GHENT UNIVERSITY

FACULTY OF ENGINEERING AND ARCHITECTURE

MASTER THESIS

Master of Science in Telecommunications Engineering

When the network operator becomes a utility company: accounting for energy cost in wireless network design.

Candidate:
Amelia Fernández Rodríguez

Relators:
Prof. Wout Joseph
Dr. Margot Deruyck

Faculty of Engineering and Architecture (FEA)

—

Ghent, June 2021

Abstract

Nowadays, it is clear that society cannot live without telecommunications anymore. Fields like Internet of Things (IoT), Machine Learning (ML) or Artificial Intelligence (AI) are becoming essential for many applications and the number of devices connected to the Internet now outnumbers the number of human beings on planet Earth.
Wireless Access Networks are the backbone of telecommunications and it is not an easy task to satisfy all the growing traffic demand caused by the increasing amount of users and devices in recent years.
In addition, it is necessary to provide the energy required by these base stations that are part of the Wireless Access Networks. This energy needs to come from renewable and decarbonised sources, in order to reduce CO_2 emissions and achieve an energy transition from fossil fuels to environmentally-friendly energy sources.
In this thesis, solar, wind and geothermal energy are considered to feed a real scenario composed by a set of macrocells and microcells located in the city of Ghent.
The algorithm developed for this purpose is combining energy and cost saving strategies to improve both energy efficiency and total economic costs of the network.
The study proves that feeding networks with a mixed combination of renewable energy sources can save energy and at the same time provide benefits if a buying and selling energy approach is considered.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Overview

The elements inside telecommunication networks architecture that provide communication between users and with the whole network are the *access networks*. They act as a gateway for the end costumers to access to all the telecommunication services provided through their immediate service provider.
Additionally, these service providers are connected between them using backbones (networks composed by high speed lines), forming the *core network*, which makes possible to reach data centres to provide the information requested by the users.
Access networks play an essential role as they are in charge of provide connectivity and quality of service (QoS) to the end costumers.
They can be classified in two types: wired and wireless, depending on the type of link that exists between the network and the final users. In this thesis, the access networks considered are wireless, which means that the information between the network and the users is shared using electromagnetic waves through the air.
Due to their relevance, huge efforts have been made to improve access networks performance as well as their energy efficiency. This is not an easy task because of the increasing number of users and the more and more demanding new applications that require increasingly data rates and bandwidth.
Specifically, the access networks analysed in this study work on LTE-A (Long Term Evolution Advance) technology, also known as 4G (4th generation).
This technology is the successor of UMTS networks (3G). There were many motivations for the emergence of LTE: to avoid collapse or degradation of the QoS of previous networks due to user growth, need for increased transmission capacity, need for improved coverage and need for improved capacity.
In order to meet the above objectives, LTE needs to implement some improvements with respect to the previous networks: improved spectral efficiency, high order modulations, latency reduction in both user plane and control plane, supporting a variable bandwidth and techniques based on using multiple antennas, like MIMO (Multiple Input Multiple Output), etcetera.
In addition, to maximize the economic performance, LTE technology should reduce the cost of migration of existing networks and provide interconnection with them.
One of the biggest milestones introduced by LTE was migrating from a network partially based on a circuit-switched network to a exclusively

packet switched and all IP network, achieving the unification of voice and data.
The network is organised by coverage areas called cells, all of them composed by user equipments and base stations.
As shown in Figure 1, LTE architecture is composed by different elements.

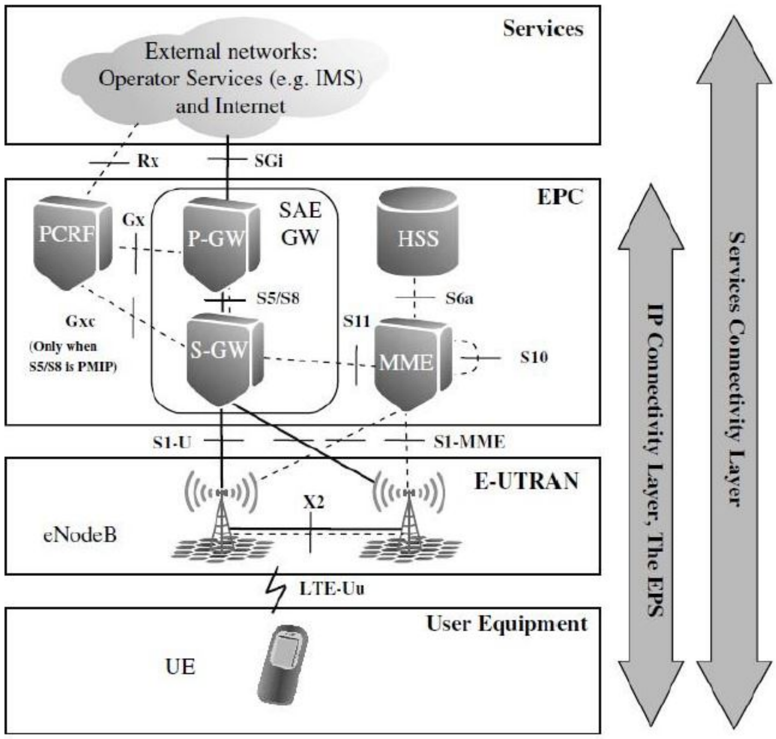


Figure 1: LTE architecture [1]

The end devices of the network are the UE (User Equipment), used by the final costumers. They can be mobile phones but also tablets or laptops.
These terminals are connected via radio to the Base Stations using E-UTRAN (Evolved Terrestrial Radio Access Network). Base Stations are in charge of the physical layer tasks: transmission and reception from and to mobile devices of the physical signals. But, in addition, they can manage control tasks as radio resources allocation depending on QoS or tasks related with handover (change of cell when users are moving from one coverage area to another during a call).
On top of the Base Stations, a set of different elements constitute the Evolved Packet Core (EPC). Evolved packet Core is a framework to track and route data packets through the network, manage quality of service, compatibility and control tasks, etcetera. The main compo-

nents inside it are:

- S-GW (Service Gateway): to route packets from and to the base stations.
- P-GW (Packet Gateway): to send and receive packets from external networks.
- PCRF (Policy and Charging Rules Function): to indicate terms and conditions of use.
- MME (Mobility Management Entity): to manage handover and track users location as well as authentication tasks.
- HSS (Home Subscriber Server): data base for authentication purposes.

