-increased energy efficiency, reduced CO2, emissions, and cost reductions - remains untapped. However, in recent years, we have seen a growing

interest in a more integrated approach (e.g. Fig. 2.2). The first is in transport, where excess power could be stored in the batteries of electric vehicles, reducing the need for liquid fuel. To make this sector coupling commercially

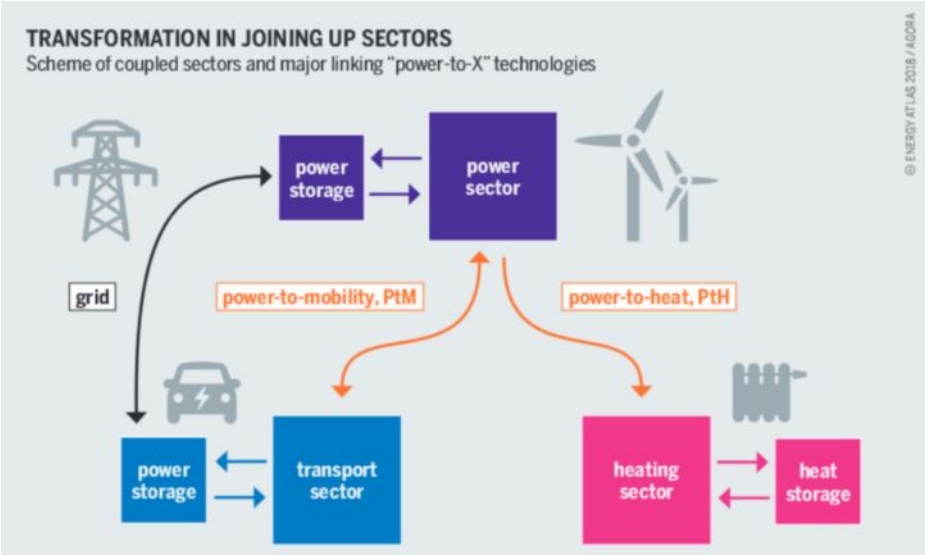


Figure 2.2: Possible joins between different energy sector [1].

viable, electricity prices for end-users need to reflect the actual supply and demand: they should be reduced when excess power is generated, and higher at times of shortage. Today, households pay the same price for electricity even when demand drops at night or during holidays, when industrial production is curbed. At such times, electricity prices on the wholesale market fall close to zero or may even be negative, meaning power plant operators actually have to pay to feed electricity into the grid. The sensible thing would be to switch off some power stations, but big conventional coal and nuclear power plants are not designed to ramp up and shut down quickly [14].

2.1.1.2 Renewable energy balance

Since electricity cannot easily be stored, the exact amount consumed generally has to equal the amount generated. Until recently, power supply systems were designed so that the supply side was managed to meet demand; large central power plants ramp up and down as electricity demand increases

and decreases. With intermittent renewables, however, power supply can no longer be adjusted easily, so demand will have to be managed [1].
On windy and sunny days, turbines whirl and solar panels sizzle, feeding lots of power into the grid. This depresses the price of power to a level that is below the amount needed for solar and wind operators to cover the costs of their initial investment. Without support schemes, they cannot make a profit. But when the wind drops and night falls, wind and solar grind to a halt, and other sources of power (or sufficiently large storage capacity) must step in to bridge the gaps in supply.

The power grid could also be better stabilized by managing the amount of power that consumers require. One strategy is to pool together consumers who are willing to adjust their immediate power consumption. These companies, known as "demand aggregators", then offer these pools of consumers to the grid operators. If there is a shortage of power in the grid (for example on a calm, cloudy day when both wind and solar generators are idle), the grid operator can reduce the amount of power used by the consumers in the pool. By being aggregated together each individual customer only needs to reduce a small amount. On sunny or windy days when power is in over-supply, the operator can increase consumption by the consumers in the pool. Such "demand-side responses" can decrease the cost and carbon footprint of the power supply system, while increasing its flexibility, as the pooled consumers can change their load faster than conventional power generators. Digital solutions, such as smart meters and grids, will help to manage demand [15].

2.1.1.3 Digitalization in the energy industry

Digitalization in the energy sector is still in its infancy; this is probably due to the fact that bringing new technologies and ideas into a tightly regulated sector is challenging. Energy giants will look for legal arguments to bar new technologies from market entry and young companies often find themselves in legal battles over the most trivial issues. The future of a digitalized energy system largely depends on whether new technologies are used as tools for de-

mocratizing the energy system, or as a means for increasing the efficiency of incumbent energy giants.
Some hail digitalization as the future market maker of a decarbonized system. Renewables, battery storage, electric cars and the grid would silently and digitally negotiate the flow of green electricity in the background, while people go about their daily lives. Other experts see digitalization as a mere hype: because of the vital role of electricity for modern life, they say that control over the system should be best entrusted to large, experienced energy companies [11].

2.1.1.4 Energy dependence

Despite progress with renewables, the European Union still imports 54 percent of its energy needs, including 90 percent of its crude oil and 69 percent of its natural gas. This import dependency comes at a high price: in 2013, the EU spent 403 billion euros for fuel imports, falling to 261 billion euros in 2015; this drop does not reflect lower demand but a fall in world market prices-indicating the EU's vulnerability to price volatility. In Fig. 2.3 we can observe the share of imports in energy consumption for the main European countries.

2.1.2 Smart energy systems and smart grids

In recent years, the terms "Smart Energy" and "Smart Energy Systems" have been used to express an approach that reaches broader than the term "Smart grid". Where Smart Grids focus primarily on the electricity sector, Smart Energy Systems take an integrated holistic focus on the inclusion of more sectors (electricity, heating, cooling, industry, buildings and transportation) and allow for the identification of more achievable and affordable solutions to the transformation of renewable and sustainable energy. So smart grids may require significant expansion of grid and storage infrastructures, while smart energy systems can succeed within existing grid and storage infrastructures [16].

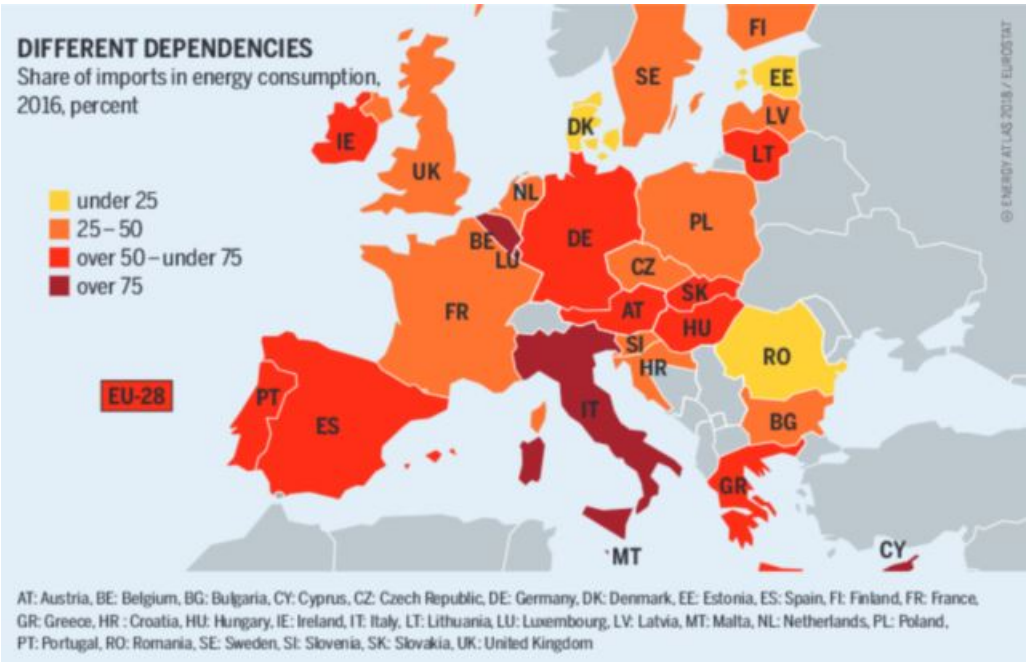


Figure 2.3: Share of imports in energy consumption for the main European countries [1].

Today, computation and control management is used in all corners of the power sector, but is far from being used to its full potential. As Amin and Wollenberg emphasize [17], practical methods, tools and technologies are allowing "power grids and other infrastructures to locally self-regulate, including automatic reconfiguration in the event of failures, threats or disturbances". Amin and Wollenberg have not included a formal definition of smart grid, but it can be understood from the paper that a smart grid is a power network that uses modern computer and communication technology to better deal with potential failures [16].
Later, the discussion of the need for changes in future power infrastructures has often been related to the "smart grid" concept in a large number of reports and papers, many of them argue for the need of this stuff for smart grids, in order to facilitate better integration of fluctuating renewable energy [18]. Also several smart grid papers focus on the consumer and how to involve the consumer in the active operation of the power balance by introducing technical operation systems and/or economic incentives to facilitate

flexible demands [16].

As showed in Fig. 2.4, the typical schema for defining a smart grid consists

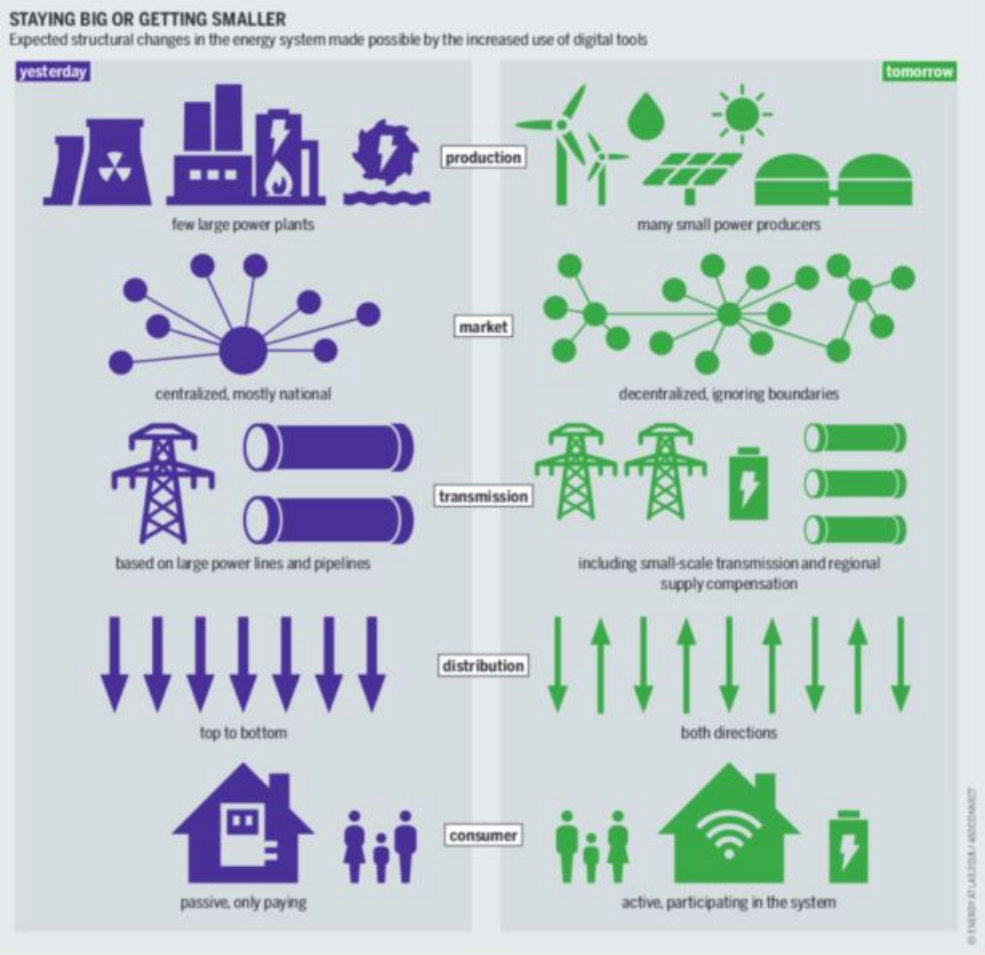


Figure 2.4: Classical energy market compared to the one who use smart grids [1].

of a bi-directional power flow, i.e. the consumers also produce to the grid, which differs from the traditional grid in which there is a clear separation between producers on the one side and consumers on the other side resulting in a uni-directional power flow. Consequently, concepts such as regulation hierarchies, distributed generation (the challenge of integrating fluctuating renewable energy sources into the electric power grid), vehicle to grid concepts (charging systems capable of transferring energy not only from the

source to the battery but also in the opposite direction, so that, if necessary, the cars themselves can be transformed into reserves to draw on at particularly critical moments to stabilize the network and avoid overloads) as well as many micro-grids all become smart grids or part of the smart grid concepts [1].

In 2013, [19] made a formal definition of a smart energy system consisting of "new technologies and infrastructures which create new forms of flexibility". In simple terms, this means combining the electricity, thermal, and transport sectors so that the flexibility across these different areas can compensate for the lack of flexibility from renewable resources such as wind and solar.
The smart energy system is built around three grid infrastructures:

- **Smart Electricity Grids** to connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources such as wind and solar power.
- **Smart Thermal Grids** (District Heating and Cooling) to connect the electricity and heating sectors. This enables the utilisation of thermal storage for creating additional flexibility and the recycling of heat losses in the energy system.
- **Smart Gas Grids** to connect the electricity, heating, and transport sectors. This enables the utilisation of gas storage for creating additional flexibility. If the gas is refined to a liquid fuel, then liquid fuel storage can also be utilised."

Based on these fundamental infrastructures, a smart energy system is defined as follows: *"A Smart Energy System is defined as an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system."*
Several synergies can be achieved by taking a coherent approach to the complete smart energy system compared to looking at only one sector. This does

not only apply to finding the best solution for the total system, but also to finding the best solutions for each individual sub-sector [16].

2.1.3 Microgrid

Following a decrease in the cost of batteries, the installation of residential, stationary battery energy storages (BES) has increased, signifying their value in reducing the electricity cost of the prosumers. BES can be combined with residential PV to increase the self-supply level of end-users during the day and can help small-scale RES owners increase their revenue by maximizing self-consumption of PV generation [7].
The coupling of small-scale generation with residential BES could promote the integration of microgrids (MG), i.e., clusters of local energy sources, energy storages, and customers which are represented as a single controllable entity. The U.S. Department of Energy has defined the MG as [20]: "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode."
MGs can be employed at various locations including both rural and urban areas. Off-grid solutions are usually ideal for remote rural areas. In cities, on the other hand, grid-connected MGs can be formed by clusters of distributed energy resources that are integrated in commercial or residential buildings [7].

2.1.3.1 Energy management

MGs are defined as clusters of distributed energy sources (generation, storage, flexible loads, etc.) and energy consumers (non-flexible load): in grid-connected mode, the difference between the MG generation and consumption can be imported or exported to the main grid; while, in island mode, the MG is completely autonomous meaning that energy is supplied exclusively from the MG resources and any excess in generation must be stored or curtailed, if self-consumption is not an option. In Fig. 2.5 we show a general micro-

grid base structure with the DMS (Distribution Management System) of the main grid that interact with the EMS (Energy Management System) of each microgrid (μ stands for one of the microgrids connected to the main grid).

Regardless of the mode of operation, a MG can be considered as a con-

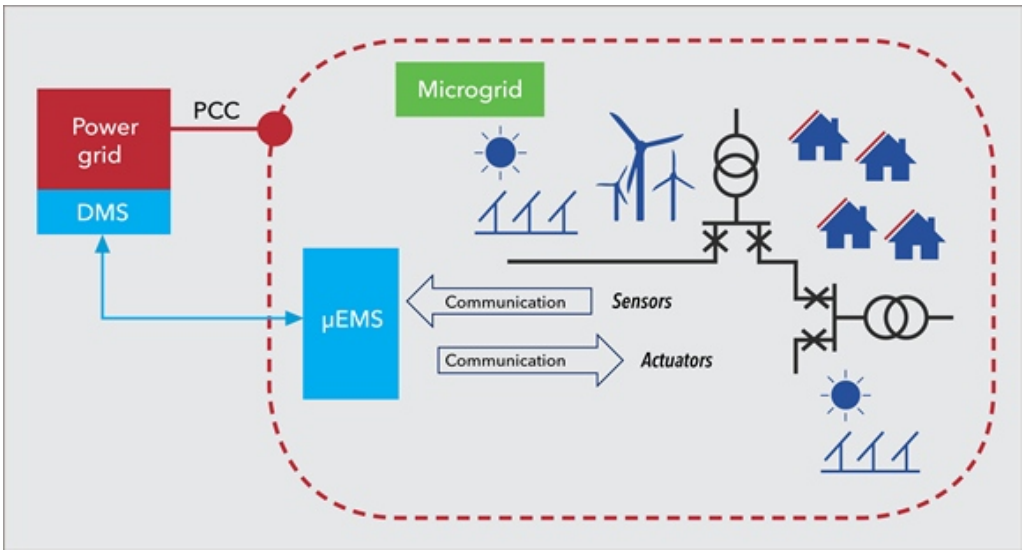


Figure 2.5: Microgrid standard structure [2].

trollable entity, which is represented as a single entity to the distribution grid. This can be achieved with the help of the MG controller, which is the key component of the MG in control of the producing and consuming units (distributed generation, flexible loads, storage) that are clustered together to form the MG. The MG controller ensures that the operation of the MG is both secure and reliable as well as efficient and economical.

The MG-EMS is employed by the MG controller and its main task is to optimally balance load and supply both in the planning phase and in the delivery phase (either by MG resources or through interconnections). The use of the MG-EMS is essential in dispatching the MG resources in an intelligent, secure, and reliable manner and in achieving coordination both among the MG components as well as with other grids. The objectives and strategies that determine the decisions of MG-EMS are defined by the MG operator. If the MG operator is different from the DSO and the MG operates

in grid-connected mode, then these objectives might not be co-aligned with the operational objectives that optimize the operation of the main distribution network [7].

For example, if the objective for the DSO is to reduce the costs paid to the TSO (thus minimising transmission costs), the whole grid operational objective for the DSO will be to make the microgrids as autonomous as possible in such a way that they do not trade on the general distribution grid; for the individual microgrids (MG operator) however the objective may be different, e.g. in the case of profit maximisation the MG controller will inform the MG-EMS to export as much energy as possible out of the microgrid, loading the distribution grid and thus raising the transmission costs for the DSO.

The MG-EMS also determines the power exchange between the MG and the main grid at the point of common coupling (PCC), which is the physical interface of the MG with the distribution network. The operation between multiple grid-connected MGs and the distribution network can be coordinated by controlling the active (and/or reactive) power exchange at the PCCs, but to achieve this level of coordination, a control and communication MG interface should be developed as an add-on DMS functionality to integrate the MG energy scheduling with the network optimal power flow (a functionality already available at the DMS) [7].

2.1.3.2 Optimal energy scheduling

The MG energy scheduling is the result of a decision-making process, where the MGs and the DSO (or a MG aggregator) need to exchange information to determine the interactions between the MGs and the main grid (e.g., power exchange, energy prices). In this decision making process, there is often a hierarchy with the DSO usually acting as the leader (upper level) and the MG operators are the followers (lower level), then this problem can be formulated as a bi-level optimization problem [7].
In most works presented in 2.1.3.1, the DSO is viewed as a supervisor and

central coordinator for the energy exchange among all interconnected network entities. Therefore, these studies usually assume that the DSO has full knowledge of MG information, which extends beyond the PCC data such as the MGs' objectives, MG grid constraints as well as DER and customer data in order to solve the bi-level optimization problem. Full knowledge helps to simplify the bi-level optimization problem, as it can then be transformed into an equivalent single-level mathematical problem with complementarity constraints. Full MG information, however, comes into conflict with the requirement of preserving the privacy of the MG data [7].