Finally, EPC of each network is connected to external networks as IMS (IP Multimedia Subsystem, all IP applications provided by the operator) or Internet Servers.
Other key features of LTE are:

- Supports many frequency bands: from 700 MHz to 3.5 GHz. In UMTS (previous technology) only frequency bands around 2 GHz were allowed.
- Use of two types of duplexing techniques: FDD (Frequency Division Duplex) and TDD (Time Division Duplex).
- Different bandwidths are allowed: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz. In UMTS, only a spread bandwidth of 5 GHz was used.
- Modulations up to 64 QAM and QPSK.
- Multiple access: OFDMA (Orthogonal Frequency Division Multiplexing) in downlink and SC-FDMA (Single-Carrier Frequency Division Multiplexing)
- MIMO technology: up to 8 transmitting and 8 receiving antennas.
- Adaptation of the bit rate depending on the propagation channel condition.
- Channel coding using turbo codes or convolution codes.
- Users scheduling, depending on the propagation channel state in time and frequency.

All these new improvements led to the success of this technology, which was deployed by the end of the first decade of the century. By 2014 [1], there were already 300 LTE networks around the world and nowadays LTE offers coverage worldwide.

1.2 Current renewable energy market

The concern about climate change and global greenhouse gas emissions has led to a significant change of electricity generation market trend in recent years. According to IEA (International Energy Agency) [2], the global electricity generation mix for the last 10 years is shown in Figure 2.

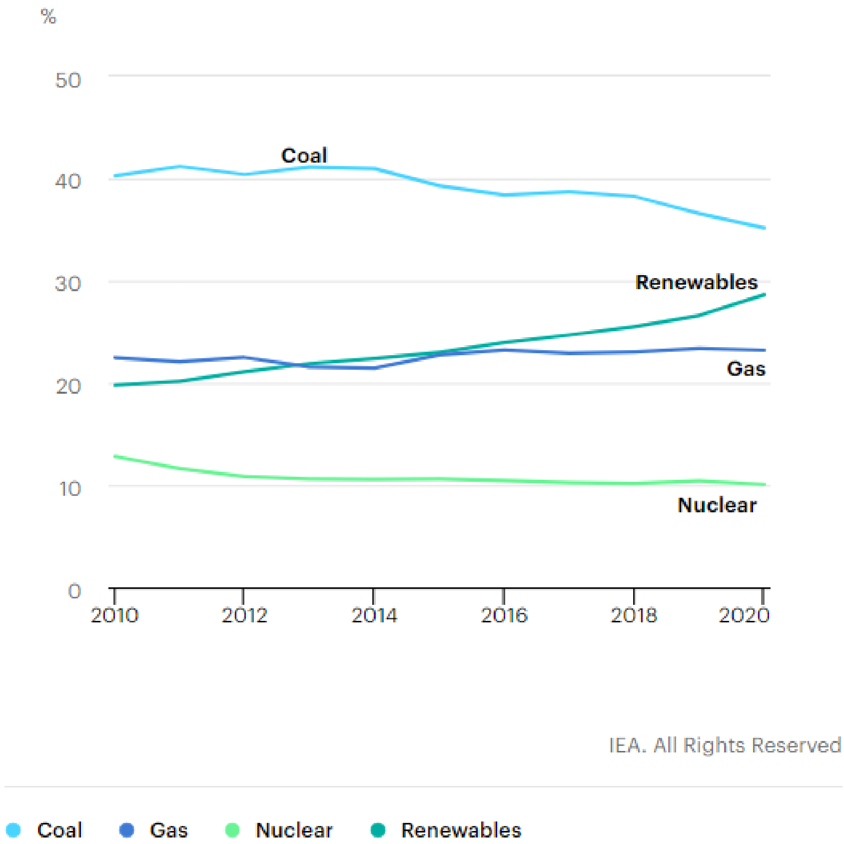


Figure 2: Global electricity generation mix, 2010-2020 [2]

The four main energy sources from which electricity is obtained are: coal, gas, nuclear energy and renewable energy. Each one of them has experienced a different evolution from 2010 to 2020. Coal share in global electricity generation has decreased from 40% to 35%. Gas has remained constant with a total share of 23% and nuclear energy has reduced its contribution to electricity generation by 3%. Regarding

renewable energy, it has been the only source that has increased its appearance in the share in global electricity generation. It rose from 20% in 2010 to 29% in 2020. Specially the last year, the increase was by 2%, which is the biggest annual increase on record.
The expected incoming trend is the gradual decrease of coal, gas and nuclear energy and the rise of the renewable energy share in the total electricity production. This energy transition to environmentally friendly sources implies to change the way in which the main contributors to CO_2 emissions are fed.
As it will be explained in following chapters of this work, telecommunications are a huge contributor of global greenhouse gas emissions. Many components need enormous quantities of energy to work, and specially access networks are one of the most energy demanding elements inside telecommunication networks.
With this motivation, this thesis will explore different ways for feeding wireless access networks using renewable energy, and paying special attention to avoid energy wasting and expensive costs.

1.3 Goal of the thesis

The goal of this master proof is to account for energy costs during the design process of the wireless access network. The provisioning system of the network will consist of renewable energy sources (solar, wind and geothermal) and an energy storage. The developed algorithm has to decide when energy should be bought in advance and store it locally as well as when to sell the energy waste from the renewable energy plants, in order to minimize total spent cost.

1.4 Thesis organization

The topics treated in each chapter are described.

Chapter 2: State of the art

In this chapter, some useful studies for the thesis are presented and discussed. First of all, the access networks contribution to global greenhouse emissions is analysed.
Then, some energy saving strategies in order to decrease emissions are proposed and special attention is paid to the tool developed by WAVES, a research group from Ghent University. This tool implements a capacity-based network, minimizing energy consumption through energy-saving strategies that will be explained in detail. This algorithm is the starting point of this thesis, and new features will be implemented in order to save both energy and costs. Finally, the chapter ends with a review of the renewable energy development and

cost in the recent years.