2.1.4 Internet of things

Internet of Things (IoT) refers to the networked interconnection of everyday objects. It is described as a self-configuring wireless network of sensors whose purpose would be to interconnect its nodes and deliver the information to where it should be processed. Internet of Things has three important characteristics:

1. Comprehensive sense, provided by the usage of sensors to collect information of objects anytime, anywhere.

2. Reliable transmission, i.e. accurate real-time delivering information of objects through meshing a variety of telecommunications networks and Internet.

3. Intelligent processing, i.e. using intelligent computing such as cloud computing to analyze and process vast amounts of data and information, for the purpose of implementation of intelligent control to objects.

IoT has some use cases in intelligent environmental protection (an important long-term strategy of national development), as the massive environmental data including water data, air data, regional environment data, nature protection data and other data, should be collected accurately by sensors and transmitted to servers to be treated and analyzed by software. The intelligent environmental protection includes intelligent environmental

monitoring, intelligent public facilities monitoring, intelligent city pipeline monitoring, intelligent sewage treatment monitoring, intelligent parks control and so on [21].

2.1.4.1 IoT role in smart grid technology

Smart Grid is a new kind of intelligent power system realized with information, communication, the computer control technology and the existing transmission/distribution power infrastructure. The applications of IoT in the Smart Grid are divided into smart power generation, intelligent transmission and substation and intelligent power use, data collection is the key to smart power grid. Sensor technology in IoT forms interactive real-time network connection between the users, corporation and power equipment to make data reading real-time, high-speed and two-way, which improve the overall efficiency of the integrated power grid [22]. Smart Grid may use more devices, including a variety of intelligent sensors, control components and electrical equipment, which require higher digitization degree of power grid and better data collection, transmission, storage and utilization in the process of power generation, transmission, substation and distribution [21].

2.1.4.2 IoT edge cloud architecture

An IoT edge cloud architecture (see Fig. 2.6) is a distributed system, typically consisting of an outer rim of IoT, sensor devices and networks, an intermediate layer of local processing capabilities and more centralised cloud systems for data processing and storage. Fog and edge architectures provide a link between centralised clouds and the world of IoT and sensors. The architectures consist of devices of different sizes that coordinate the communication with sensors and cloud services, and that process data from or for the sensors and the cloud locally [23].

The next generation of factories will be digital, it will mostly work autonomously and will adapt its production processes dynamically in order to improve the product quality, detect machine failures, etc. This is fueled by the integration in real time of big data, edge and cloud computing, analytics,

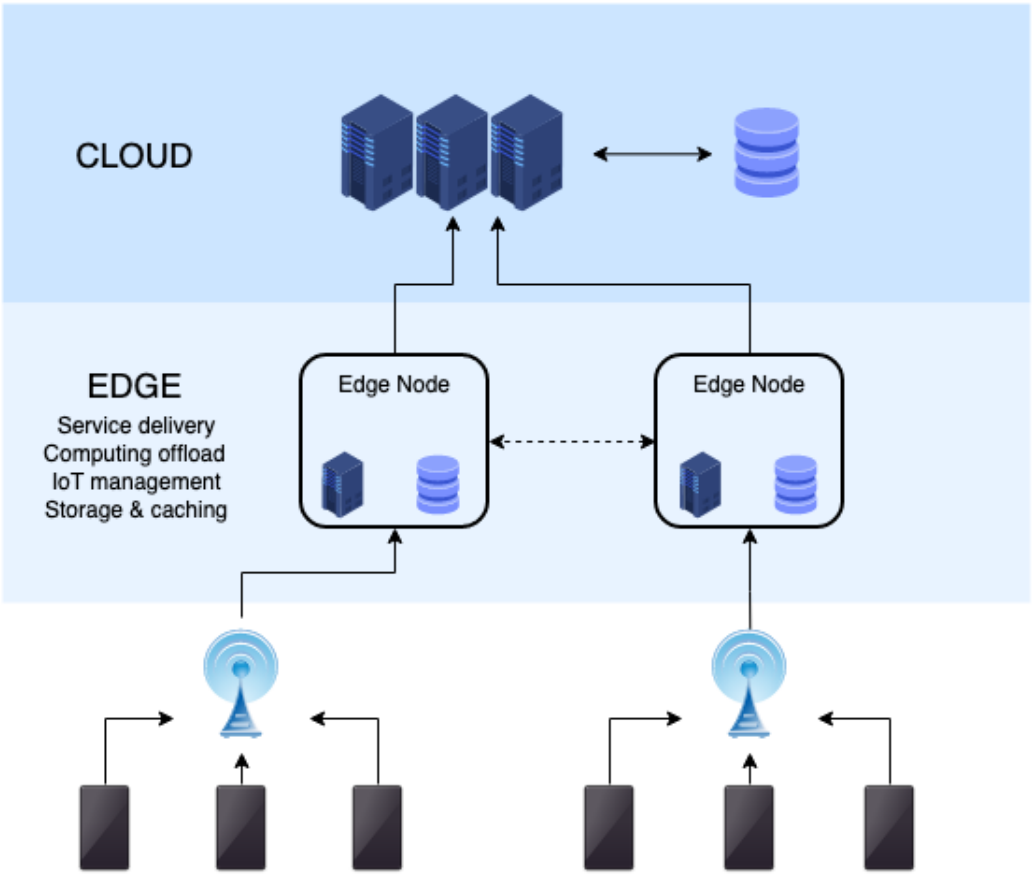


Figure 2.6: The edge computing infrastructure.

machine learning and networks. For this purpose, the machines will have numerous sensors and actuators, which detect, perceive and they act in real time with a significant level of autonomy and adaptation. For this, artificial intelligence and machine learning methods are very important. To adapt quickly, intelligence must be close to machines, spreading analytical intelligence on "network-edges", to run AI algorithms inside the factory both on small integrated boards near the machines and on larger computing nodes within the factory's IT services. This edge/cloud-based architecture requires reliable and real-time communication and custom hardware/software in local controllers to support large-scale AI-based applications that can work with temporal constraints [24].

Smart grids employ smart meters which are responsible for two-way flows of electricity information to monitor and manage the electricity consumption. In a large smart grid, smart meters produce tremendous amount of data that is hard to process, analyze and store. The regular monitoring is expected to be performed with all kinds of IoT devices and processing servers instead of manpower, where IoT devices such as sensors and cameras will collect and upload the real-time videos and other information about the power line to the processing servers. Such information will then be automatically processed by the servers running ML algorithms to detect potential threats and, if necessary, trigger appropriate actuations to achieve timely and intelligent monitoring with automatic threat identification.
Since deep learning algorithms are extremely data intensive, computation intensive and hardware-dependent, the processing servers of smart grid are expected to be equipped with abundant computation resources. This makes cloud computing be widely proposed as a natural choice to host such servers. However, transferring large volume of data into the cloud will push significant pressure to the network and generate huge communication costs. In addition, from power providers perspective, moving data to the remote cloud may also incur privacy concerns. Moreover, the latency in the network can become a severe performance bottleneck due to the latency sensitivity of real-time monitoring.

Recently, the concept of edge computing has been proposed as a complement of cloud computing, attracting great interests from both academia and industry. In contrast to cloud, edge usually refers to a geographical concept which is in close proximity to the end devices in the network [25]. By pushing applications, data and services away from centralized cloud to edge servers, the computing paradigm will be extended to an edge-cloud collaborative computing, which has shown outstanding performance on communication latency and traffic reduction, and ease the privacy concerns of users as well [26].
In conclusion, edge computing is an environment that offers a place for collecting, computing and storing smart meter data before transmitting them to

the cloud. This environment acts as a bridge in the middle of the smart grid and the cloud. It is geographically distributed and overhauls cloud computing via additional capabilities including reduced latency, increased privacy and locality for smart grids [27].

2.2 Related Works

2.2.1 Existing Microgrid-based Energy Management Systems models

Traditionally, energy consumers pay non-commodity charges (e.g. transmission, environmental and network costs) as a major component of their energy bills. With the distributed energy generation, enabling energy consumption close to producers can minimize such costs. The physically constrained energy prosumers in power networks can be logically grouped into virtual microgrids (VMGs) using communication systems.
There are centralized and distributed optimization approaches: distributed approaches are, for example, based on game theory as no global information is available and each agent makes its own decisions. Peer-to-peer (P2P) energy trading offers an approach to produce and sell energy at the edge of the network and can help in reducing charges. Since there are multiple producers and consumers involved, attaining optimal pricing as well as utility for the consumers and producers respectively, can be complicated.
[28] introduces a game theory-based approach to optimize energy trading costs in a single VMG. In this work prosumers can act as consumers when they need to buy energy. In the model, A (a producer) sets up its own energy price and the consumer has the liberty to choose who to purchase energy from. Typically, the energy price defined by A is cheaper than the grid-price at the prevailing transaction interval. Thus, the price set by A depends on the prices set by other A's and the grid. This type of coupling between prosumers' trading strategies necessitates the use of game theory to model the interaction between the producers and consumers. Specifically, is adopted a multi-leader multi-follower Stackelberg game.

For [3] there are some reasons game theory is applied to model the energy management of future distribution networks with the presence of multiple microgrids, the main reasons for authors to use game theory in this problem have been listed as follow:

- The strategic game is used to model selfish behaviors of other agents.
- Networked optimization usually consists of multiple agents who can observe and react to their environment. Game theory offers a powerful tool set to analyze interactions between such intelligent entities.
- Although network components or agents would like to cooperate, it might be impractical or impossible to exchange the information required to implement presented method. It might then be better for agents to optimize their local or private objective and react to limited network information.
- Game theory provides a way to predict, analyze or even to improve the outcome of a non-cooperative interaction, e.g. the notation of equilibrium.

[3] present optimal scheduling of resources from the DNO's point of view considering reaction of multiple autonomous microgrid; since multiple microgrid are considered multi follower bi-level programming has been implemented. In general, MFBP is a bi-level decision-making problem which has three significant characteristics:

- There exists two decision levels within a principally ordered structure.
- The decision level at the lower order executes its policies in consequence of decision making at the upper level.
- Each level autonomously optimizes its objective but it is affected by the reactions of other level.

The decision maker at the upper level is denominated as the leader, and at the lower level, is named as the followers. The leader cannot adequately control the decision making process of the followers, however, it is affected by the reaction of the followers. The optimal solution of the followers allow the leader to execute his/her objective functions value. Since, this type of decision making process has been appeared in many decentralized organizations, and been mainly handled by bi-level programming technique.
As shown in the Fig. 2.7 the problem has been formulated in two level witch DNO as upper level determines its decision making considering reaction of MGs.

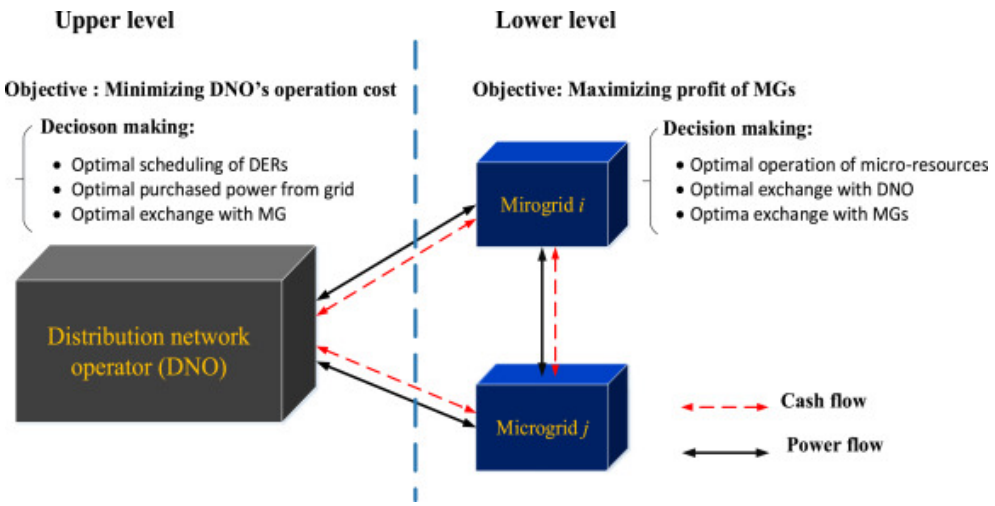


Figure 2.7: Problem statement as a bi-level programming [3].

For [29], a critical point for the distributed management can be that each microgrid control centre is not informed of generated and consumed powers of other rivals, consequently, the microgrids may face the problem of common line congestion.
Assuming a line limitation in PCC and some microgrids are connected to the grid through this point. When grid electricity price is cheap/expensive, each microgrid starts to buy/sell from/to grid without knowing about neighbouring microgrids. For this purpose, in this work, a new unit to manage congestion called MGA is proposed. This unit is responsible for line utilisa-

tion, and allocating fair capacity among various microgrids.
The proposed mathematical framework for solving the problem is based on a bi-level model: in the first level, microgrids implement day-ahead scheduling independently and provide the aggregator with the results; In the second level, a novel energy management mechanism is carried out by the aggregator, taking PCC constraints into consideration.

[30] and [31] formulate the problem as a stochastic bi-level problem with the DNO in the upper level and MGs in the lower level and also for [32] the MMG system is a hierarchical decentralized SoS. Individual MGs are independently managed and operated, and they can choose to join the MMG system, but a controller for the MMG system, the DMS, is present to coordinate the power exchange among the participating MGs and the trading with the DN. Energy management at the level of MMG system interacts with the DN and coordinates participating MGs in the system. In other words, the MGCC of each participating MG derives an optimal solution of energy management for the MG with consideration of the request for power exchanges and trading from the DMS. Meanwhile, the DMS assesses the optimality of energy management solutions for the MMG system based on the optimal solutions provided by the MGCCs.

The development of a cluster-based (similar to microgrid) energy management scheme with a mathematical model for residential consumers of a smart grid community is proposed by [33] to reduce energy use and monetary cost. Solar and wind generators, an energy storage system and a typical energy consumption profile for residential consumers are also considered. Furthermore, the home appliances considering peak-load, mid-peak, and off-peak loads and real-time electricity prices scenarios are modeled.

However, we highlight that most models take into account a "simplified" microgrid structure (see Fig. 2.8) only with "produce" and "consume" agent-types, in which the prosumer entity (an agent that both "produce" and "consume") is not present.

The energy scheduling problem illustrated in the work [7] takes into con-

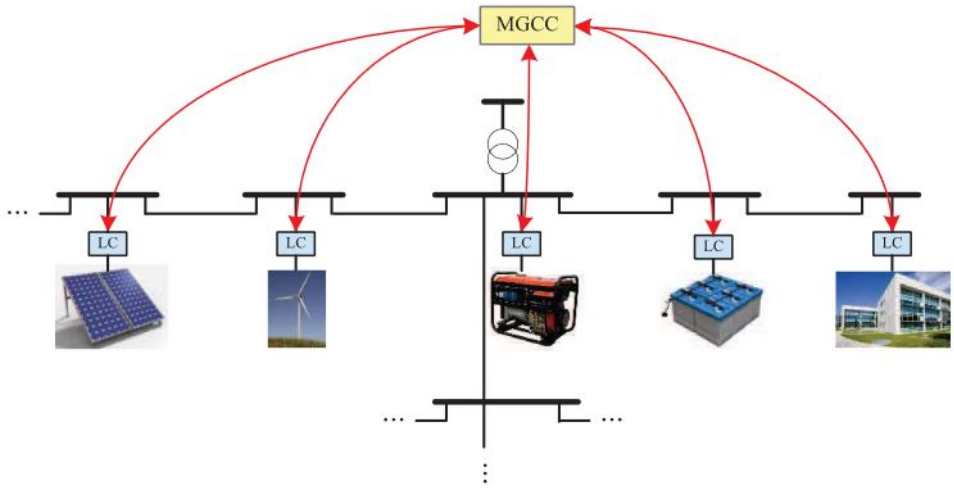


Figure 2.8: Standard MG system communication infrastructure, linking the microgrid central controller (MGCC) and the local controllers (LCs) [4].

sideration the prosumer entity and, respect to all the others works that mostly focus on the dynamic prices based on supply/demand, this establish fixed prices (considered in the decision making process) and the main issue is the energy exchange between the microgrid agents. For this reason this was chosen as the starting point for the optimization component in this work.

2.2.2 Microgrid Energy Management optimization problem

The energy management in microgrids is typically formulated as an offline optimization problem for day-ahead scheduling, most of the offline approaches assume perfect forecasting of the renewables, the demands, and the market, which is difficult to achieve in practice. Existing online algorithms, on the other hand, oversimplify the microgrid model by only considering the aggregate supply-demand balance while omitting the underlying power distribution network and the associated power flow and system operational constraints. Consequently, such approaches may result in control decisions that violate the real-world constraints [4].

2.2.3 Real-world Deployments of Microgrid Energy Management Systems

MG-EMSs are already offered by several manufacturers including Siemens, Hitachi, and General Electric among others. Some of these platforms provide also integration with the supervisory control and data acquisition (SCADA) system of the utility through standard industrial protocols. Thus, the technology for both MG deployment and DSO integration is available. The adoption of MGs could benefit both end-users, which could reduce their energy cost, and the operation of the distribution system, which can exploit the energy flexibility offered by MGs [7].

2.2.3.1 Siemens

Microgrid Control Microgrid Control from Siemens provides reliable control and monitor a microgrid, ensuring an independent power supply and balancing out grid fluctuations as well as fluctuations in energy consumption, the Fig. 2.9 illustrates the components over which control is exercised [5]. It offers the following functionalities:

- Blackout detection, black start, and automatic grid modes;
- Automatic start of backup generators;
- Optimization of operating points;
- Reserve monitoring;
- Peak shaving;
- State-of-charge management.

Spectrum Power™ Microgrid Management System The Siemens Spectrum Power™ MGMS is an advanced control and optimization software – used to maximize the value of onsite generation and energy storage in coordination with local utility rates, it can be used as a support tool for the more

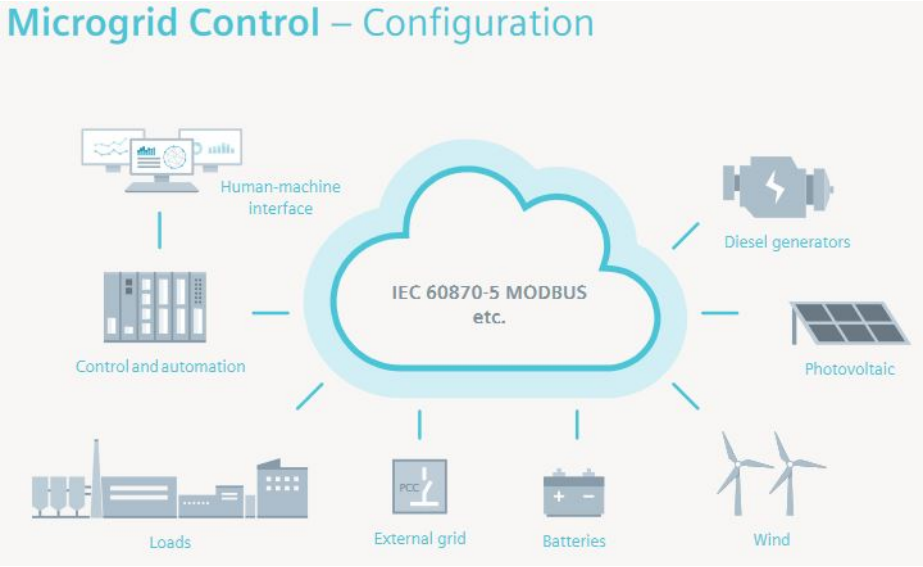


Figure 2.9: Microgrid Control, by Siemens [5].

general Microgrid Controller. Spectrum Power™ has the ability to forecast site electrical and thermal loads – and while taking into account the current electric and fuel/gas utility tariffs, will execute a comprehensive plant operation routine in order to find the economic optimal unit schedules for the next 24 hours or 7 days. These schedules are then dispatched in real time, turning units on and off, and sending the economic optimal operating set points and charge/discharge rates. This results in significantly decreased operating expenses from electricity and fuel/gas purchases.
The overall function of MGMS (as showed in Fig. 2.10) is the optimal coordination of dispatchable generation (gas, diesel generators, etc.), renewable generation (PV, wind, etc.), energy storage (batteries), and load (via Building Management System or remotely-operated switches) [6].