Chapter 3: Methodology and Settings

The proposed scenario for the simulations taking into account the considered resources is presented. Then, the system configuration including batteries is described, and the data used for energy production is analysed for both seasons: summer and winter.
Finally, each energy-saving strategy is explained in detail, and the metrics used for the techno-economic analysis are discussed.

Chapter 4: Proposed scenario results

In this chapter, results obtained using the proposed scenario in Chapter 3 are presented, in terms of the cost and performance metrics described previously.
Conclusions are extracted from the different graphs collected and finally the best and the worst case are compared in order to find out the total improvement.

Chapter 5: Other scenarios

In this chapter, different scenarios from the described in Chapter 4 are used, in order to verify if a more efficient network is obtained when using only one type of renewable energy.

Chapter 6: Conclusions.

Conclusions and final considerations based on results obtained in previous chapters are discussed. Possible future works are mentioned.

2 State of the art

2.1 Access networks and CO_2 emissions

It is undeniable that telecommunications are becoming essential for society. Nowadays, a world without interconnection between people is unimaginable. Smartphones, laptops and tablets are accessible for most of the population in developed countries and all these devices need to be connected to the Internet using access networks.
In recent years, both users and traffic per user have been increasing exponentially, implying that access networks are more and more energy demanding.
The fact that the Information and Communication Industry (ICT) is a significant contributor of global greenhouse gas emissions (GHGE) cannot be ignored. And is going to get worse in the near future.
Many studies [3] predict worrying data for the incoming years, as it is shown in Figure 3 below.

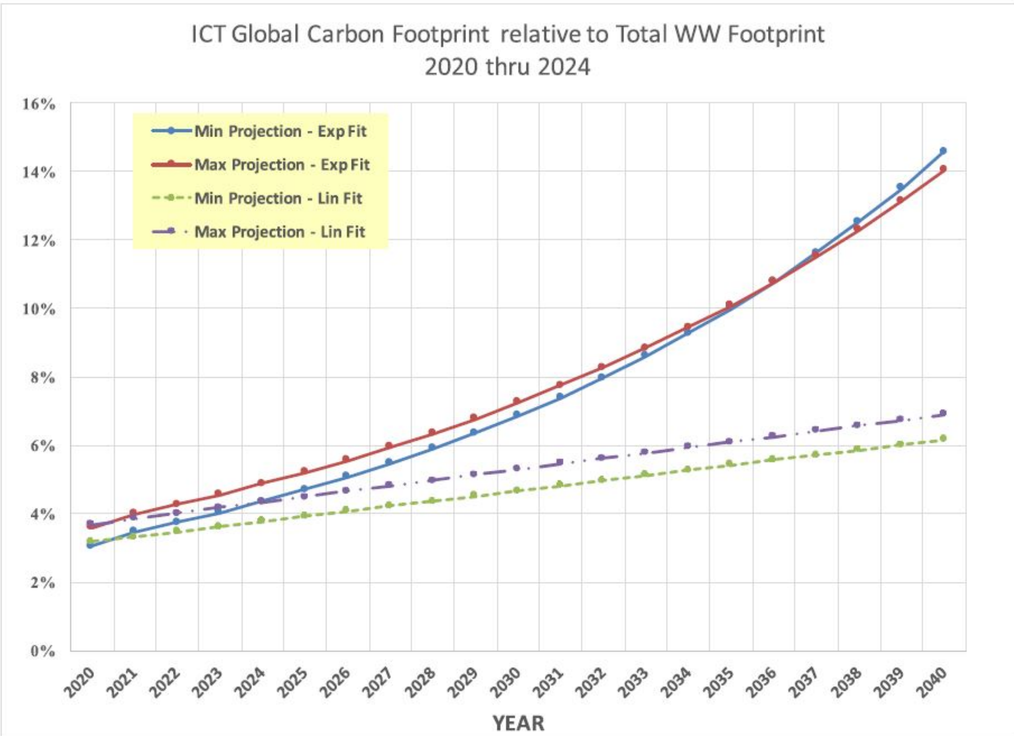


Figure 3: ICT footprint as a percentage of total footprint projected through 2040 using both an exponential and linear fits.

This study, based on the real data of ICT footprint from 2007 to 2018, performs both a linear and exponential fit to the data collected

for predicting the future behaviour of ICT footprint till 2040.
In the worst case considered, which is an exponential fit with coefficient of determination R^2 of 0.9978 and an average annual growth rate of 8.1%, it is predicted that, by 2040, the ICT carbon footprint could account for as much as 14% of the total worldwide footprint.
This level is clearly unacceptable as it will definitely undermine any reductions achieved from the other GHGE emissions sources.
The linear fit is not realistic but it acts as a lower bound of the projections. Even in this unrealistically conservative case, the linear fit still shows almost a doubling of the relative contribution of ICT from 2020 levels.
A more detailed analysis is provided by this study on the specific components that cause this carbon footprint.
In Figure 4, the individual contribution of each category of devices is shown. Largest contributors are data centres, causing 45% of the total ICT footprint. In the second place, we have communication networks with 24% of the total footprint.

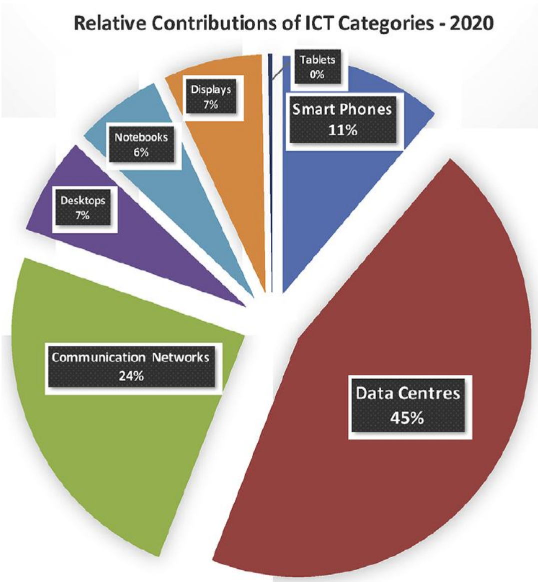


Figure 4: Relative contribution of each ICT category.