2.2.3.2 Hitachi e-mesh Energy Management System

Hitachi ABB Power Grids' e-mesh™ EMS is specially designed to manage distributed energy and renewable resources, conventional power generation sources, and controllable loads like electric vehicle chargers. e-mesh EMS is a flexible and highly scalable application that allows for easy expansion as

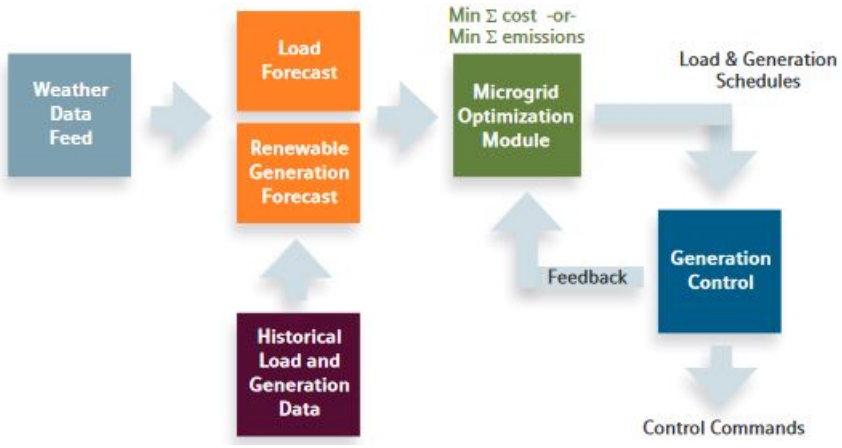


Figure 2.10: MGMS Operational Flow, by Siemens [6].

the number of energy resources and the size of the operation grow [34].

The application comes with four key features:

- EMS Optimize: improves energy production whilst reducing costs and emissions. With the optimisation module the assets' management is based on each unit's constraints and costs. Flexible and scalable models are implemented to rapidly expand from few to several units.
- Simulate & Plan: helps in making cost-effective decisions.
- Analyze: enhances transparency whilst providing energy insights.
- Integrate: enables connectivity options for integration with SCADA ("Supervisory Control And Data Acquisition") systems, third-party systems such as forecast providers and trade platforms can also be easily integrated with the application, allowing meaningful data exchange.

2.2.4 Identified research gaps

At present there are many practical and theoretical solutions that adopt the technique of optimisation in distributed systems using e.g. game theory which do not assume global knowledge, while there are missing centralised

solutions that can calculate good solutions fast.

In addition, we would like to avoid using off-the-shelf products, this to ensure maximum low coupling between the various components from the very beginning of the project, in such a way that you can test the performance and add, modify or remove components when necessary (for research purposes of new solutions, testing for machine learning models, etc.).

As [7] has observed, studies on coordinated operation of the MGs and the DSO have exclusively focused on defining the amount of energy trade between the DSO and the MGs often without considering the underlying constraints of the distribution network operation.
For efficient BES dispatch and accurate evaluation of the BES utilization, it is important to consider both real-life performance and usage constraints of the BES for each prosumer.

Chapter 3

Design

This chapter first presents the general structure of the existing context in which we operate. It then illustrates the software architecture designed to manage and process the data, irrespective of the technologies used. This is followed by a presentation of the data sources used for the simulations, the machine learning model used to derive the energy production data, the theoretical structure of the energy scheduling problem and, finally, the performance metrics chosen for the subsequent evaluation phase.

3.1 Energy network structure

The Fig. 3.1 shows the basic general structure of the smart grid on which the project will be developed.

Each microgrid contains a cluster of prosumers, each with an associated control board (edge unit) that is responsible for collecting data from the various sensors (battery state of energy, energy consumption and energy production from the photovoltaic panels) and for receiving any instruction for the battery scheduling from the controllers. In the cloud we find the microgrid controllers, which are responsible for collecting all local information and making optimal decisions at a global level (such as how much energy each prosumer has to draw/feed from/into its battery); the main grid provides other information such as energy buying and selling prices etc. and a circuit

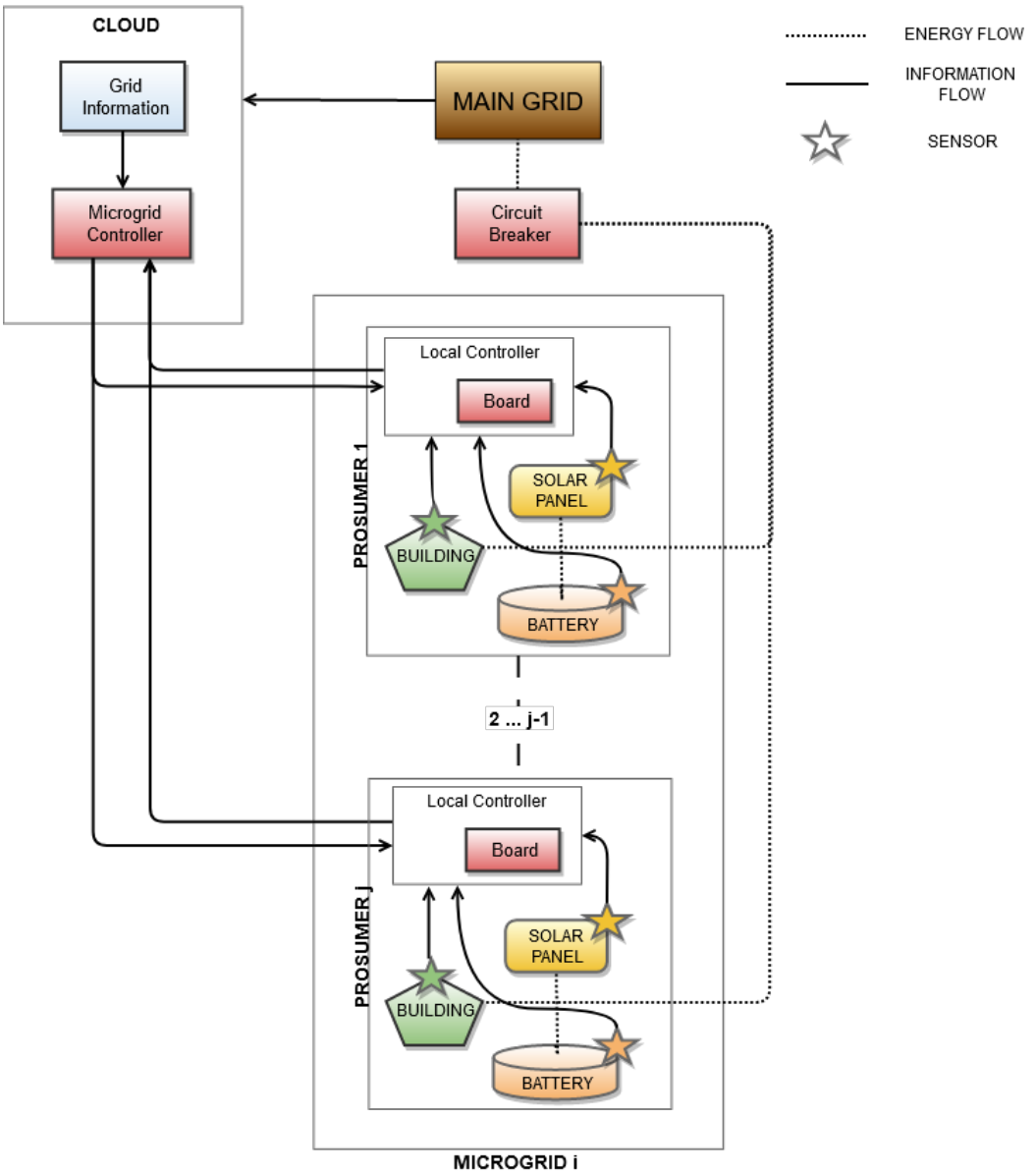


Figure 3.1: Network structure with microgrids. In the microgrid (i) in the scheme there are j prosumers.

breaker acts as an automatically operated electrical switch.
As illustrated in the legend, there are two "parallel" flows:

- the energy flow that, starting from the main grid, branches out on the electricity grid and arrives at each prosumer (this configuration is independent of the microgrid as the latter is intended to represent an abstract level cluster only);
- the flow of information (depending on the configuration of the prosumer cluster in the microgrid) which can be divided into two phases: sending data to the server and receiving results/decisions.

3.2 General system architecture

Based on the structure illustrated in the previous section, the hardware/-software system in Fig. 3.2 has been designed to achieve the objective of this project: each prosumer predicts its energy supply and demand locally using edge computing and pushes this information to the cloud that, in a marketplace, optimize energy exchanges between prosumers.

Each edge unit receives the data from the sensors and, together with those values, it sends to the server (as telemetries) also the data predicted by the machine learning model for the next time interval. In the cloud server, the data is received by a device manager that passes it to an aggregator that groups together all the time series data-points received in a certain time interval for each microgrid; the aggregated real-time data are sent to a tool for graphical representation (consumption and production), while the aggregated data becomes the input for the energy scheduling optimizer. The result of the optimisation (which devices should charge or discharge their battery in the next time interval) is finally communicated to the respective boards.

3.2.1 Data structure in the flow

The table 3.1 shows the structure of the data collected and sent (in out use case, sent every 30 seconds) from the board (edge unit) to the server.

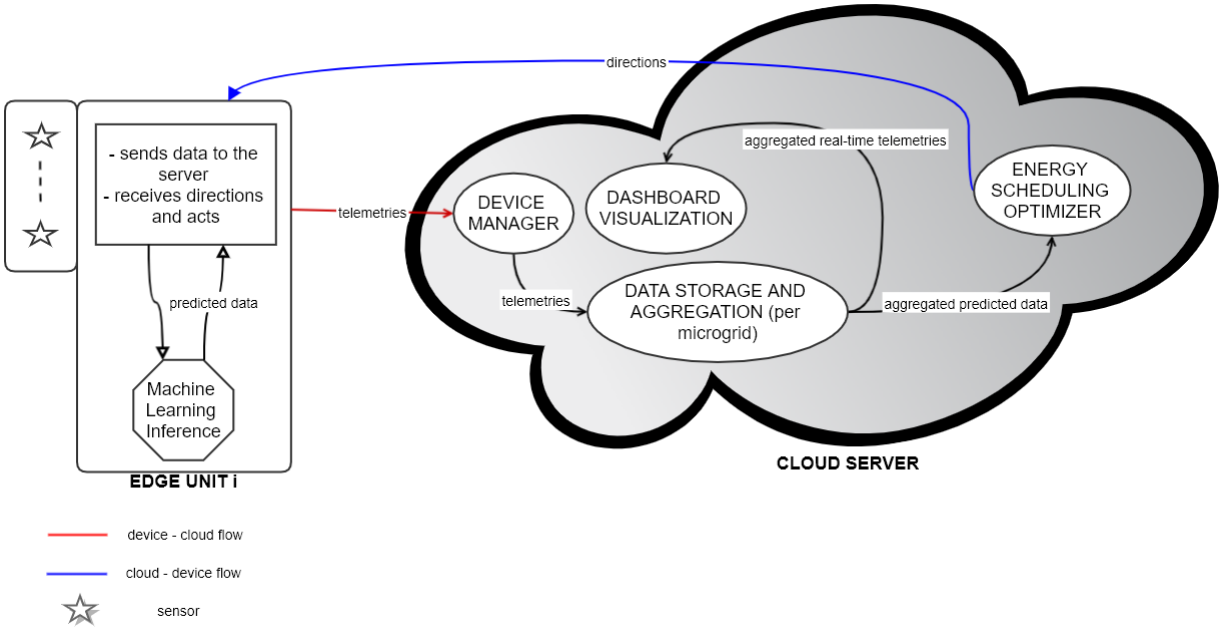


Figure 3.2: General system architecture. In this schema is represented, as an example, only one edge unit (i).

Depending on the strategy used (local or global, see section 3.5 for a detailed explanation) some of these fields may be empty or not.

This data structure is similar even after aggregation for each device and then for each microgrid; indeed, the output of the aggregator contains the attributes concerning the individual prosumer together with the ones of the microgrid. As showed in table 3.2, the data that regard a property of the single device are the ones with index: 1, 2, 7, 9, 10; while the ones which are an aggregation of the values produced by the board in a 5-minute interval have index: 3, 4, 5, 6, 8, 11, 12. Data such as consumption and production are aggregated by summing all the data-points while the battery state of charge is averaged over the 5-minutes interval. The attribute microgridAggregator (index 13) has the structure represented in table 3.3 and contains the sum (for that precise time interval) of consumption, production, import and export for the microgrid stated in microgridID (index 1) and is replicated in every device belonging to that microgrid.

Index	Data	Source	Strategies that use the data
1	microgridID	board	local, global
2	deviceID	board	local, global
3	consumption (kW): energy consumption of the building in the previous time step	sensor	local, global
4	production (kW): energy production of the PVs in the previous time step	sensor	local, global
5	predictedConsumption (kW): predicted energy consumption of the building for the next time step	ML inference	global
6	predictedProduction (kW): predicted energy production of the PVs for the next time step	ML inference	global
7	batteryCapacity (Ah)	battery attributes	global
8	batteryStateOfCharge (Ah)	sensor	global
9	chargingLimit (percentage): maximum amount of battery charge for a time step	battery attributes	global
10	dischargingLimit (percentage): maximum amount of battery discharge for a time step	battery attributes	global
11	energyImport (kW)	local computation	local
12	energyExport (kW)	local computation	local

Table 3.1: Data structure from the board.

Index	Data	Strategies that use the field
1	microgridID	local, global
2	deviceID	local, global
3	sumConsumption (kW)	local, global
4	sumProduction (kW)	local, global
5	sumPredictedConsumption (kW)	global
6	sumPredictedProduction (kW)	global
7	batteryCapacity (Ah)	global
8	averageBatteryStateOfCharge (Ah)	global
9	chargingLimit (percentage over the battery capacity)	global
10	dischargingLimit (percentage over the battery capacity)	global
11	sumEnergyImport (kW)	local
12	sumEnergyExport (kW)	local
13	microgridAggregator	local

Table 3.2: Data structure of the output of the aggregator (for each device).

Index	Data
1	microgridID
3	sumConsumption (kW)
4	sumProduction (kW)
5	sumEnergyImport (kW)
6	sumEnergyExport (kW)

Table 3.3: Data structure of the attribute microgridAggregator.

3.3 Input data preparation

For this project it has been decided to simulate consumption and production data, in order to create prosumers with different profiles (e.g. residential or commercial), otherwise connecting real sensors to the board would have simulated at most one single prosumer at a time.
A number of datasets containing numbers on energy consumption and production over the course of a day have been then used to simulate real data.

3.3.1 Datasets

3.3.1.1 Production

The data source for energy production has been the dataset of FerroAmp's EnergyCloud portal (desktop version: [35]) where selected segments of the time series (containing both production and consumption) of some residential dwellings can be viewed and downloaded (a snapshot of the system can be seen in Fig. 3.3). The downloaded file is a CSV file and contains data about a single residential prosumer for one day.

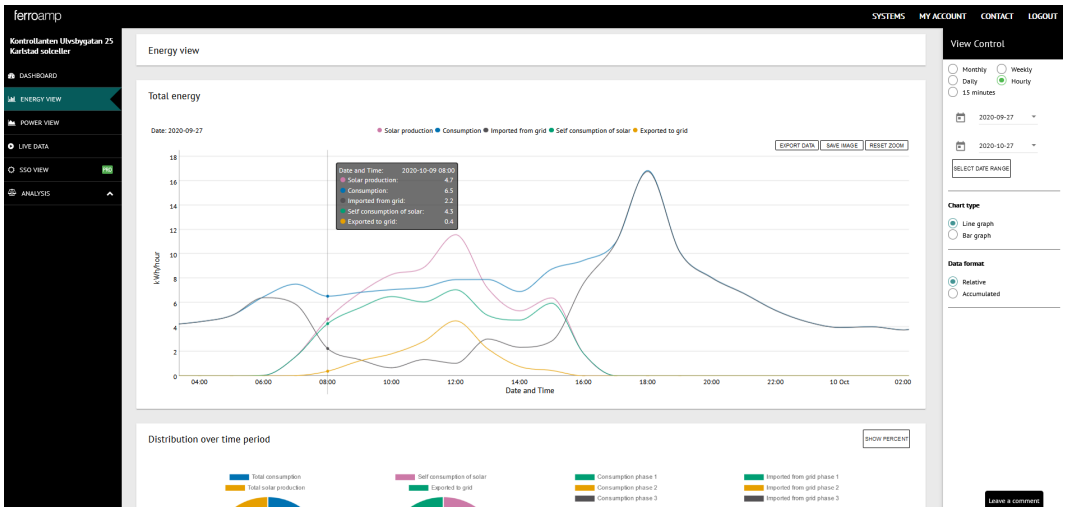


Figure 3.3: Snapshot of the desktop version of the monitoring application ferroAmp.

3.3.1.2 Consumption

Two data sources were used for consumption:

- FerroAmp for residential consumption (see 3.3.1.1), also in this case the data are about a single residential prosumer in one day;
- OpenEI (desktop version: [36]) for commercial buildings for one day data; the chosen types are (one each): hospitals, hotels, schools, supermarkets, warehouses.

In both cases the downloaded file is a CSV file.

3.3.2 Pattern extraction

For both consumption and production it has been decided to find the daily pattern. For each time series of data (residential production/consumption and commercial) hourly mean and standard deviation have been calculated over a single prosumer, starting from a data granularity of 1 minute.
Arithmetic mean and standard deviation have been computed as well:

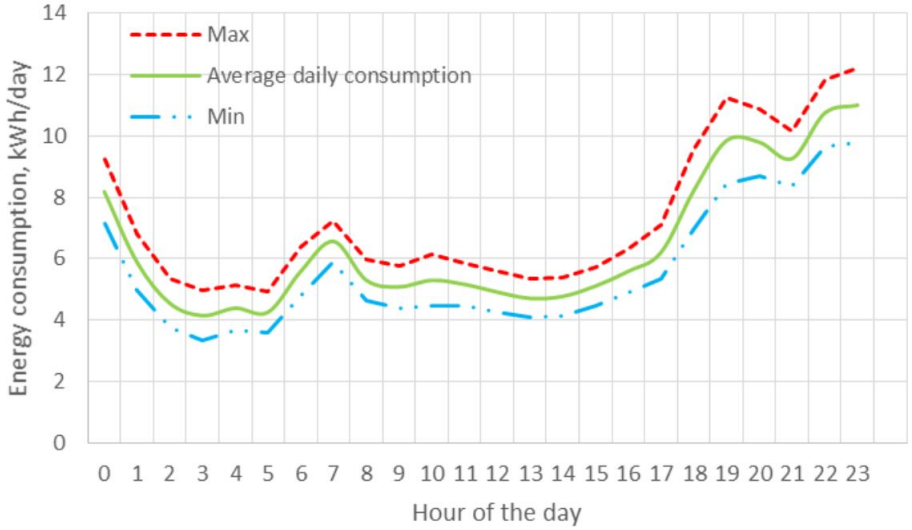
$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{3.1}$$

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{3.2}$$

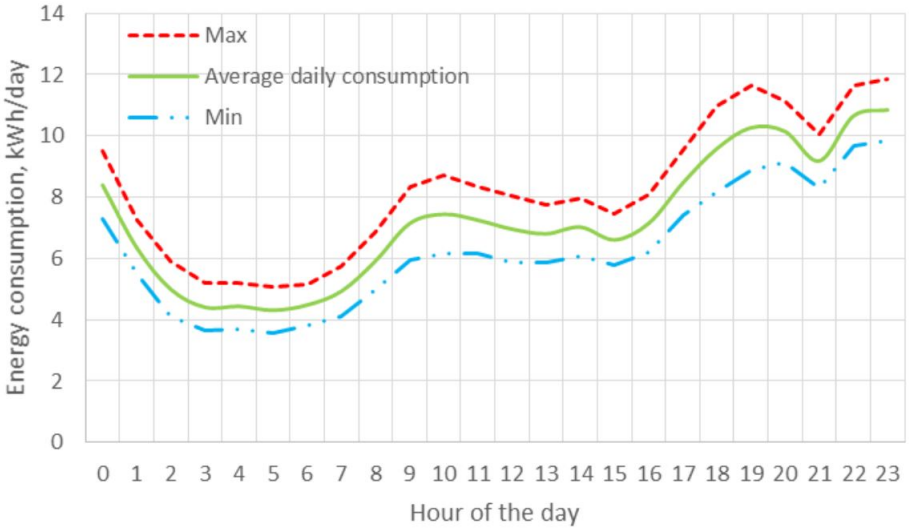
because, when looking at various graphs and/or time series representing production and/or consumption values, it was noted that the values follow a normal distribution (see figures 3.4 and 3.5).
Having these two values for each hour, the simulator generate a significant value (a normally distributed random number) for any time of day and at any granularity (depending on the frequency chosen for sending telemetry from the board to the server) proportioning the values to the granularity of the original dataset.

3.4 ML model for production inference

In our case, a 4-layer bidirecional LSTM model (from[38]) has been used to infer the energy production of the photovoltaic panels.
In comparison to normal MLP (Multilayer Perceptron), which consists of many layers with neurons in it and the input data is propagated through the network itself, the LSTM (Long Short-Term Memory Network) has recurrent connections. This means, that the state of the previous activations is also used as a context for the output. Long short-term memory (LSTM) is, in fact, an artificial recurrent neural network (RNN) architecture mostly used in the field of deep learning and, unlike standard feedforward neural networks,

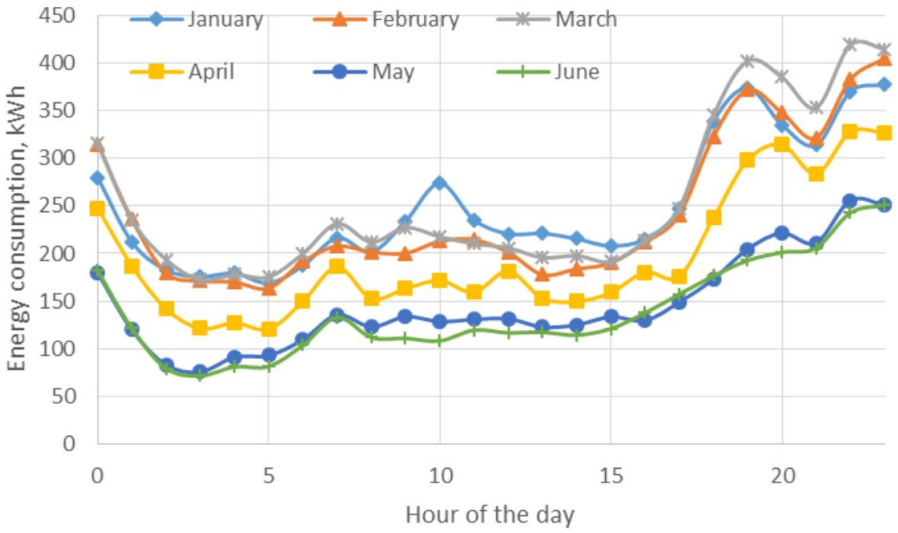


(a) Average daily energy consumption during the weekdays and the variation throughout the different months [37].

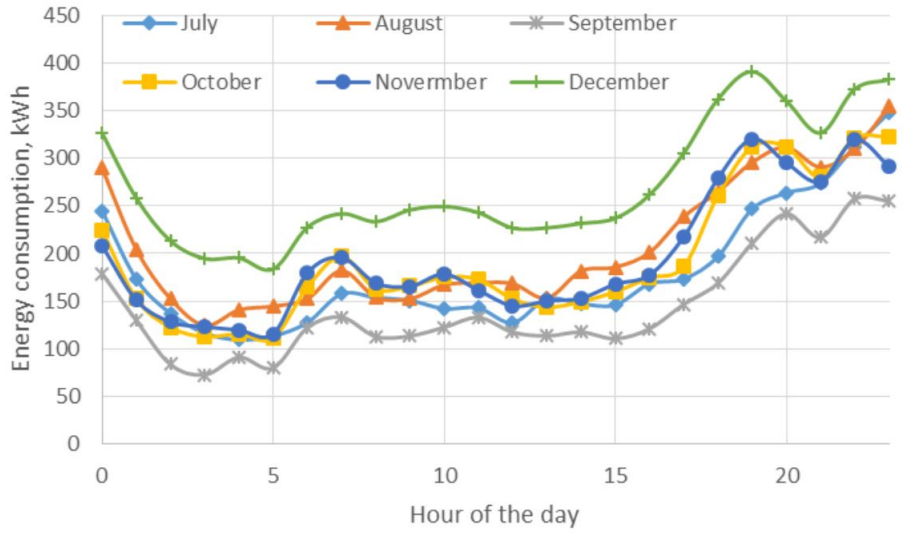


(b) Average daily energy consumption during the weekdays and the variation throughout the different months [37].

Figure 3.4: Average daily energy consumption and the variation throughout the different months.



(a) Average monthly load profiles of the block of flats from January to June [37].



(b) Average monthly load profile of the block of flats from July to December [37].

Figure 3.5: Average monthly load profiles of the block of flats.

LSTM has feedback connections, this means that it can not only process single data points (such as images), but also entire sequences of data (such as speech or video). In addition, in comparison to normal RNN the design of the LSTM Network allows to overcome the problem of the vanishing or exploding gradients (the weight update procedure changes the weights so fast in one direction or the other, that it is graduate to zero or infinity) as those phenomena make the neural network useless. Moreover, in general RNNs are good for the processing of sequential data and for the prediction of those, but those networks suffer from short-term memory. LSTM networks overcome this obstacle processing a time series one step at a time and maintaining an internal state that summarises the information acquired up to that moment [38].

A Bidirectional LSTM, or biLSTM, is a sequence processing model that consists of two LSTMs: one taking the input in a forward direction, and the other in a backwards direction. BiLSTMs effectively increase the amount of information available to the network, improving the context available to the algorithm (e.g. knowing what words immediately follow and precede a word in a sentence) [39]. In Sec. 4.6 the technical details of the model for inference will be explained.

3.5 Structure of the energy scheduling problem and solution approaches

The solution of the MG energy scheduling problem depends on the operational objectives of the MG operator. It is assumed that the MG operator has full access to the installed DERs in the MG and is responsible for delivering power to the MG customers; the MG operator is a different entity from the DSO.

The architecture proposed by [7] for the integration of the MG to the distribution system can be seen in Fig. 3.6, which is a schematic representation of the interface between the MG-EMS and the DMS. Two-ways communication is always assumed between the MG-EMS and the DMS. No communication or

interaction is considered between different MG-EMSs, i.e., the MG-EMSs can only interact with the DMS. Three different schemes of coordination between the MG-EMS and the DMS are depicted, these coordination schemes, which affect the approach followed for the solution of the MG energy scheduling problem, can be described as follows:

- No coordination: the MG-EMS solves the energy scheduling problem and dispatches the MG resources according to this solution.
- Centralized coordination: it is assumed that the DMS is empowered to dispatch the MG resources, the MG-EMS receives the reference set-points from the DMS and then transmits them to the MG resources.
- Decentralized coordination: the DMS can only transmit the desired reference values for the PCC and is in no other way involved in the MG energy scheduling.

In our use case we have decided to use "No coordination" for the two global strategies (see Sec. 3.5.3).

3.5.1 Rolling horizon

An energy management scheme can have a scheduling horizon that depends on the accuracy of the forecasted values of load, non-dispatchable generation and electricity price. It can be applied hour-ahead, day-ahead, week-ahead or even month-ahead. The scheduling horizon is divided in time steps (time discretization steps), which usually (although not necessarily) correspond to the frequency update of the dispatched set-points and the resolution of the input data (resolution of forecast).
Typically, hourly or 15-minutes time intervals are used in energy management. Energy management schemes with time intervals which are shorter than 5 minutes can be classified as real-time energy management schemes.
For implementation of real-time or close to real-time energy management, the rolling horizon (RH) approach must be adopted. When the MG energy scheduling follows a RH approach, the energy scheduling problem is solved

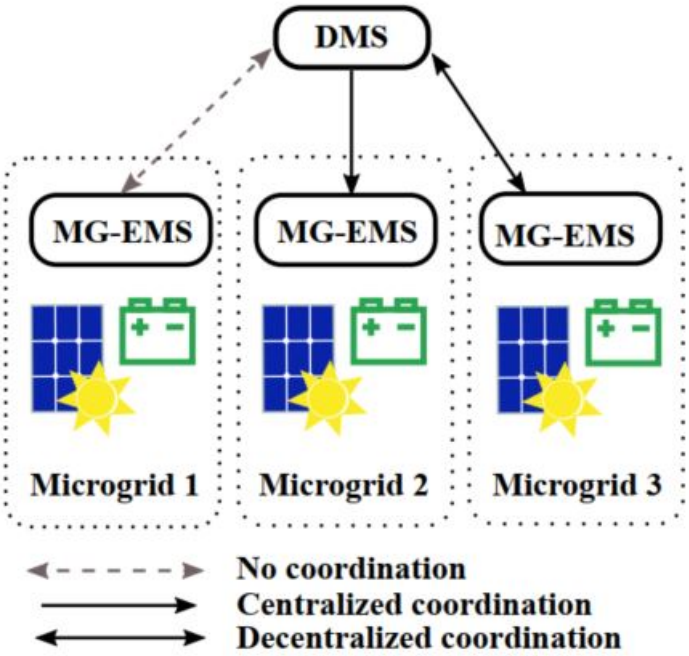


Figure 3.6: The integration of the MG-EMS to the DMS [7].

before each time step [7]. In our case, as we have a 5 minutes time step (to determine the transactions between the components of the microgrid) we have decided to use the rolling horizon approach in our scheduling problem. As showed in Fig. 3.7, during the time step 1 (between t and t+1, where +1 means 5 minutes) together with the real time data, the board also sends the predicted data (production and consumption) for time step 3 (between t+2 and t+3), because we take into account time step 2 as the time-frame for the computation of the optimised energy scheduling; therefore the decisions for time step 3 will be made based on data received in time step 1. This procedure is performed at each time step, shifting 2 units for the results.

3.5.2 Business As Usual (local) strategy

In this scenario, the dispatch of the BES follows a rule-based algorithm local to the edge unit; each prosumer then acts independently of the others and charges/discharges its battery and buys/sells energy only according to its needs. The procedure showed in the Algorithm 1 is actuated in each board,

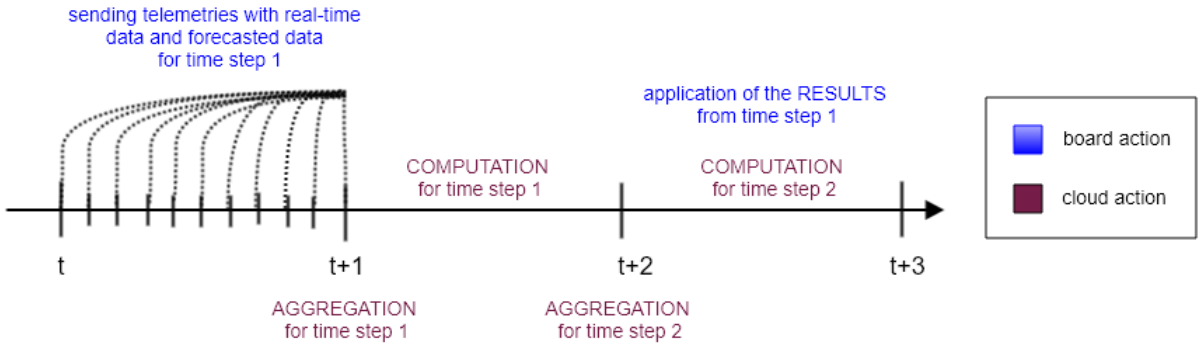


Figure 3.7: The rolling horizon approach.

in case the chosen strategy is the BAU (Business As Usual, normal execution of operations will be followed) this will also be the final local configuration of the edge-unit. The first step is to check whether the prosumer has an energy deficit or surplus, after this the energy balance of the single prosumer is levelled with two possible alternatives:

- charging (in case of surplus) or discharging (in case of deficit) the battery: in this case it is checked that this meets the conditions indicated in the Equations 3.4, 3.5, 3.6, 3.7, 3.8;
- importing/buying (in case of surplus) or exporting/selling (in case of deficit) energy: this solution is adopted if and only if the energy balance has not been completely levelled out by using the battery.

More in detail, the Algorithm 1 adopts the following procedure to check that the scheduling meets the conditions indicated in the Equations 3.4, 3.5, 3.6, 3.7, 3.8:

- At line 1 it calculates the difference between production and consumption, if this value is positive the prosumer has a surplus of energy, otherwise there is a deficit.
- In case of surplus (from line 6 to 20) it is checked if it is possible to recharge the battery of that particular building for the entire amount of the extra energy (line 7) based on the maximum charging level for a time-step.

  - If the quantity does not exceed the maximum charging level (lines 8-13), it is checked that the maximum SoE for that prosumer (corresponding to 80% of the battery capacity) is not exceeded (line 8); if this value is surpassed, the feasible amount is stored in the battery and the remaining amount is exported (lines 12-13).
  - If the quantity exceeds the maximum charging level (lines 15-20), it is checked that the maximum SoE for that prosumer is not exceeded by just adding the maximum charge quantity (line 15); if the maximum SoE is surpassed, the feasible amount is stored in the battery and the remaining amount is exported (lines 19-20).

- In case of deficit (from line 22 to 36) it is checked if it is possible to balance the entire amount of the deficit of energy by discharging the battery of that particular building for of the based on the maximum discharging level for a time-step (line 23).

  - If the quantity does not exceed the maximum discharging level (lines 24-29), it is checked that the minimum SoE for that prosumer (corresponding to 20% of the battery capacity) is not exceeded (line 24); if this value is surpassed, the feasible amount is drawn from the battery to be used and the remaining amount is imported (lines 25-26).
  - If the quantity exceeds the maximum discharging level (lines 31-36), it is checked that the minimum SoE for that prosumer is not exceeded by withdrawing the maximum discharge quantity (line 31); if the minimum SoE is surpassed, the feasible amount is withdrawn from the battery and the remaining amount is imported (lines 19-20).

3.5.3 Optimized (global) strategies

The MGs can have different objectives (minimize the exchange with the main grid or minimize the total cost) and centrally (respect to the MG) coordinated energy scheduling (microgrid global optimization) is considered

in this case. Depending on the strategy (operational objectives), a different energy scheduling problem is formulated and solved.
The optimisation strategies are addressed to the single microgrid, foreseeing energy exchanges only between prosumers within the same microgrid and not between those belonging to different microgrids; outside the cluster there are exchanges only with the DSO and the microgrids do not cooperate with each other. We are not looking at individual prosumer exchanges within a microgrid and we assume that they all cooperate because, otherwise, there should be a rationale about what should be doe with surplus of money of the microgrid, how should that be distributed to individual prosumers and which prosumers are willing to exchange energy with others. This problem is solved by the MG-EMS of each individual MG. However, the solution can also be affected (or even directly dispatched) by the DMS of the DSO depending on the level of interaction between the MGs and the DSO (in our case the only interaction consist in communicating the energy prices).

3.5.3.1 General constraints

MG energy balance In 3.3, C is the set/cluster of prosumers in that microgrid, p^{im} and p^{ex} are its import and export. For each prosumer j, b^{ch}, b^{dis} respectively refer to the charging/discharging of his battery, p^{PV} is his photovoltaic energy production and p^{C} is his energy consumption. This constraint is necessary to ensure that the energy balance in the individual microgrid is maintained.

$$\sum_{j \in C} (p^{PV}_{j,t} - p^{C}_{j,t} - b^{ch}_{j,t} + b^{dis}_{j,t}) + p^{im} - p^{ex} = 0 \tag{3.3}$$

BES scheduling The BES model that has been most frequently used in the latest literature on BES scheduling (for [7]) assumes that the SoE of the BES at each time step is linearly dependent on the cumulative BES throughput of the previous time steps. This model is described by the following equations:

$$soe_{j,t} = soe_{j,t-1} + b^{ch}_{j,t-1} - b^{dis}_{j,t-1}, \forall j \in C \tag{3.4}$$

$$SoE_j^{min} < soe_{j,t} < SoE_j^{max}, \forall j \in C \tag{3.5}$$

$$0 \leq b_j^{ch} \leq k_j^{ch}, \forall j \in C \tag{3.6}$$

$$0 \leq b_j^{dis} \leq k_j^{dis}, \forall j \in C \tag{3.7}$$

$$b_{j,t}^{ch} * b_{j,t}^{dis} = 0, \forall j \in C \tag{3.8}$$

In the above formulation, C is the set/cluster of prosumers in that microgrid, k^{ch}, k^{dis} denotes the maximum charging/discharging power according to the specifications of the battery manufacturer. Moreover, b^{ch}, b^{dis} respectively refer to the charging/discharging of the battery, SoE is the state-of-energy, which must lie between the lower and upper limit (SoE^{min} and SoE^{max}, respectively). It is also noticeable that the battery of a prosumer can only be charged or discharged in a time step, is impossible having both values different than 0.

3.5.3.2 Objective functions

Minimum exchange strategy In this case the objective function is the energy exchange minimization and is related to the desired level of interaction between the single microgrid and the main grid (as the microgrids do not cooperate with each other).

$$min(p^{im} + p^{ex}) \tag{3.9}$$

In 3.9, p is the power imported im and exported ex in that microgrid that wants to minimize its energy exchange. These two variables are the resulting value for the entire microgrid after the energy deficits and surpluses of the prosumers within it have been aligned and possibly compensated for by charging and/or discharging the batteries.

Minimum cost strategy In this case the objective function is cost minimization for the single microgrid, which can alternatively be formulated as profit maximization, and is related to economic operation targets.

$$min(p^{im} * P^{SLOT^{im}} - p^{ex} * P^{SLOT^{ex}}) \tag{3.10}$$

In 3.10, p is the power imported im and exported ex in that microgrid that wants to minimize its cost/maximize its profit and P^{SLOT} is the price, given by the main grid for import im and export ex. Also in this case p^{im} and p^{ex} are the resulting value for the entire microgrid after the energy deficits and surpluses of the prosumers within it have been aligned and possibly compensated for by charging and/or discharging the batteries, with the goal of minimizing the cost.