These two biggest sources of CO_2 emissions must be required to run 100% on renewable energy. This task is more challenging in communication networks than in data centres,because unlike data centres, which are massive and centralized infrastructures, communication networks are small, scattered and highly diverse in their characteristics and energy consumption profile. They range from cellular base towers and stations, to switches and routers, to wired, wireless and smart-grid networks.

In this thesis, efforts are focused specifically on feeding wireless access networks with renewable energies: solar, wind and geothermal.

2.2 Energy saving in wireless access networks

Uncountable aspects and requirements need to be taken into account when designing wireless access networks.
Some of them are quite obvious, like achieve maximum data rate or enough Quality of Service (QoS).
However, other aspects like energy efficiency or the cost needed to supply base stations are sometimes forgotten.
As it has been discussed in previous chapters, the fact that cellular communication networks have a huge ecological impact cannot be ignored anymore.
Therefore, energy consumption and CO_2 emissions of the mobile network infrastructure receive now more attention and many studies in recent years have focused on how to reduce greenhouse gas emissions of wireless access networks. This energy reduction can be approached in different ways. In [5], some energy saving strategies at component and network levels are proposed by project EARTH (Energy Aware Radio and Network Technologies":

- At component level, equipment manufacturers have already achieved big progress in energy efficiency, mainly by increasing the power efficiency of the transceivers in base stations. From 1995 to 2009, this increase of the power efficiency has resulted in an 80% reduction in energy consumption.
  In addition to improved energy efficiency, future components need to implement measures to reduce the signal peak-to-average power ratio (PAPR) parameter, like new interfaces and algorithmic intelligence, so the transceiver can adapt to the system load by analysing the incoming base band signals. Finally, techniques as MIMO, adaptive antennas, coordinated multipoint transmission mechanisms and advances retransmission techniques are proposed. All these proposals are summarized in Figure 5.

- At network level, it has been proved that energy efficiency generally increases with decreasing cell size. This smaller cells are limited by the fact that base stations must permanently support some basic functionality and also there is a stronger inter-cell interference. Mixed scenarios composed by small cell deployments and hierarchical deployments with overlay macrocells are under development and the results obtained are encouraging. In high load situations the solution is to provide coverage using many small cells, whereas in low load situations cells with only few

users can be turned off by the network management.
Other options are, for example, to optimize energy efficiency of the radio transmission process. These advanced techniques include channel coding, cognitive radio transmission, multi-hop transmission, cooperative scheduling, etcetera. All of them are listed in Figure 6.

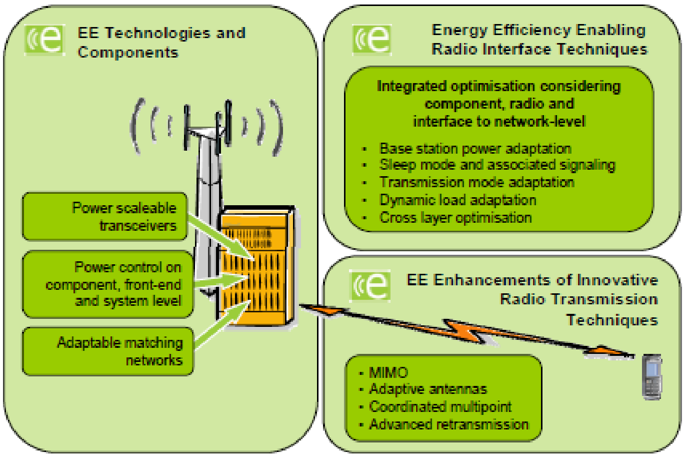


Figure 5: Green component level proposals by EARTH

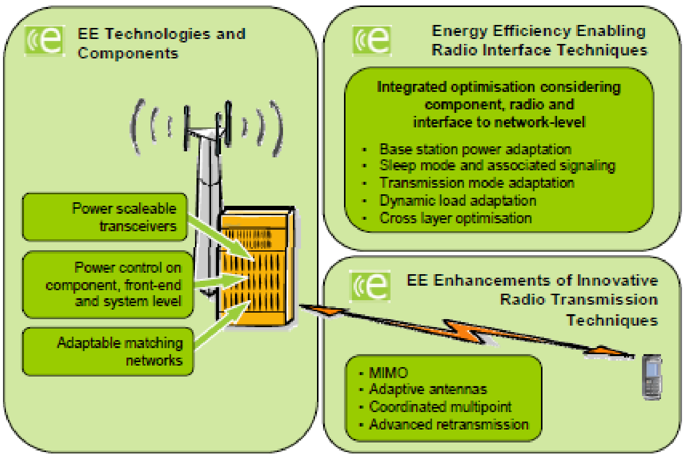


Figure 6: Green network level proposals by EARTH

The network analysed in this work is composed by macrocells and microcells. As it has been mentioned, this type of mixed scenario contributes to decrease energy consumption in wireless access networks. In addition, it is fed with renewable energy sources, which are managed in a centralized manner, avoiding energy wasting.

2.3 Algorithm development

The starting point of this thesis is the optimization algorithm for the design of energy-efficient wireless access networks developed by Silvia Bova [6], in collaboration with WAVES, a research group from Ghent University. At the same time, the work of Silvia Bova is an extension of the tool developed by Greta Vallero [7], also in collaboration with Ghent University.
In these studies, a capacity-based tool was proposed, and it responded to the bit rate required by the users in the considered area.
The scenario was composed by a set of macrocells (8) and microcells (4 pear each macrocell), working on LTE technology. These base stations were powered with renewable energy sources (wind, solar and geothermal) and, in addition, equipped with batteries as well as connected to the traditional energy grid for back-up power in case of shortage of the energy coming from the renewable sources.
To avoid energy wasting, and to minimize the energy bought from the traditional power grid, the algorithm proposed some energy-saving strategies, that will be explained in following chapters.
The results obtained were interesting. Combining more than one renewable resource improved the energetic performance of the network, especially regarding to the energy bought from the traditional energy grid. On average, more than 90% of energy can be supplied by renewable energy sources, not affecting neither the user coverage and the network capacity. This value could even drop below 0.1% if the weather conditions are favourable and energy saving techniques are applied.