3.6 Evaluation metrics

In order to evaluate the project, we consider in different scenarios the differences between the global optimisation strategies and the local BAU strategy. For example, in the case of minimizing cost / maximizing profit, the cost incurred by the microgrid in case of adoption of the global strategy will be compared with the cost sustained in case of BAU. Different configurations for the algorithms and their impact on the final performance (e.g. solving times) will also be compared.

Algorithm 1: BAU local algorithm

Data: $prevBatterySoe, batteryCapacity, maxCharging, maxDischarging, production, consumption$
Result: $export, import, newBatterySoe$

```
1  diff ← production − consumption;
2  import ← 0 ;
3  export ← 0 ;
4  newBatterySoe ← 0;
5  if diff > 0 then
6      charging ← diff;
7      if charging < maxCharging ∗ batteryCapacity then
8          if (prevBatterySoe + charging) < 0.8 ∗ batteryCapacity then
9              newBatterySoe ← prevBatterySoe + charging;
10             export ← 0;
11         else
12             newBatterySoe ← 0.8 ∗ batteryCapacity;
13             export ← charging − (newBatterySoe − prevBatterySoe);
14     else
15         if (prevBatterySoe + (maxCharging ∗ batteryCapacity)) <
            0.8 ∗ batteryCapacity then
16             newBatterySoe ←
                prevBatterySoe + (maxCharging ∗ batteryCapacity);
17             export ← charging − (maxCharging ∗ batteryCapacity);
18         else
19             newBatterySoe ← 0.8 ∗ batteryCapacity;
20             export ← charging − (newBatterySoe − prevBatterySoe);
21 else
```

```
(21)
(22)  discharging ← −1 ∗ diff;
(23)  if discharging < maxDischarging ∗ batteryCapacity then
(24)      if (prevBatterySoe − discharging) < 0.2 ∗ batteryCapacity
           then
(25)          newBatterySoe ← 0.2 ∗ batteryCapacity;
(26)          import ←
               discharging − (prevBatterySoe − newBatterySoe);
(27)      else
(28)          newBatterySoe ← prevBatterySoe − discharging;
(29)          import ← 0;
(30)  else
(31)      if
           (prevBatterySoe − (maxDischarging ∗ batteryCapacity)) <
           0.2 ∗ batteryCapacity then
(32)          newBatterySoe ← 0.2 ∗ batteryCapacity;
(33)          import ←
               discharging − (prevBatterySoe − newBatterySoe);
(34)      else
(35)          newBatterySoe ←
               prevBatterySoe − (maxDischarging ∗ batteryCapacity);
(36)          import ←
               discharging − (maxDischarging ∗ batteryCapacity);
```

Chapter 4

Implementation

This chapter describes the implementation of the designed solution described in the previous chapter. First of all, there is an overview of the technologies used, from the development environment to the programming languages, both edge and cloud side. Then the chosen software architecture is presented and finally the individual interaction mechanisms between the components are explained.

4.1 Development environment

For the development of the project Eclipse IDE for Java Developers has been used. In our case, it has been chosen firstly for the possibility of using different languages thanks to the plug-ins and secondly for the presence of the "Remote System Explorer" tool which, by supporting SSH connections, has made it possible to carry out the development phase directly on the servers in a more user-friendly manner, speeding up and simplifying the procedures. In addition to the programming language Node.js (see Sec. 4.2.2), Java and Python were also used.

4.2 Technologies used for the edge unit

4.2.1 Jetson Nano Developer Kit

The NVIDIA Jetson Nano development kit 4.1 is a small, powerful computer that enables multiple neural networks to run in parallel for applications such as image classification, object recognition, segmentation and speech processing. At 70 x 45 mm, the Jetson Nano-Module is the smallest Jetson device. It has four USB 3.0 ports for peripherals, HDMI and display-port connectors, a Micro-USB port to supply power or allow remote operation, an Ethernet port, two ribbon connectors for attaching Raspberry Pi-compatible camera modules, and a barrel jack socket for providing the additional power needed for intensive computations [40].
It has been used as edge unit for sensor connection, computation and machine learning inference.

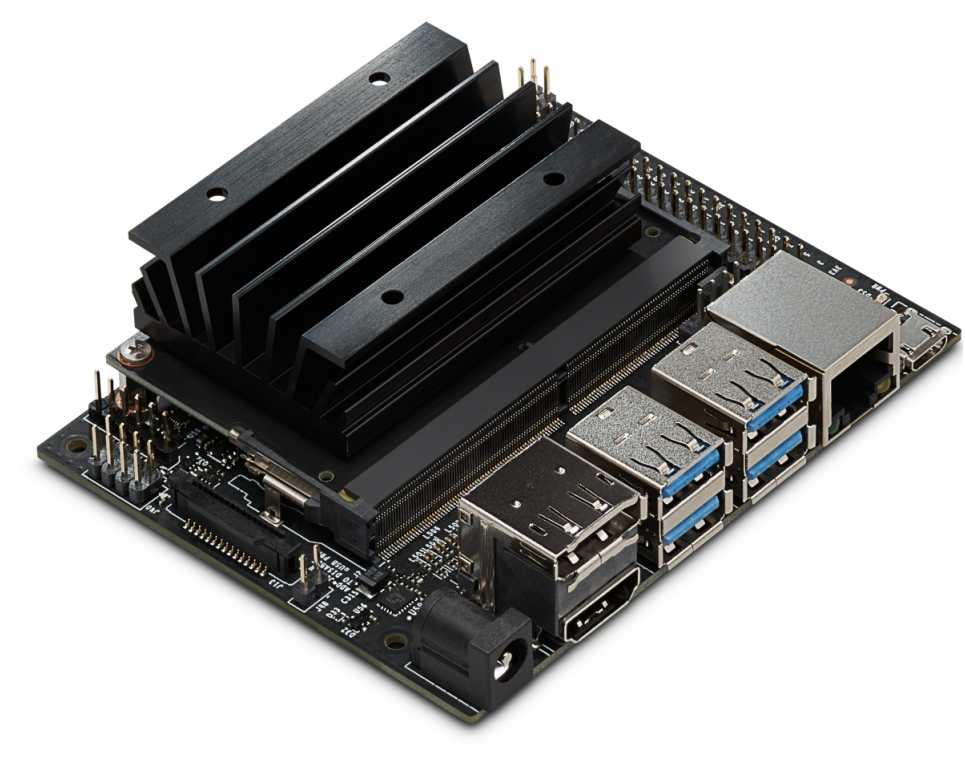


Figure 4.1: NVIDIA Jetson Nano Developer Kit.

4.2.2 Node.js

Node.js is an open-source, cross-platform, back-end JavaScript runtime environment that runs on the Chrome V8 engine and executes JavaScript code outside a web browser. Node.js lets developers use JavaScript to write command line tools and for server-side scripting—running scripts server-side to produce dynamic web page content before the page is sent to the user's web browser. Consequently, Node.js represents a "JavaScript everywhere" paradigm, unifying web-application development around a single programming language, rather than different languages for server-side and client-side scripts.

Node.js allows the creation of Web servers (primary use) and networking tools using JavaScript and a collection of "modules" that handle various core functionalities. Modules are provided for file system I/O, networking (DNS, HTTP, TCP, TLS/SSL, or UDP), binary data (buffers), data streams, and other core functions. Node.js's modules use an API designed to reduce the complexity of writing server applications [41].

4.2.3 TensorFlow

TensorFlow, is an end-to-end open source platform for machine learning. It allows to create dataflow graphs structures that describe how data moves through a graph, or a series of processing nodes. Each node in the graph represents a mathematical operation, and each connection or edge between nodes is a multidimensional data array, or tensor.

Basically, to develop a deep learning program, a set of graph nodes (operations) and tensors (multidimensional data) must be designed. Tensors are usually created by external data (i.e. the datasets images and annotations) and are processed by the graph nodes to build and train, in this case, a deep neural network [42]. In our case it has been used, together with python for running the ML model for the inference.

4.2.4 MQTT

MQTT (MQ Telemetry Transport or Message Queue Telemetry Transport) is an ISO standard (ISO/IEC PRF 20922) lightweight publish-subscribe messaging protocol placed on top of TCP/IP. It is designed for situations where low impact is required and where bandwidth is limited [43]. The MQTT protocol defines two types of network entities: a message broker and a number of clients. An MQTT broker is a server that receives all messages from the clients and then routes the messages to the appropriate destination clients. An MQTT client is any device (from a micro controller up to a fully-fledged server) that runs an MQTT library and connects to an MQTT broker over a network.

Information is organized in a hierarchy of topics. When a publisher has a new item of data to distribute, it sends a control message with the data to the connected broker. The broker then distributes the information to any clients that have subscribed to that topic. The publisher does not need to have any data on the number or locations of subscribers, and subscribers, in turn, do not have to be configured with any data about the publishers. If a broker receives a message on a topic for which there are no current subscribers, the broker discards the message unless the publisher of the message designated the message as a retained message. A retained message is a normal MQTT message with the retained flag set to true. The broker stores the last retained message and the corresponding QoS for the selected topic. Each client that subscribes to a topic pattern that matches the topic of the retained message receives the retained message immediately after they subscribe. The broker stores only one retained message per topic. This allows new subscribers to a topic to receive the most current value rather than waiting for the next update from a publisher. Clients only interact with a broker, but a system may contain several broker servers that exchange data based on their current subscribers' topics [44].

4.3 Technologies used in the cloud

4.3.1 Kubernetes and Docker

Kubernetes (abbreviated K8s) is an open-source container orchestration and management system. Initially developed by Google, it is now maintained by the Cloud Native Computing Foundation. It works with many containerisation systems, including Docker. Kubernetes is software made up of several software components arranged according to the orchestrator pattern. This pattern distinguishes participants into masters and nodes. They coordinate the execution of the workload on the servers that form a cluster controlled by Kubernetes.

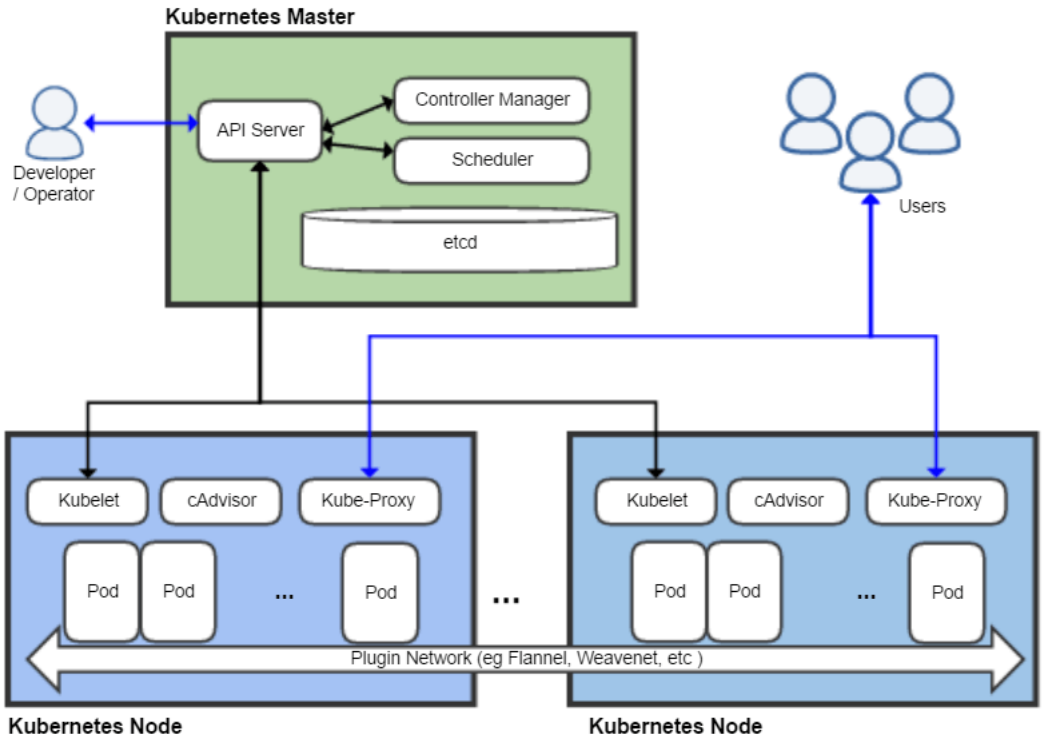


Figure 4.2: Architecture of a Kubernetes cluster.

Fig. 4.2 shows the architecture of a cluster, in the case of this project only one cluster was developed, with two worker nodes and one master node. The pod is the resource describing the elementary unit executable on a cluster node. A pod groups containers that share resources and run on the same node. The pod abstracts network and storage in order to be easily moved and replicated on cluster nodes, allowing strong horizontal scalability, especially for microservice oriented applications.
Pods can be managed manually via Kubernetes APIs or more frequently via controllers that ensure their execution is maintained [45] [46].

Docker is an open-source project that automates the deployment (delivery or release to the customer, with associated installation and commissioning or operation, of an application or software system typically within an enterprise information system) of applications within software containers, providing an additional abstraction through virtualization at the Linux operating system level [47]. Docker uses Linux kernel resource isolation features such as cgroup and namespace to allow independent "containers" to coexist on the same Linux instance, avoiding installation and maintenance.
Docker implements high-level APIs to manage containers that run processes in isolated environments [48]. Because it uses Linux kernel functionality (primarily cgroup and namespaces), a Docker container, unlike a virtual machine, does not include a separate operating system [49]. Instead, it uses kernel functionality and leverages resource isolation (CPU, memory, block I/O, network) and separate namespaces to isolate what the application can see of the operating system. So is supported having multiple containers with different application requirements and dependencies to run on the same host, as long as they have the same operating system requirements.

According to industry analysis firm 451 Research, "Docker is a tool that can package an application and its dependencies into a virtual container that can run on any Linux server" [49].

Using Docker to create and manage containers can simplify the creation of distributed systems, allowing different applications or processes to work

autonomously on the same physical machine or on different virtual machines.

4.3.2 IoT managing platform - ThingsBoard

First of all ThingsBoard is presented and then some other existing platforms specialised in managing, processing and monitoring data and devices from the IoT are described. For example, classical databases cannot be relied upon because we are talking about much larger data volumes.

ThingsBoard is an open-source IoT platform that enables rapid development, management, and scaling of IoT projects. It provides an out-of-the-box IoT cloud that enable server-side infrastructure for IoT applications, offering device management, data collection, visualization, and processing. The platform integrates fault-tolerance, production and scalability.
With ThingsBoard, is possible to:

- Provision devices, assets and customers, and define relations between them.
- Collect and visualize data from devices and assets.
- Analyze incoming telemetry and trigger alarms with complex event processing.
- Control devices using remote procedure calls (RPC).
- Build work-flows based on a device life-cycle event, REST API event, RPC request, etc.
- Design dynamic and responsive dashboards and present device or asset telemetry and insights to your customers.
- Enable use-case specific features using customizable rule chains.
- Push device data to other systems.

More specifically, as showed in Fig. 4.3, TB provides a rich set of features related to telemetry data [8]:

- Collect data from devices using MQTT, CoAP, or HTTP protocols;
- Store time series data in Cassandra (efficient, scalable, and fault-tolerant NoSQL database);
- Query the latest time series data values or all data within the specified time-frame;
- Subscribe to data updates using WebSockets (for visualization or real-time analytics);
- Visualize time series data using configurable and highly customizable widgets and dashboards.

Here below is presented a deeper explanation of the features of TB used in this project.

4.3.2.1 Entities and relations

ThingsBoard provides the user interface and REST APIs to provision and manage multiple entity types and their relations in an IoT application. The supported entities of our interest are:

- Devices: basic IoT entities that may produce telemetry data and handle RPC commands. For example, sensors, actuators, switches;
- Assets: abstract IoT entities that may be related to other devices and assets. For example factory, field, vehicle;
- Dashboards: visualization of IoT data and ability to control particular devices through the user interface;

Each entity supports:

- Attributes: static and semi-static key-value pairs associated with entities. For example serial number, model, firmware version;

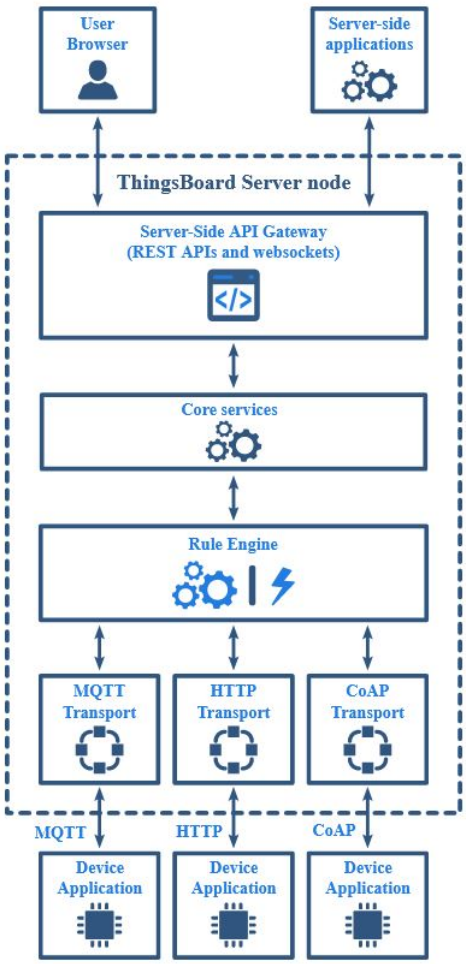


Figure 4.3: High-level ThingsBoard architecture overview.

- Telemetry data: time-series data points available for storage, querying and visualization. For example temperature, humidity, battery level;

- Relations: directed connections to other entities. For example contains, manages, owns, produces.

In our case the microgrids (Assets) contain various boards (Devices), see Fig. 4.4.

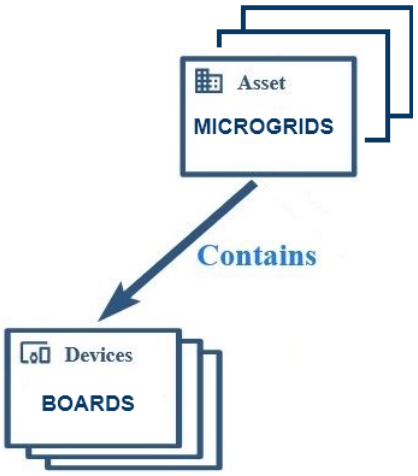


Figure 4.4: ThingsBoard Assets - Devices relations in our use case [8].

4.3.2.2 Dashboards

ThingsBoard provides the ability to create and manage Dashboards. Each Dashboard may contain plenty of widgets (e.g. Fig. 4.5) and display data from many entities: devices, assets, etc.

4.3.2.3 Rule Engine

Rule Engine is an easy to use framework for building event-based workflows. There are 3 main components:

- Message: any incoming event. It can be an incoming data from devices, device life-cycle event, REST API event, RPC request, etc.
- Rule Node: a function that is executed on an incoming message. There are many different Node types that can filter, transform or execute some action on incoming Message.
- Rule Chain: nodes are connected with each other with relations, so the outbound message from rule node is sent to next connected rule nodes.

Here are some common use cases that one can configure via ThingsBoard Rule Chains:

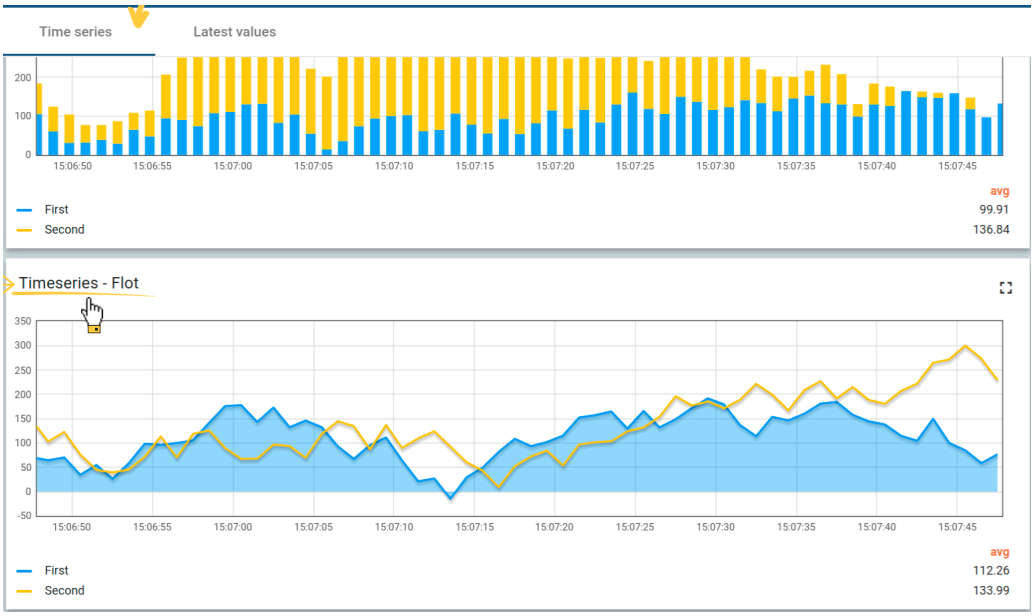


Figure 4.5: Widget example [8].

- Data validation and modification for incoming telemetry or attributes before saving to the database.
- Trigger actions based on device life-cycle events. For example, create alerts if Device is Online/Offline.
- Load additional data required for processing. For example, load temperature threshold value for a device that is defined in Device's Customer or Tenant attribute.
- Trigger REST API calls to external systems.
- Send emails when complex event occurs and use attributes of other entities inside Email Template.
- Integrate with external pipelines like Kafka, Spark, AWS services, etc.

4.3.2.4 REST Client

The ThingsBoard REST API Client helps you interact with ThingsBoard REST API from your Java application, with Rest Client you can program-

matically create assets, devices, customers, users and other entities and their relations in ThingsBoard [8].

4.3.2.5 Others IoT platforms

Astarte Astarte is an Open Source IoT platform focused on Data management. It takes care of everything from collecting data from devices to delivering data to end-user applications.
Ii is an Open Source IoT platform written in Elixir and it is a turnkey solution which packs in everything needed for connecting a device fleet to a set of remote applications. It performs data modeling, automated data reduction and real-time events.
Although Astarte's main supported protocol is MQTT, Astarte can work with any transport which provides a mean of authentication/authorization and can be mapped to a key/value paradigm. Astarte can be used with CoAP, HTTP and pretty much any protocol. And being Open Source, developers can implement their favorite protocol or wrapper, and have Astarte work with it seamlessly.

InfluxDB InfluxDB is an open-source time series database (TSDB) developed by InfluxData. It is written in Go and optimized for fast, high-availability storage and retrieval of time series data in fields such as operations monitoring, application metrics, Internet of Things sensor data, and real-time analytics [50].
InfluxDB has no external dependencies and provides an SQL-like language with built-in time-centric functions for querying a data structure composed of measurements, series, and points. Each point consists of several key-value pairs called the fieldset and a timestamp. When grouped together by a set of key-value pairs called the tagset, these define a series [51].

Grafana Grafana is a multi-platform open source analytics and interactive visualization web application. It provides charts, graphs, and alerts for the web when connected to supported data sources.
As a visualization tool, Grafana is a popular component in monitoring stacks,

often used in combination with time series databases such as InfluxDB; monitoring platforms and other data sources [52].

4.3.3 Kafka as message broker

Apache Kafka is an open-source stream-processing software platform developed by the Apache Software Foundation, written in Scala and Java. The project aims to provide a unified, high-throughput, low-latency platform for handling real-time data feeds. Kafka can connect to external systems (for data import/export) via Kafka Connect and provides Kafka Streams, a Java stream processing library. Kafka uses a binary TCP-based protocol that is optimized for efficiency and relies on a "message set" abstraction that naturally groups messages together to reduce the overhead of the network roundtrip.
Apache Kafka is based on the commit log, and it allows users to subscribe to it and publish data to any number of systems or real-time applications [9].

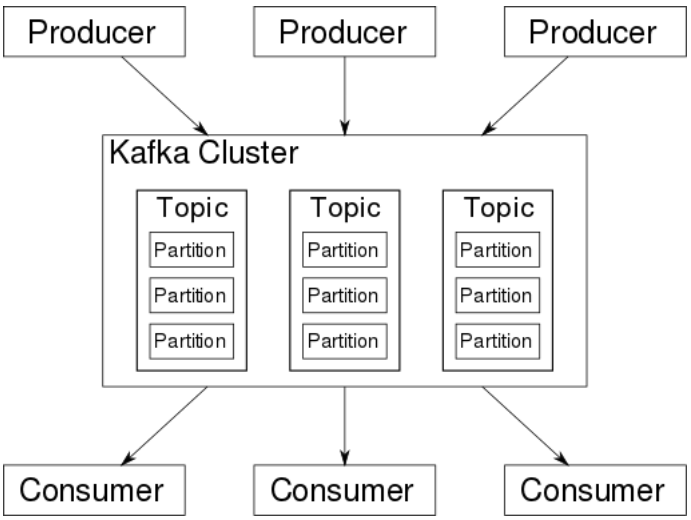


Figure 4.6: Overview of Apache Kafka [9]

As showed in Fig. 4.6, Kafka stores key-value messages that come from arbitrarily many processes called producers. The data can be partitioned into different "partitions" within different "topics". Within a partition, messages

are strictly ordered by their offsets (the position of a message within a partition), and indexed and stored together with a timestamp. Other processes called "consumers" can read messages from partitions. For stream processing, Kafka offers the Streams API that allows writing Java applications that consume data from Kafka and write results back to Kafka.
Kafka runs on a cluster of one or more servers (called brokers), and the partitions of all topics are distributed across the cluster nodes. Additionally, partitions are replicated to multiple brokers. This architecture allows Kafka to deliver massive streams of messages in a fault-tolerant fashion.

4.3.3.1 Kafka Streams or Streams API

In a modern context, where speed of data processing seems to be the most functional approach in the management of many services, Kafka Streams offers itself as one of the most performing and scalable solutions. In fact, it goes beyond a Batch data processing model, performed in the background and at predefined intervals. It provides real-time data processing and enrichment, while ensuring robustness and ease of use.

This API converts the input streams to output and produces the result; allows for the development of stateful stream-processing applications that are scalable, elastic, and fully fault-tolerant. The main API is a stream-processing domain-specific language (that offers high-level operators like filter, map, grouping, windowing, aggregation, joins, and the notion of tables).

4.3.4 Node.js

Node.js programming language is also used in the cloud programming as in the case of the edge unit, see Sec. 4.2.2.

4.3.5 OptaPlanner

OptaPlanner is an Open Source AI Constraint Solver. It solves constraint satisfaction problems with construction heuristics and metaheuristic algo-

rithms, using multithreaded incremental solving [53].
It is a lightweight, embeddable engine which optimizes planning problems. A planning problem has an optimal goal, based on limited resources and under specific constraints. Optimal goals can be any number of things, such as: maximized profits (the optimal goal results in the highest possible profit), minimized ecological footprint (the optimal goal has the least amount of environmental impact), maximized satisfaction for employees or customers (the optimal goal prioritizes the needs of employees or customers); the ability to achieve these goals relies on the number of resources available, such as: the number of people, amount of time, budget, etc.
Specific constraints related to these resources must also be taken into account, such as the number of hours a person works, their ability to use certain machines, or compatibility between pieces of equipment.

OptaPlanner is able to solve constraint satisfaction problems efficiently by combining optimization heuristics and metaheuristics with very efficient score calculation.
Usually, a planning problem has at least two levels of constraints: a (negative) hard constraint that must not be broken (e.g. 1 teacher cannot teach 2 different lessons at the same time) and a (negative) soft constraint that should not be broken if it can be avoided (e.g. teacher A does not like to teach on Friday afternoon). Some problems have positive constraints too, a positive soft constraint (or reward) should be fulfilled if possible (e.g. teacher B likes to teach on Monday morning).
These constraints define the score calculation (AKA fitness function) of a planning problem. Each solution of a planning problem can be graded with a score. With OptaPlanner, score constraints are written in an Object Oriented language, such as Java code or Drools rules. Such code is easy, flexible and scalable.

A planning problem has a number of solutions. There are several categories of solutions:

- A possible solution is any solution, whether or not it breaks any number

of constraints. Planning problems tend to have an incredibly large number of possible solutions, many of those solutions are worthless.

- A feasible solution is a solution that does not break any (negative) hard constraints. The number of feasible solutions tends to be relative to the number of possible solutions, sometimes there are no feasible solutions (every feasible solution is a possible solution).

- An optimal solution is a solution with the highest score. Planning problems tend to have 1 or a few optimal solutions. There is always at least 1 optimal solution, even in the case that there are no feasible solutions and the optimal solution is not feasible.

- The best solution found is the solution with the highest score found by an implementation in a given amount of time. The best solution found is likely to be feasible and, given enough time, it's an optimal solution.

Counterintuitively, the number of possible solutions is huge (if calculated correctly), even with a small dataset. As there is no silver bullet to find the optimal solution, any implementation is forced to evaluate at least a subset of all those possible solutions.

OptaPlanner supports several optimization algorithms to efficiently wade through that incredibly large number of possible solutions. Depending on the use case, some optimization algorithms perform better than others, but it's impossible to tell in advance. With OptaPlanner, it is easy to switch the optimization algorithm, by changing the solver configuration in a few lines of XML or code [10].

The Fig. 4.7 shows the solving process: a construction heuristic builds a pretty good initial solution in a finite length of time, its solution isn't always feasible but it finds it fast, and metaheuristics can finish the job. The algorithms used by default are:

- First Fit regarding the Construction Heuristics phase: the First Fit algorithm cycles through all the planning entities (in default order),

initializing one planning entity at a time, it assigns the planning entity to the best available planning value, taking the already initialized planning entities into account. It terminates when all planning entities have been initialized and it never changes a planning entity after it has been assigned. A construction heuristics terminate automatically, so there's usually no need to configure a Termination on the construction heuristic phase specifically.

- Late Acceptance (Meta Heuristic) for the Local Search phase: heuristics are often problem-dependent (an heuristic is defined for a given problem), metaheuristics are problem-independent techniques that can be applied to a broad range of problems.
  Local Search starts from an initial solution and evolves that single solution into a mostly better and better solution. It uses a single search path of solutions, not a search tree. At each solution in this path it evaluates a number of moves on the solution and applies the most suitable move to take the step to the next solution. It does that for a high number of iterations until it's terminated (usually because its time has run out).
  Late Acceptance (also known as Late Acceptance Hill Climbing) also evaluates only a few moves per step. A move is accepted if does not decrease the score, or if it leads to a score that is at least the late score (which is the winning score of a fixed number of steps ago)[10].

4.4 Actual system architecture

The MAPE-K (Monitor-Analyze-Plan-Execute over a shared Knowledge) loop is the most influential reference control model for autonomic and self-adaptive systems. Here in Fig. 4.8 is presented how this can be applied to our system:

- Monitoring: pushing data from edge-devices to TB in the cloud with the simulator.

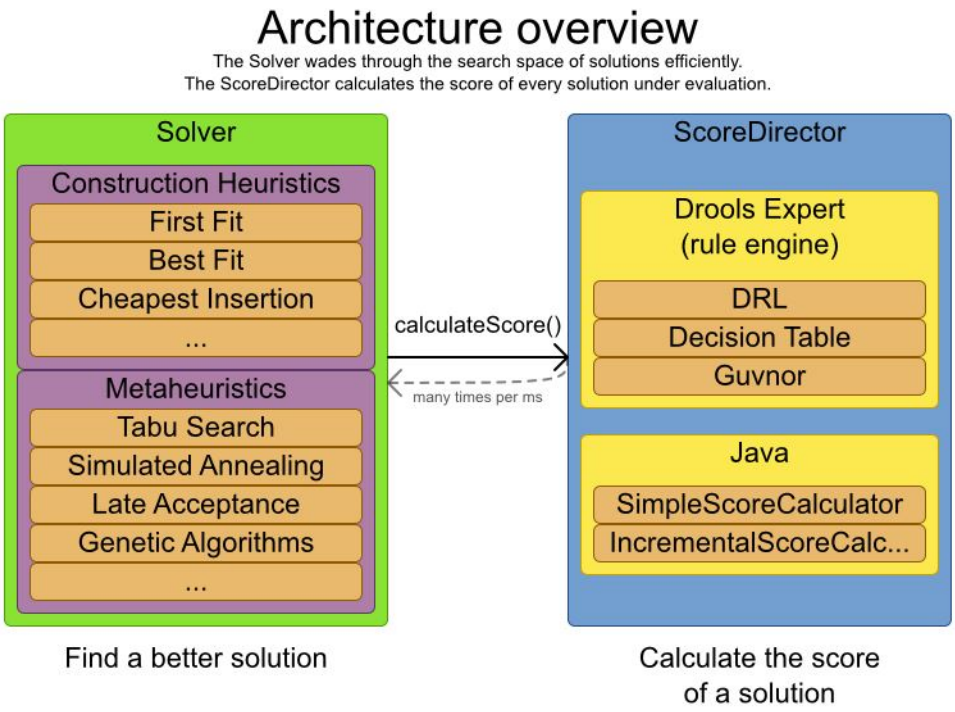


Figure 4.7: OptaPlanner solving process. [10]

- Analyzing: pre-processing with Kafka Stream aggregator together with python consumer.
- Planning: Algorithms caller and OptaPlanner optimizer.
- Executing: Algorithm caller sends instructions to edge units.
- Shared Knowledge: Thingsboard stores the values and could implement machine learning on data to pre-plan better actions.

The Fig. 4.9 shows the final software architecture, after choosing the technologies for the components and the types of interaction between them. The first component to come into play is the ThingsBoard REST Client that has the duty to create the elements representing our case in the abstract (Devices as boards, Assets as microgrids and Dashboards) within ThingsBoard; once inserted and obtained the access credentials, it is the turn of the data simulator that generates consumption and production values (following patterns according to the prosumer typology, see 3.3.2) for real-time data and

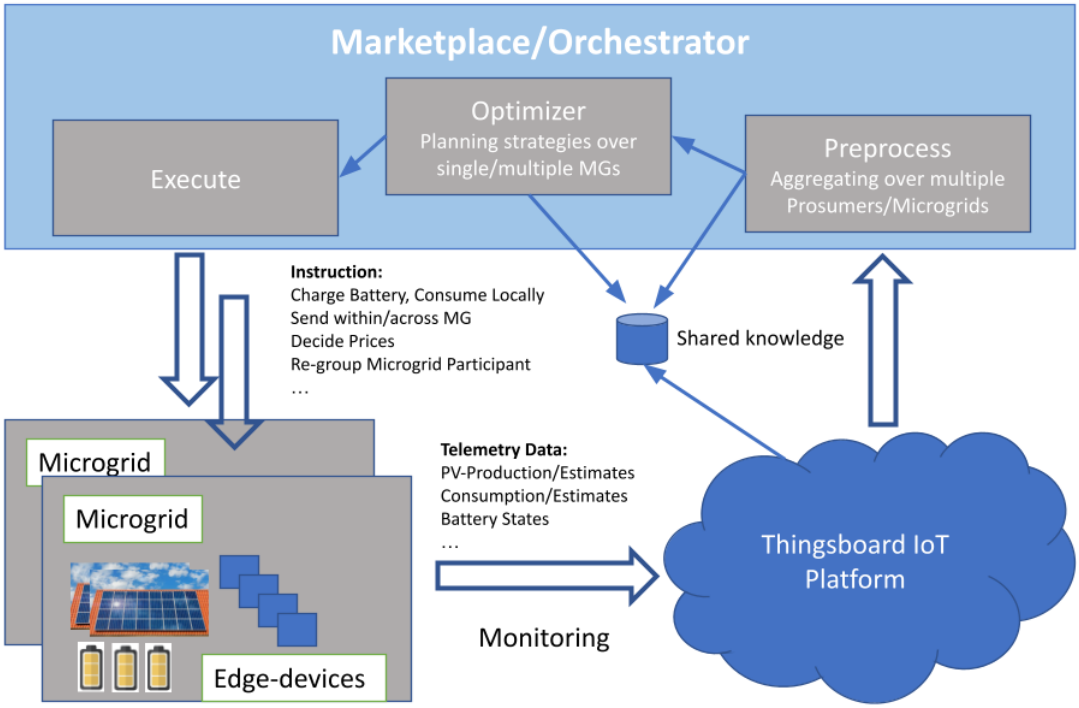


Figure 4.8: MAPE-K loop in the actual system architecture.

the data of future consumption, while inferring (through ML) the data on future production.

When ThingsBoard receives the data from the devices, it forwards them to the Kafka broker, to which an application is connected that, intercepting the stream of timeseries, aggregates them according to the device and the microgrid to which it belongs.

To this out-topic of Kafka is subscribed a consumer that, first of all, publishes on TB the aggregated real-time data for production and consumption of each microgrid (so that we can observe the trend in the dashboards) and, after that, depending on the chosen strategy decides whether to use the algorithms for the optimization of energy scheduling in OptaPlanner and communicate the decisions taken on the batteries to the boards via RPC or whether to communicate directly the values of import and export to ResultsTracker that will store them on CSV files.