The algorithm work-flow can be summarised into the following three steps.

2.3.1 Traffic generation and power consumption calculation

The input data needed for the algorithm to work is the shape file of the analysed area. In this file, details as buildings location, shape and height are defined.
To determine traffic, the shape file is combined with information about the users: distribution, location and requested bit rate. As traffic depends on many factors and is constantly variable over the day, it needs to be calculated hourly. Per each hour, traffic distribution is determined based on the following three elements:

- Number of active users: users that are simultaneously active in each time interval. It depends on the hour of the day and on the population density. For this work, data provided by [8] is used, and the hourly user distribution is showed in Figure 7 below.

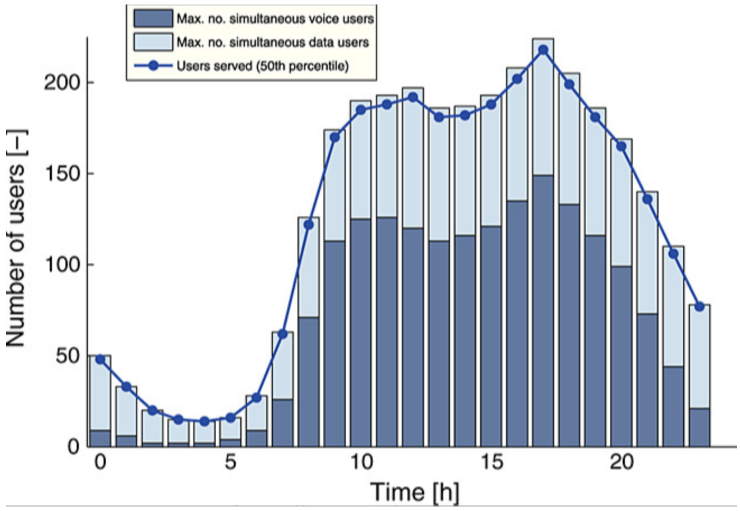


Figure 7: Hourly users distribution

As it is shown in the bar graph, traffic is almost null between 2 and 5 a.m and it increases abruptly till 10 a.m, where is constant till 5 p.m (peak hour) and then it gradually decreases during the evening. These data were provided by a Belgian operator.

- Location of the users: it determines the position of the users in the analysed area. It is considered to be uniform.

- Bite rate distribution: is the bit rate that the users request. It depends on the type of service that the users are consuming. For a voice call, 64 kbps are needed, while 1 Mbps is requested by users transferring data.

Once the information mentioned above is combined, it is used to generate and store traffic files, which are needed to create the network in the next step of the algorithm. For each time interval, 40 simulations are executed and the average value is considered.
Each one of this traffic files contains a list of users including their position (X and Y coordinates), their bit rate required and their identifier.

2.3.2 Dynamic energy system generation

Network calculation
When traffic files have been obtained, the next input file in this step for the algorithm to work is the file containing the base stations characteristics. In the analysed scenario, 8 macrocells are provided and 4 microcells are added per each one of them, which means a total of 36 base stations.
For each timestamp, the algorithm designs a network. Per each active

user at the considered time interval, a list of possible base stations to which the user could be connected is obtained.
Firstly, it is checked if the user could be covered by a base station already enabled, as it is the most energy-efficient solution, instead of enabling a new one. However, if it is not possible to cover the user with the powered on base stations, the algorithm will verify if it is a suitable option to serve the user with one of the base stations that are initially powered off. Finally, if a new base station is enabled, the algorithm checks if the users already served by other base stations can be reconnected to the new one.
The criteria taken into account when determining if a user can be connected to a certain base station or not are the following:

- Path Loss: the path loss experienced by the user must be lower than the maximum defined. To calculate the path loss, the straight line between the user and the base station is determined.
- Bit rate: the bit rate that the base station needs to provide to the user has to be at least equal to the bit rate that the user is requesting.
- Maximum input power: depending on the type of base station considered (macrocell or microcell) the maximum input power of the base station changes. To be able to cover a new user, the base station has to use less power than the maximum allowed.

Once the list of possible base stations to which one user can be connected is obtained, to choose the best one is required. To determine this, a fitness function is used and the solution that minimizes power consumption and exposure, getting the highest fitness function value, is chosen.

Feeding structure calculation
The system will be fed, as mentioned before, using a combination of wind, geothermal and solar energy.
The energy supply structure that determines how many energy resources are needed to fed the network is dynamically built per each time stamp using an heuristic search algorithm, concretely through a Genetic Algorithm.
These type of algorithms take as input a set of potential solutions to the problem and a metric called fitness function, that allows each candidate to be quantitatively evaluated. The working principle of this algorithm is based on the theory of natural evolution, by Darwin. It follows four steps: initialization, calculation of fitness function, application of the algorithm itself and termination.
During initialization, a set of possible solutions is randomly generated.

Each one of this possible solutions is called *individual* and the whole set of individuals is called *population*. The next step consists on the calculation of the fitness function. In order to avoid energy cost and energy wasting, the fitness function tries to select the solutions that minimize three metrics: LCOE (Levelized Cost of Energy), cost of the energy bought from the electricity grid and money wasting due due to overproduction. The individuals with the highest fitness function have more probability to get selected.
Once the fittest individuals have been selected through the fitness function, they are allowed to reproduce and be introduced into the genetic algorithm. These chosen individuals are the *parents* and the new generation of possible solutions are a crossover of them. In addition to the crossover, these individuals of the next generation can be subjected to a mutation with a low random probability in order to maintain diversity within the population and prevent premature convergence of the algorithm.
The last step consists on the termination of the algorithm. After 10 iterations, the final solution is provided.
This solution consists on a combination of a certain capacity of each source. The maximum capacity for solar energy was established to 100 kWp. For wind energy, up to 7 wind turbines were allowed and finally, for geothermal energy, a maximum capacity of 21% was available. In addition to this combination of renewables, the system is equipped with batteries for storing energy in overproduction periods and a backup is also provided from the traditional power grid, to use in case of shortage of energy. All these ways for feeding the system are managed in a centralized manner and the final structure of the network is shown in Figure 8 below:

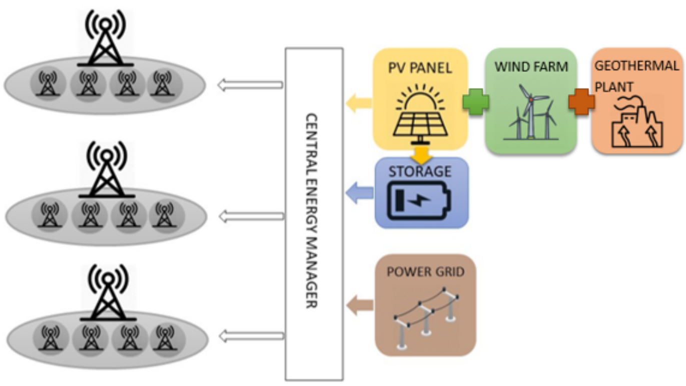


Figure 8: Feeding system of the network

2.3.3 Energy-saving strategy execution (if needed)

Once the traffic, the power consumption, the network and the feeding system have been calculated, the network is ready to work. As mentioned before, the system can use directly the energy produced by the renewable energy sources or it can draw energy from the storage. When there is not available energy and neither energy from the batteries, the base stations need to drain the energy from the grid. To avoid this, the algorithm also introduces some energy-saving strategies in order to reduce the amount of energy bought from the main power grid during critical shortage period. These strategies take advantage of the fact that the network is composed by a mixed combination of two different Base Station types: macrocells and microcells.

- Macrocells: they provide the largest coverage area but they consume more energy than microcells due to its higher input power. However, they are more energy-efficient.

- Microcells: they provide a smaller coverage area than a macrocell base station (from 1 to 2 Km of coverage radius) and they consume much more less energy than macrocells, because of the smaller number of users that they can cover.

For each timestamp, the total available energy is calculated. This available energy is computed as the one produced by the feeding network plus the one stored in the batteries. If the network consumption does not overcome the available energy at that timestamp, there is no need to apply any energy-saving strategy.
Otherwise, if the network is not capable of being self-contained, one of the following strategies needs to be applied:

- **No Action:**
  Undertake no action means that no modifications are applied to the network. As no energy is saved, the amount of extra energy needed for feeding the network needs to be bought from the traditional power grid.

- **Deactivate All Microcells:**
  When energy shortage is detected, if this strategy is used, all microcells are turned off. The users that were connected to these microcells need to be reconnected to the active microcells. Once the strategy is applied, a possible situation could be that there is still shortage even if the energy coming from the microcells is being saved. In this case, the rest of the energy is obtained from the power grid. In the same way, if there is overproduction of energy when this strategy is used, the extra amount of energy is stored in batteries for future usage.

- **Deactivate as much Microcells as needed - intelligent way:**
  The last strategy than can be applied consists on deactivate from 1 to 4 microcells per macrocell. When energy shortage is detected, if the energy produced and the energy stored are not enough for feeding the network, the algorithm needs to calculate the number of microcells that will be turned off. This process is gradual. The algorithm evaluates first if it is enough with putting into sleep mode one microcell per macrocell (eight in total). If not, the options of deactivating 2 and 3 microcells per macrocell are considered. In the worst case, when 4 microcells per macrocell are turned off, this strategy matches the previous one.
  As soon as the network's consumption becomes lower than the amount of available renewable energy produced plus the energy stored, we know how many microcell base stations per macrocell base station to turn off. To decide which ones to deactive first, the number of users covered by each one is taken into account. The ones that are covering the lower number of users are the first to switch off.
  In the same way as the previous strategy, the users that belonged to the switched off microcells need to be reconnected and if there is overproduction, energy is stored in batteries.

2.4 Renewable energy development and cost

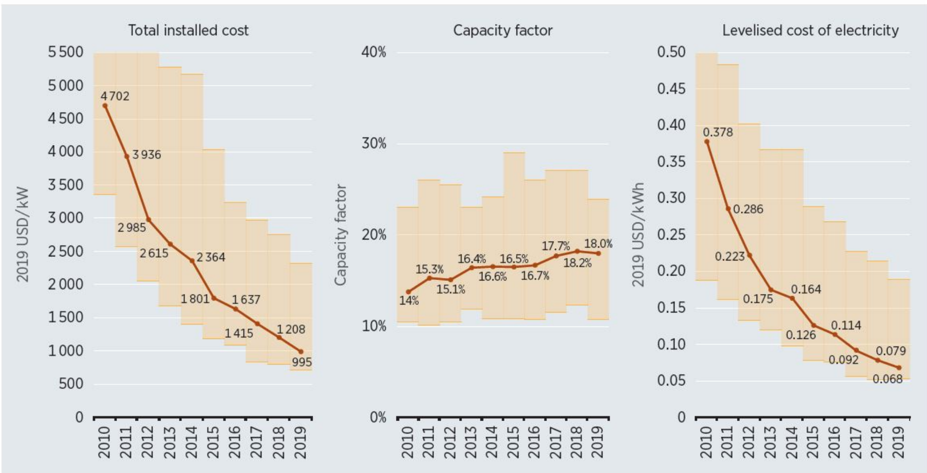
The debate on decarbonisation and the use of renewable energies to combat climate change is increasingly often on the table.
Due to this fact, the deployment of renewable power generation technologies has been growing during the last years, at the same time as the prices have been falling.
There are many sources of renewable energy and more and more emerge every year. The well known ones include solar power, wind power, geothermal power, hydro power, biofuels and biomass. In addition, other ones as biogas, marine or osmotic power are under development with a lower level of maturity.
The use of environmentally-friendly sources of energy is essential if we really want to avoid the worst effects of climate change and mitigate greenhouse gas emissions.
In this thesis, three main energy sources are used and will be analysed: solar energy, wind energy and geothermal energy, according to [4].
For each of them, three main aspects will be discussed:

- LCOE (Levelised Cost of Electricity): metric used to assess and compare alternative methods of energy production. Is an indicator to express the cost of energy or electricity over the lifetime of a system. It takes into account investment cost, operation and maintenance costs, etcetera. This value is usually given per kWh or MWh.