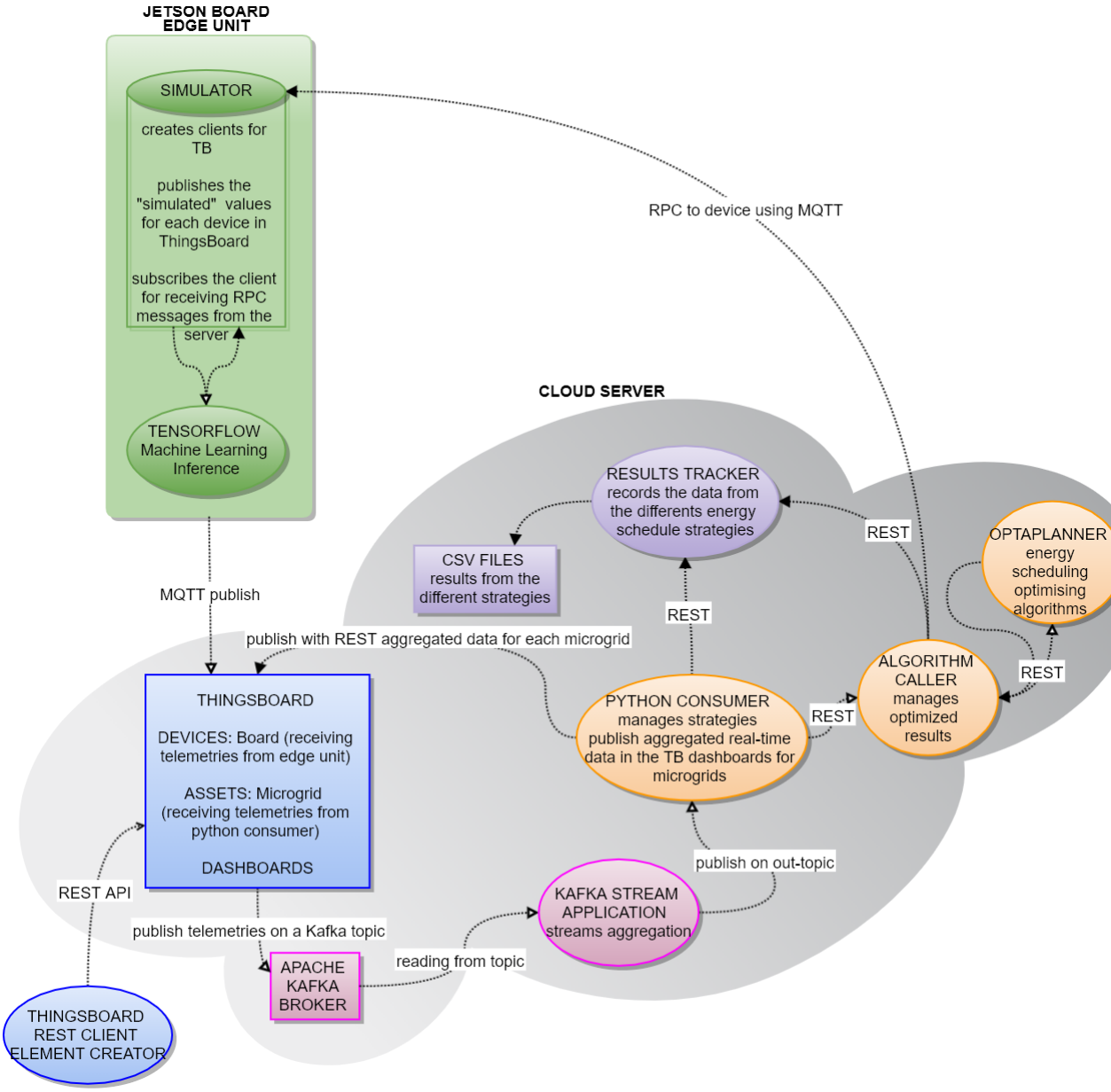


Figure 4.9: Actual system architecture with used technologies.

4.5 Data simulation

In order to simulate a data flow in our system, as we did not have several boards with their respective sensors, we decided to create some scripts capable of simulating the devices and the reading of the data of our interest from the sensors.

4.5.1 Device and Assets creation

Using the ThingsBoard REST API, a Java tool was developed that, taking as input a CSV file containing the necessary information for each board/edge-unit: type of building (residential, hospital, school, etc.) represented and microgrid membership, inserts the boards into ThingsBoard in the form of Devices and microgrids in the form of Assets, then creates the necessary membership relationships. A Dashboard is also automatically created for each asset, which will then be where the total data of the devices for that asset will be displayed.

The main features of the tool are as follows:

- Class `MyAsset`: represents an object of type microgrid, the attributes present are in fact the name of the microgrid and the assetId (subsequently needed as a key to publish via REST the telemetries relating to the asset such as production and total consumption).

- Class `MyDevice`: represents a device type object, the attributes are in fact the name of the microgrid it belongs to, the name of the device itself, the intended use of the building, the existing panel units (useful element to parameterize the simulated data on production), the capacity and the maximum power of charge/discharge of the battery, the accessToken of the device (subsequently needed as a key to publish via MQTT the telemetries related to the device) and the deviceId (subsequently needed as a key to publish via REST the telemetries related to the device).

- Class `ThingsboardElementsCreator`: first of all the CSV file containing the characteristics of the desired boards is read, after which the corresponding Devices are created on Thingsboard, together with the microgrids that are created in the form of Assets, through the REST client; for each Device at the creation the accessToken and the deviceId are assigned, while for the Assets only the assetId. Then the relationships between Devices and Assets are established so that a microgrid contains the correct boards and finally all the information on Device and Asset (in particular the credentials) are saved in CSV files to be used later.

- Class `ThingsboardDashboardCreator`: after reading the asset characteristics (microgrid name and assetId) from the CSV file created as output by ThingsboardElementsCreator, this class is responsible for publishing on Thingsboard a dashboard for each of the assets using a given JSON format dashboard template and modifying the attributes of this JSON for each assets/microgrid.

4.5.2 Consumption and production creation

The script that takes care of this functionality is in JS format and is laid out using NodeJS. To start it reads the content of the two CSV files produced in the previous phase (devices and assets) through the Node module "fs", that is responsible for all the asynchronous or synchronous I/O operations; at the success of the operation it reads the content of the CSV file containing the mean and variance for the production and consumption patterns; these data are then used at the time of the creation of an MQTT client for each board/edge-unit as input for the simulation of data (generating a random number normally distributed) consistent with the building typology.
For the creation of an MQTT client, able to send telemetry to ThingsBoard via MQTT, the accessToken of the device is required; when the connection is successful the consumption and production data are simulated (generating a random number following the normal distribution). Moreover, if the chosen strategy is BAU, the local logic for the energy balance will be applied, as

seen in the previous section and illustrated in the algorithm 1; if the strategy is global, no pre-computation will be done in the board before sending the telemetries to ThingsBoard via MQTT.
A further function of the MQTT client used in this case (except with the BAU strategy) is the ability to receive RPCs (Remote Procedure Calls): the client, immediately after the connection registers to receive messages and defines the actions to be performed following a given communication, in our case the body of the message will contain how much to vary (charge/discharge) the state of battery charge in the next time step.

4.6 ML for inference of production data

With regard to the PV panel production forecasts, introduced in the previously mentioned tool for simulation, an ML model (4-layer bi-directional LSTM [38]) already trained for inference was used, while for consumption forecasts the patterns of the respective prosumers are used. The input of the inference is the production data of the previous 15 minutes with a granularity of 30 seconds (so 30 data-points), the same for the output produced.
The Python support file inference.py uses the Tensorflow module to load the model (this can be done once) while the simulator invokes a specific inference function (the loaded model predicts the data based on the input) at the beginning of each time step (5 minutes), in order to obtain the prediction information for time step +2 to be attached to the following telemetry.

4.7 ThingsBoard telemetries collection and processing

When receiving telemetries, Thingsboard follows the so-called "Root rule chain": the basic rule chain in which all messages arrive. As shown in Fig. 4.10, telemetries once saved are forwarded to Kafka broker as stream with the predefined topic, simply by adding a node and configuration to the rule chain.

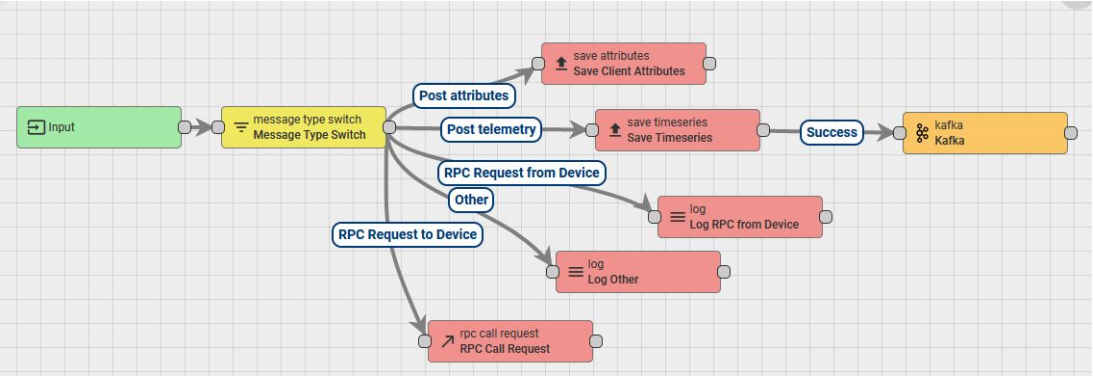


Figure 4.10: Root rule chain forwarding to Kafka stream.

4.8 Kafka stream aggregator application

A Maven application was deployed in the cloud to manage the stream of telemetries. Kafka broker receives the messages for a certain topic (in our case we record the stream for the same topic outgoing from ThingsBoard). The application must then first deserialize the message, save the content as an object, aggregate the data in the chosen range, reserialize the output and publish it in the out-topic.

In detail, the input is given by each telemetry coming from a device, with the following attributes: microgridID, deviceID, consumption, production, energyImport, energyExport, predicted consumption, predicted production, battery capacity, battery state of charge, charging and discharging limit. If the chosen strategy is BAU all these attributes will have a value because they are the result of a pre-computation local to the board (except for predicted consumption and production that are not used because in this case we are not interested in forecasting because prediction is used to decide on the scheduling of prosumer batteries based on the exchanges they have to make within the microgrid, but with the local BAU strategy each prosumer decides autonomously), vice versa for the other strategies energyImport and energyExport will not be initialized because we will refer directly to the global ones of the microgrid once the scheduling problem is optimized.

Regarding aggregation, it is performed according to the key that is declared, in this case the key defined was (microgridID, deviceID); each telemetry pub-

lished as output of the stream in the cloud is therefore the aggregation by device in a 5-minute interval with also the aggregation by microgrid (see the following JSON schema that respects what is specified in the tables 3.2 3.3), consequently the aggregation by microgrid could be redundant.

Listing 4.1: JSON schema of the message for aggregated data about a device

```
"type": "object",
"properties": {
    "microgridID": {"type": "string"},
    "deviceID": {"type": "string"},
    "count": {"type": "number"},
    "sumConsumption": {"type": "number"},
    "sumProduction": {"type": "number"},
    "sumPredictedConsumption": {"type": "number"},
    "sumPredictedProduction": {"type": "number"},
    "sumEnergyImport": {"type": "number"},
    "sumEnergyExport": {"type": "number"},
    "capacity": {"type": "number"},
    "sumStateOfEnergy": {"type": "number"},
    "avgStateOfEnergy": {"type": "number"},
    "chargingLimit": {"type": "number"},
    "dischargingLimit": {"type": "number"},
    "microgridAggregator":
    {   "type": "object",
        "properties": {
            "microgridID": {"type": "string"},
            "count": {"type": "number"},
            "sumConsumption": {"type": "number"},
            "sumProduction": {"type": "number"},
            "sumPredictedConsumption": {"type": "number"},
            "sumPredictedProduction": {"type": "number"},
            "sumEnergyImport": {"type": "number"},
            "sumEnergyExport": {"type": "number"}
```

```
                }
            }
        }
```

It should be noted finally that in order to aggregate all parameters, except for the state of charge of the battery where a mathematical average of the values is made, the data are summed.

4.9 Consumer of the aggregated data

The application that consumes the data from the topic containing the aggregated values has been written in Python (see Python Consumer in Fig.4.9). Once the message is received, it checks that it respects the default JSON schema Lst. 4.1, if not, the content is ignored. If the schema is compliant, the content is parsed and processed:

1. The "properties" of the "microgridAggregator" element are sent with the ThingsBoard REST API to the microgrid assets, to be visualized in a dashboard (see Fig. 4.11), as they represent the aggregation of all the telemetries received for the devices of that microgrid. Since, as explained above, this data is redundant for all aggregated devices, it is sent to ThingsBoard only the first time, to identify the uniqueness of the data the microgridID (formed by the ID of the microgrid and the time-step identifier) is taken into account.

2. (a) In the case where the chosen strategy is BAU type, without having to turn to the optimisation algorithm, the data aggregated by microgrid on import and export are directly sent to the Node service created ResultsTracker which, for the purposes of performance evaluation and comparison, keeps them updated by writing them in a CSV file.

   (b) If the chosen strategy is a global one (minimum cost or minimum exchange), all the aggregated data of the devices present in the same microgrid are collected and sent to the supporting

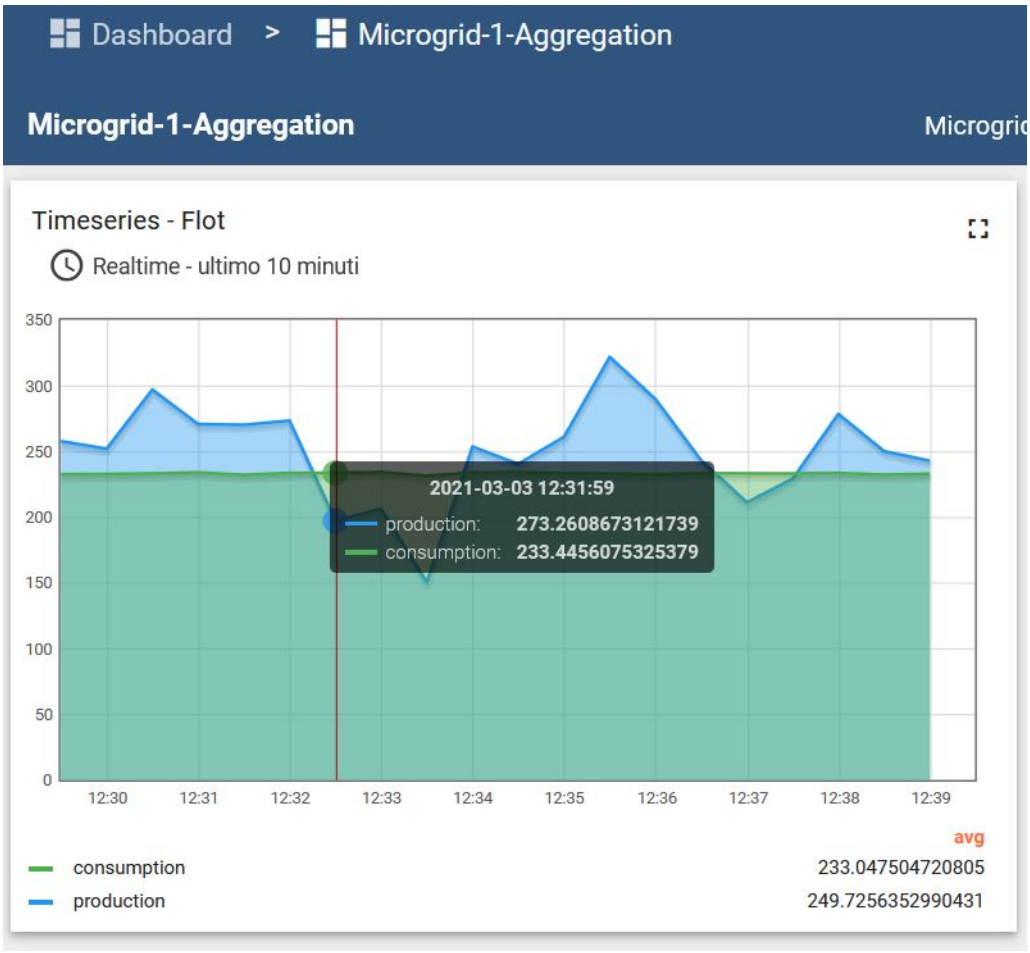


Figure 4.11: Dashboard of a microgrid showing aggregated data of its devices about the last 10 minutes.

Node service AlgorithmCaller so that the latter can manage asynchronously the request to the algorithm in the OptaPlanner application.

4.10 Support web service AlgorithmCaller

This web service exposes a number of APIs, in particular the ability to call the optimisation algorithm on OptaPlanner given the aggregated edge-devices data as input. The endpoint for the request is '/addsolve' and the parameters in the body accepted are the list of prosumer data and the type of strategy

to be used for the algorithm, all in JSON format; once the request is received the service makes the solve enquiry to OptaPlanner sending it also the device data and, at regular intervals, checks if a solution has been found or not: in case of positive outcome the optimised energy scheduling is obtained, otherwise it is tried again after a certain time.
When the solution is found:

1. the results are sent (import and export of the microgrid) to the ResultsTracker service which will update its data;

2. the settings points on how to manage the prosumer's devices (e.g. how to charge/discharge the battery) are sent to the to the prosumer's local controller, via ThingsBoard RPC.

4.11 Energy scheduling optimizer

In our case we have two planning problems that differ in the goal (minimising the total cost incurred by the microgrid or minimising the amount of energy exchanged with the main grid) but have constraints in common (see 3.5.3.1 regarding the energy balance and battery scheduling).

A Maven project has been therefore created in Java using OptaPlanner to solve these planning problems.

First, the classes representing the problem domain were defined (see Fig. 4.12):

- Prosumer: is considered a PlanningEntity, i.e. it varies during the resolution of the problem. Its static attributes are: id of the microgrid it belongs to, id of the device itself, expected consumption and production, battery capacity and charge/discharge limits, battery charge status; while the PlanningVariable is the battery scheduling in the next time-step (charge/discharge and quantity). The energy balance of a prosumer is given by the difference between expected production and consumption to which the battery scheduling is added.

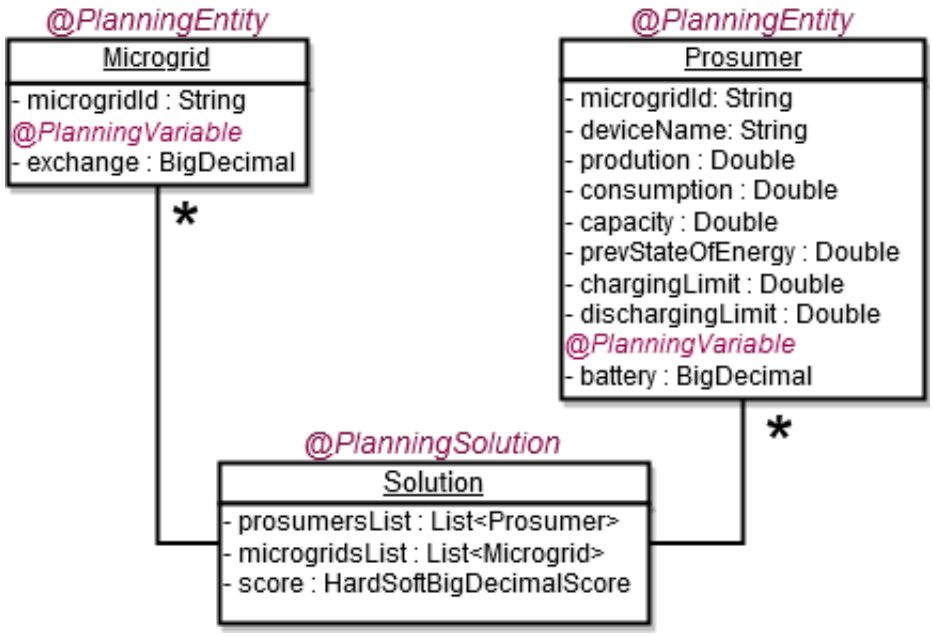


Figure 4.12: Class diagram of the domain model.

- Microgrid: is considered a PlanningEntity, the attribute that varies is the energy exchange while the only other attribute is the identifier of the microgrid itself. A microgrid can contain one or more prosumers.

- Solution: in this class of type PlanningSolution the attributes are the list of microgrids and the list of prosumers as PlanningEntityCollection and the relative score. Here the value ranges for the PlanningVariables of the PlanningEntities are also specified, i.e. the possible values for the prosumers' battery charge/discharge and the amount of energy exchanged between the microgrids and the main grid.

After that, for the "Entity" classes (Microgrid.java and Prosumer.java) repositories were created with Panache Quarkus to give persistence.

For each of the three classes listed above, the possibility of access via REST API to the resource has also been created; the Solution.java class is however the only one which, in addition to the simple REST methods for adding or removing, implements further endpoints such as launching a search

for a solution, displaying it, etc. Through the endpoint "/addAllProsumers" one can, from the outside, add prosumers and microgrids as resources and start the process of solving the energy scheduling problem.

Finally, the MicrogridConstraintProvider.java class contains the implementation of both soft (the goal of the planning problem) and hard (the generic constraints that cannot be broken) constraints.
Below is the code (for illustrative purposes) for the energy balance constraint equal to 0 inside the microgrid:

```
31    Constraint energyBalance(ConstraintFactory
         constraintFactory) {
32        return constraintFactory
33            .from(Prosumer.class)
34            .groupBy(Prosumer::getMicrogridId,
                 ConstraintCollectors.sumBigDecimal(
                 Prosumer::getBalance))
35            .join(Microgrid.class)
36            .filter((microgridId, balance, microgrid) ->
                  {
37                if( microgridId.equals(microgrid.
                     getMicrogridId())
38                && (balance.doubleValue() + microgrid.
                     getExchange().doubleValue() != 0.0) )
                      {
39                  return true;
40                }else {
41                  return false;
42                }
43            })
44                .penalize("energyBalance",
                     HardSoftBigDecimalScore.ONE_HARD);
45    }
```

As it can be seen, the sum of the energy balances of the prosumers is calculated respecting the constraint stated in equation 3.3 (it is not obligatory for each prosumer to be 0 as in the end the overall positive or negative balance of the microgrid is compensated by the import/export of the microgrid itself) and is then compared with the energy exchange value of the microgrid with the main grid, this value must compensate for the balance in order to reach 0; if it is not 0, the HardScore of the solution is penalised by 1 point, going negative. In our use case all solutions with a HardScore equal to 0 are considered feasible solutions, but they are not always optimal.

In order to evaluate which solution is better than another among the feasible ones, the SoftScore is analysed, as an example the code of the goal for the minimum energy exchange strategy is shown:

```
46    Constraint minEnergyExchange(ConstraintFactory
          constraintFactory) {
47        return constraintFactory
48            .from(Microgrid.class)
49            .penalizeBigDecimal("minEnergyExchange",
                  HardSoftBigDecimalScore.ONE_SOFT,
50                    Microgrid::getAbsValExchange );
51    }
```

In this case, as it can be seen, for each microgrid the amount of energy exchanged (import or export) is checked and the SoftScore is penalised by that value; the optimality in this case would be that all the microgrids had an exchange of 0.

4.12 Support web service ResultsTracker

This service has been created in order to have an automated record of the results obtained with both the local BAU scheduling and the global ones, so that they can be compared. Its API exposes an endpoint for each strategy

and when a scheduling solution is received it is temporarily saved in the corresponding support array (one for each strategy). Every 10 seconds it updates the content of the CSV files (one for each strategy) with the import and export values of the supporting arrays.

Chapter 5

Evaluation

This chapter presents the results of the final phase of the project's performance evaluation. First of all, an environment useful only for testing was recreated, then different scenarios of microgrid composition were created, and finally the parameters (briefly introduced in Sect. 3.6), different for each of the strategies according to the objective, were evaluated.

5.1 Scenarios

Three scenarios have been created for testing:

- 2 microgrids with only residential prosumers: with the characteristics shown in Tab. 5.1;
- 2 microgrids with only commercial prosumers: with the characteristics shown in Tab. 5.2;
- 2 microgrids with residential and commercial prosumers together: with the characteristics shown in Tab. 5.3.

We remind that the optimisation strategies are addressed to the single microgrid, foreseeing energy exchanges only between prosumers within the same microgrid and not between those belonging to different microgrids. Outside the cluster there are exchanges only with the DSO.

Microgrid ID	Device ID	Building Type	Panels Units	Battery Capacity	Charging Limit	Discharging Limit
Microgrid-1	Device-1	Residential	1	50	0.4	0.4
Microgrid-1	Device-2	Residential	1	50	0.4	0.4
Microgrid-1	Device-3	Residential	1	50	0.4	0.4
Microgrid-2	Device-4	Residential	1	50	0.4	0.4
Microgrid-2	Device-5	Residential	1	50	0.4	0.4
Microgrid-2	Device-6	Residential	1	50	0.4	0.4

Table 5.1: Microgrids testing scenario 1.

Microgrid ID	Device ID	Building Type	Panels Units	Battery Capacity	Charging Limit	Discharging Limit
Microgrid-1	Device-1	Hotel	70	100	0.4	0.4
Microgrid-1	Device-2	Supermarket	70	100	0.4	0.4
Microgrid-1	Device-3	Mall	70	100	0.4	0.4
Microgrid-2	Device-4	Hospital	230	100	0.4	0.4
Microgrid-2	Device-5	School	120	100	0.4	0.4
Microgrid-2	Device-6	Supermarket	70	100	0.4	0.4

Table 5.2: Microgrids testing scenario 2.

With regard to the prices of energy imported and exported by the microgrid, in our use case we have referred to the Eurostat 2020 statistics and the Eurostat 2020 statistics [54] and to [55].
The EU-27 average price in the first semester of 2020, a weighted average using the most recent (2020) data for electricity consumption by non-household consumers (given that the microgrid is considered a single entity with an overall consumption level higher than residential), was 0.1254 €/kWh (in our case approximated to 0.13 EUR per kWh). As far as energy fed into the grid is concerned, this is valued on average at 0.09-0.10 €/kWh.

Microgrid ID	Device ID	Building Type	Panels Units	Battery Capacity	Charging Limit	Discharging Limit
Microgrid-1	Device-1	Residential	1	50	0.4	0.4
Microgrid-1	Device-2	Residential	1	50	0.4	0.4
Microgrid-1	Device-3	Mall	70	100	0.4	0.4
Microgrid-2	Device-4	Residential	1	50	0.4	0.4
Microgrid-2	Device-5	School	120	100	0.4	0.4
Microgrid-2	Device-6	Supermarket	70	100	0.4	0.4

Table 5.3: Microgrids testing scenario 3.

5.2 Testing dataflow

In order to obtain comparable results in the strategies, we decided to create a standard input for each scenario in order to have the same production and consumption values for each prosumer.
For the set of devices indicated in each of the three different scenarios, the simulator (4.5.2) was then started for a period of one hour, during which the BAU strategy (local decisions to each device) was performed. After the aggregation phase by the Kafka Stream, via the Python consumers, from the aggregated telemetries obtained:

- the summed import and export values for each microgrid were stored by the ResultsTracker (in an external CSV file);
- the consumption and production values were forwarded to the energy scheduler in OptaPlanner to obtain the import and export values also in the two global strategies, also in this case the results were sent to the ResultsTracker.

It should be noted that, running everything at the same time, in the case of the BAU strategy the SoE battery was changed automatically by the device, while with the global strategies instead of changing it with the RPC (which would have affected the changes made in real-time by the local strategy) it was changed in the AlgorithmCaller in the next time-step for each device.

5.3 Results

This section presents the results obtained in the three scenarios, comparing the different strategies.
The outcomes show that just applying an optimisation strategy to a cluster of prosumers is not enough. It is necessary to evaluate the composition of a microgrid in such a way as to have deficits and surpluses roughly balanced between them, which can be done by comparing past production and consumption data for each prosumer, the more balanced they are the better the optimisation will be.
It is also good practice to assess the best battery capacity for each requirement, e.g. if a minimum exchange strategy is to be pursued it is good to have a high storage capacity.

5.3.1 Residential scenario

Regarding the results in the residential scenario (see Tab. 5.4) we can note that the results are not optimized.
This is due to the fact that, as we can already see in the BAU strategy, there is in general no energy surplus in either of the two microgrids.
In the two strategies, initially the deficits of the single prosumers are compensated with the batteries of all the others that have charge available but, since there is never an energy surplus, the batteries are not given the possibility to recharge and these, remaining at the minimum level, have no possibility to exchange energy.
Each prosumer can therefore rely solely on the main grid to import energy and respect the energy balance.

5.3.2 Commercial scenario

Regarding the results in the business scenario (see Tab. 5.5) we can note that:

- With the minimum exchange strategy, an overall reduction in exchanged power was effectively achieved, for both microgrids, compared to the

BAU strategy						
Microgrid ID	Import (kW)	Export (kW)	Exchanged Power (kW)	Cost (€)	Income (€)	Profit (€)
1	1.128	0	1.128	146,64	0,0	-146,64
2	1.043	0	1.043	135,59	0,0	-135,59
Minimum Exchange strategy						
Microgrid ID	Import (kW)	Export (kW)	Exchanged Power (kW)	Cost (€)	Income (€)	Profit (€)
1	1.128	0	1.128	146,64	0,0	-146,64
2	1.043	0	1.043	135,59	0,0	-135,59
Minimum Cost / Maximum Profit strategy						
Microgrid ID	Import (kW)	Export (kW)	Exchanged Power (kW)	Cost (€)	Income (€)	Profit (€)
1	1.128	0	1.128	146,64	0,0	-146,64
2	1.043	0	1.043	135,59	0,0	-135,59

Table 5.4: Results of microgrids testing scenario 1 (residential prosumers only).

sum of imports and exports calculated from the localised policies of the individual prosumers.
The exchanged power of microgrid 2 is optimised (compared to BAU) to a greater extent, as the excess energy produced is used to cover a greater demand in proportion to microgrid 1, where demand is low and therefore the surplus produced (as in the BAU strategy) cannot be used within the cluster and must therefore be exported.
There is also a reduction in costs / increase in profits due to a decrease in the quantity imported.

- Both microgrids also achieved their goal in the case of the minimum cost strategy by reducing imports or, as we can see by comparing the case of microgrid 1 in the minimum exchange strategy and the maximum cost strategy, by increasing exports (discharging the batteries instead

of storing the energy).

BAU strategy						
Microgrid ID	Import (kW)	Export (kW)	Exchanged Power (kW)	Cost (€)	Income (€)	Profit (€)
1	277	20.559	20.836	36,01	2.055,90	2.019,80
2	15.617	13.133	28.750	2.030,21	1.313,30	-716,91
Minimum Exchange strategy						
Microgrid ID	Import (kW)	Export (kW)	Exchanged Power (kW)	Cost (€)	Income (€)	Profit (€)
1	0	20.821	20.821	0,0	2.082,10	2.082,10
2	4.516,5	979,5	5.496	587,14	97,95	-489,19
Minimum Cost / Maximum Profit strategy						
Microgrid ID	Import (kW)	Export (kW)	Exchanged Power (kW)	Cost (€)	Income (€)	Profit (€)
1	0	20.890	20.890	0,0	2.089,90	2.089,90
2	3.737,5	1.302,5	5.040	485,87	130,25	-355,62

Table 5.5: Results of microgrids testing scenario 2 (commercial prosumers only).

5.3.3 Mixed scenario

Regarding the results in the scenario with both residential and commercial prosumers (see Tab. 5.6) we can note that:

- For the minimum exchange strategy, in both microgrids, the overall exchanged power corresponds more or less to the balance that would be obtained in the BAU strategy by subtracting the energy deficit to the surplus (by acting with the BAU locally to each device without having a global overview, it is however impossible to achieve this objective if not with a global strategy such as minimum exchange); profits are also increased.

- As regards profit maximisation, we can say that, again, balancing import (low) and export (high) and selling the stored energy of the batteries (thus not keeping them always at a high level of charge) resulted in a good increase in profits, but increased exchanged power.

BAU strategy						
Microgrid ID	Import (kW)	Export (kW)	Exchanged Power (kW)	Cost (€)	Income (€)	Profit (€)
1	1.010	2.625	3.635	131,3	262,50	131,20
2	929	13.219	14.148	120,77	1.321,90	1201,13
Minimum Exchange strategy						
Microgrid ID	Import (kW)	Export (kW)	Exchanged Power (kW)	Cost (€)	Income (€)	Profit (€)
1	0	1.682,5	1.682,5	0,0	168,25	168,25
2	0	12.271,5	12.271,5	0,0	1.227,15	1.227,15
Minimum Cost / Maximum Profit strategy						
Microgrid ID	Import (kW)	Export (kW)	Exchanged Power (kW)	Cost (€)	Income (€)	Profit (€)
1	13	1.700,5	1.713,5	1,69	170,05	168,81
2	0	12.321	12.321	0,0	1232,10	1232,10

Table 5.6: Results of microgrids testing scenario 3 (mixed types of prosumers).

Moreover, only for this scenario, the graphs in Fig. 5.1 and 5.1 show the aggregated production and consumption values for Microgrid 1 in the considered interval of 1 hour and the exchange values (positive in case of export and negative in case of import) that the microgrid would have if the prosumers did not have any kind of storage device (BES).

The Tab. 5.7 presents the import and export values (and respective costs) of the two microgrids analysed, in the case where prosumers can compensate each other for individual surpluses and deficits but do not have a storage

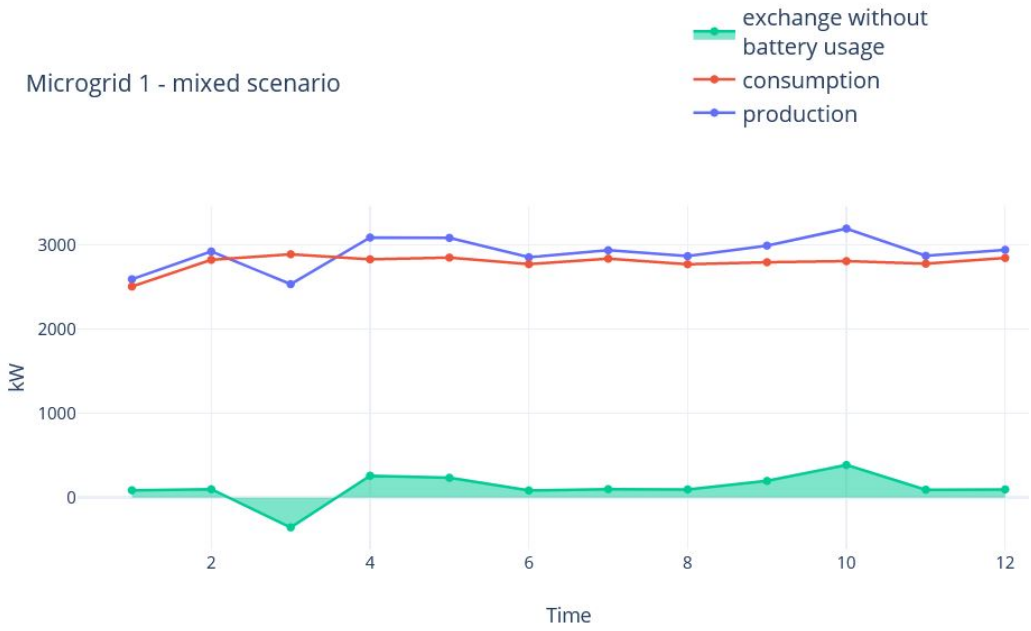


Figure 5.1: Aggregated values for Microgrid 1 in the observed interval of 1 hour.

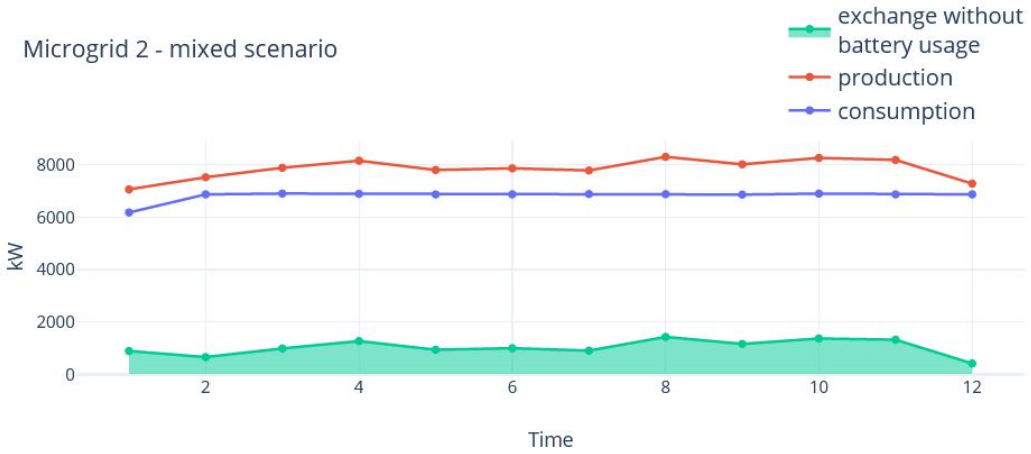


Figure 5.2: Aggregated values for Microgrid 2 in the observed interval of 1 hour.

device (BES).
Analysing the values and comparing them with those in Tab. 5.6 it emerges that:

- Microgrid 1: the total exchanged power is higher than for the two global optimisation strategies but still lower (therefore better to give autonomy to the grid) than for the local non-cooperation prosumer (BAU) strategy, the total profit is lower than for all three previous strategies.
- Microgrid 2: the total exchanged power is higher than that obtained with the minimum exchange algorithm but lower than the value that would be obtained with the local optimisation or the minimum cost strategy; the same result is obtained with the total profit, which is worse only than the amount obtained with the profit maximisation strategy.

No battery usage						
Microgrid ID	Import (kW)	Export (kW)	Exchanged Power (kW)	Cost (€)	Income (€)	Profit (€)
1	354,5	1.727	2.081,5	46,09	172,70	126,61
2	0	12.295,5	12.295,5	0	1.229,55	1.229,55

Table 5.7: Results of microgrids testing scenario 3 without BES.

5.4 Testing of different algorithms configurations

For both global strategies the default optimizing algorithms are applied (first fit for the construction heuristics phase and late acceptance for the local search phase), as after some tests it was noticed that the score obtained (or the number of moves to obtain it) did not improve with the other alternatives.

These algorithms are also influenced by the resolution times and termination conditions imposed in the configuration phase:

- *solver.termination.spent-limit*: with this element we configure the maximum processing time for the algorithm, for the test a time limit of 2 minutes was used, after having proven that even with 5 minutes it gave the same result and did not give a better score.
- *solver.termination.best-score-limit*: this element imposes an early termination on the algorithm in case of premature achievement of the goal (e.g. score 0hard/0soft means getting 0 hard and soft constraints broken, which is usually the optimal solution). However, not all strategies benefit from the inclusion of this condition (which usually avoids unnecessary computation in the server), such as cost minimisation or profit maximisation because it ends the solving process as soon as it has a positive score and, in the case of energy exports, that score can be improved because selling energy gives a positive score with a reward.

Chapter 6

Conclusions and Future Works

The aim of this thesis was to create a hardware and software architecture for monitoring and managing energy resources in microgrids, optimising the exchange of energy resources between the various "prosumers" that make up the microgrid.
The result was an edge-cloud structure, with initial processing of data near the place where it is generated (prosumer) and subsequent management in the cloud for resources shared with other edge nodes.
From the analysis of the results obtained by applying this optimisation to real scenarios, it is emerged that the heterogeneity of the types of prosumers that constitute a microgrid (i.e. their production and consumption patterns) and the type of storage chosen have a great impact on the quality of energy scheduling, regardless of the hardware and software technologies used.
Despite this, both strategies implemented have good optimizations (minimum exchange and minimum cost) compared to traditional (BAU) or a microgrid whose prosumers have no energy storage devices for the extra-production.

6.1 Future Work

For the extension of the work presented in this master thesis, the first step could be to introduce the possibility for prosumers within a certain geograph-

ical radius to switch the microgrid they belong to in order to optimise the overall performance (as shown in the evaluation, optimisation was more effective if import and export were balanced with each other) or, using ML based clustering with graph networks, to identify prosumers with optimal exchange possibilities.

Furthermore, in combination with the ML model used for inference regarding the energy production of PVs, we could add a model that predicts consumption for different profiles of prosumers (commercial or residential and, in the case of residential, also have as data the number of occupants etc.) based on a larger training dataset (so that, for example, the season of the year or the day of the week is also taken into account).

Finally, it would be very useful to add an internal energy market within the microgrid with prices that vary according to the supply and demand of individual prosumers; in connection with this, the demand of prosumers could be dynamically managed by shifting it from peak to off-load periods for non-essential energy consumption (e.g. recharging an electric vehicle).

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