- Capacity factor: ratio of the total energy produced over a definite period of time, to the energy that would have been produced if the plant had operated continuously at the maximum rating.
- Total installed cost: costs to develop and provide durable assets for the system, including machinery or intellectual property.

2.4.1 Solar power

The sun is a natural resource available everywhere in the world. The devices capable of converting sunlight into electricity are photovoltaic solar (PV) panels. These panels are commonly made of crystalline silicon (c-Si) technology. They have some advantages like no fuel costs and relatively low operation and maintenance costs (O&M). In addition, PV technologies are small and highly modular and can be used virtually anywhere. On the other hand, the amount of energy available per unit of time is limited (clearly dependant on the weather conditions), and due to this they are often combined with batteries. Due to the increasingly interest for this technology, in the recent years, many improvements have been achieved as well as cost reductions as we can see in Figure 9.



Source: IRENA Renewable Cost Database.

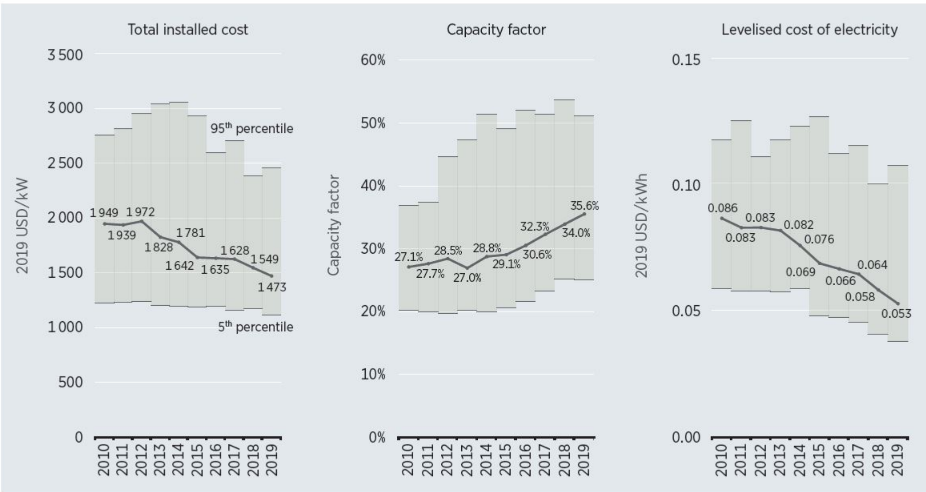
Figure 9: Global weighted average total installed costs, capacity factors and LCOE for PV, 2010–2019

According to IRENA (International Renewable Energy Agency)

Power Generation Costs report of 2019, the global weighted-average Levelized Cost of Electricity (LCOE) of utilityscale PV plants declined by 82% between 2010 and 2019.
In addition, global capacity weighted-average total installed cost of projects commissioned in 2019 was USD 995/kW, 79% lower than in 2010 and 18% lower than in 2018. The total installed cost reductions are related to many factors: improved manufacturing processes, reduced labour costs and enhanced module efficiency. Regarding to O&M costs, they have declined due to several innovations achieved in recent years, like robotic cleaning or *big data* analysis of performance data to identify issues and preventative interventions ahead of failures. The global weighted-average capacity factor for utility-scale solar PV increased from 13.8% in 2010 to 18.0% in 2019. This was predominantly driven by the increased share of deployment in sunnier locations. The cost of crystalline solar PV modules sold in Europe declined by around 90% between December 2009 and December 2019.
As a result of all these advances, solar power generation has become more affordable, which contributes to the increasing popularity of this technology, consolidated as one of the most renewable energy sources used nowadays.

2.4.2 Wind power

Wind power is extracted using turbines. These turbines can be located on the ocean (offshore) or on land (onshore). As an urban network is going to be analysed in this work, onshore turbines are the ones chosen for feeding the system.
Onshore wind turbine technology has made significant advances over the past decade. Larger and more reliable turbines have achieved an increase in capacity factors. In addition to these technology improvements, total installed costs, O&M costs and LCOE have been falling as a result of economies of scale, increased competitiveness and maturity of the sector.
As a drawback we can mention that wind is unpredictable. Research is done to ensure that the turbines are located into excessively windy areas, but that does not guarantee anything, and sometimes other energy sources must be employed to deal with the lack of wind. Unlike solar energy, which is found in every part of the world, wind energy is only able to be harnessed when there is wind available, which is not as widely found as one might first expect. This fact, along with the need to put them in unpopulated regions, greatly limits the potential areas where turbines can be installed.
However, these disadvantages do not overcome the benefits of using wind energy, and its popularity has increased in the last decade.



Source: IRENA Renewable Cost Database.

Figure 10: Global weighted average total installed costs, capacity factors and LCOE for onshore wind, 2010–2019

As shown in Figure 10 [4], the global weighted-average LCOE of onshore wind fell 39% between 2010 and 2019. Operation and maintenance costs for onshore wind often make up a significant part (up to 30%) of the LCOE for this technology. Technology improvements, greater competition among service providers, and increased operator and service provider experience are, however, driving down O&M prices.
In addition, the global weighted-average total installed cost has fallen by 24%, from USD 1949/kW in 2010 to USD 1473/kW in 2019. This has been driven by wind turbine price and balance-of-plant cost reductions.
Finally,almost one-third improvement in the global weighted-average capacity factor, from 27in 2010 to 36% in 2019 has been achieved.
In 2019, onshore wind deployment was second only to solar PV.

2.4.3 Geothermal power

Geothermal energy is the heat produced deep in the Earth's core and it is a renewable resource that can be harnessed for use as heat and electricity.
Geothermal resources are found in active geothermal areas or near the surface of the Earth's crust, as well as at deeper depths. Geothermal power generation is very different in nature to the other renewable power generation technologies. Sub-surface resource assessments are expensive to conduct and need to be confirmed by test wells that will allow developers to build models of the reservoir's extent and flows. Extensive geothermal resource mapping can reduce the costs

of development, by minimising the uncertainty about where initial exploration should be conducted.

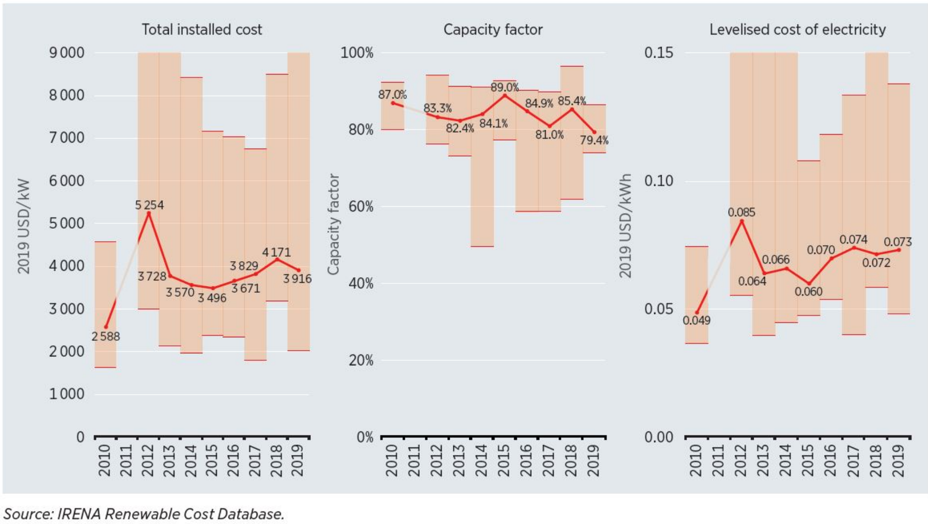


Figure 11: Global weighted average total installed costs, capacity factors and LCOE for geothermal, 2010–2019

As shown in Figure 11,the global weighted-average LCOE of the projects commissioned in 2019 was USD 0.073/kWh, broadly in line with values seen over the last four years [4].
Between 2014 and 2019, total installed costs increased from USD 3570/kW to USD 3916/kW. Geothermal power plant installed costs are highly site sensitive. They consist of the project development costs, the costs of exploration and resource assessment (including seismic surveys and test wells), and the drilling costs for the production and injection wells. Total installed costs also include field infrastructure, geothermal fluid collection and disposal systems, along with other surface installations. These are in addition to the cost of the power plant and grid connection costs.
Regarding to capacity factor, it depends on the location of the geothermal plant and the technology used to extract the energy. The average capacity factor of geothermal plants using direct steam is around 85%, while the average for flash technologies is 82%. Binary geothermal power plants that harness lower temperature resources are expected to achieve an average capacity factor of 78%.
Geothermal power plants provide firm, 'always on' power, as their energy production is almost constant in time. They provide more stable energy production than wind turbines and PV panels, more depending on the concrete weather conditions.

3 Methodology and Settings

3.1 Proposed scenario

It has been explained in previous chapters that the implementation of an scenario composed by macrocells and microcells brings several advantages in terms of energy efficiency due to the flexibility that provides to turn on and off microcells easily.
For this work, the considered scenario is shown in Figure 12.

Figure 12: Considered scenario

The considered area is a suburban area of 0.3 km^2 (orange box) of the city center of Ghent, in Belgium, with 8 macrocell Base Stations (rose points) and 4 microcell per macrocell Base Stations (purple points). The locations of the macrocells are the real locations in a network from a mobile operator that provides services in that area. The microcell base stations have been placed around the macrocells forming a diamond shape.
Each node of the system is fed by RES (renewable energy sources). The energy generator system is common for all base stations and is in addition equipped with batteries. The algorithm takes decisions according to the total available energy and power consumption, as all the nodes are managed in a centralised way and treated as a part of the whole network and not independently.
As an enhancement with respect to previous works ([6]), the connection of the network to the traditional electricity grid is removed. As all the advantages of using renewable energy sources as well as the importance of decoupling electricity generation from coal and other sources with a huge negative impact on greenhouse gas emissions have been analysed previously in this work, the chosen strategy is not to rely in these type of sources and bet on wireless access networks totally powered by RES.
Two periods of analysis have been considered, one in summer and

another one in winter, as the energy produced by RES is strongly dependent on weather conditions. Both periods correspond to the year 2017. Concretely, considered summer period is June 10th-16th and winter period goes from December 23rd till December 29th. Regarding to energy generation data, needed for calculating total available power on the system, it is provided by Terna S.p.A [9], an operator from Italy that works on energy production.
Users are uniformly distributed over the area and regarding to bit rates 1Mbps is considered when the user is transferring data and 64kbps are assumed for voice calls.
Finally, LTE Advanced is used as the working technology for the network at a frequency of 2.6 GHz and the rest of important parameters that need to be defined in wireless communications are listed for both macrocells and microcells in Table 1 below:

Parameter	Macrocell Base Station	Microcell Base Station
Frequency	2.6 GHz	2.6 GHz
Max input power antenna	43dBm	33dBm
Antenna gain base station	18dBi	4dBi
Antenna gain mobile station	2dBi	2dBi
Soft hand over gain	0 dB	0dB
Feeder loss base station	0 dB	0dB
Feeder loss mobile station	0 dB	0dB
Fade margin	10dB	10dB
Yearly availability	99.995%	99.995%
Cell interference margin	0 dB	0dB
Bandwidth	5MHz	5MHz
Used subcarriers	301	301
Total subcarriers	512	512
Noise figure mobile station	8dB	8dB
Implementation loss mobile stations	0 dB	0dB
Height mobile station	1.5m	1.5m
Coverage requirement	90%	90%
Shadowing margin	13.2dB	13.2dB
Building penentration loss	8.1dB	8.1dB

Table 1: Link budget parameters

3.2 Energy Production and Storage System

The network is provided by an energy production and storage system. As a difference with respect to the work described in the previous chapter, the feeding system will be fixed for all the timestamps considered in the simulations and not different for each one of them, which is a more realistic approach.
However, results provided by the Genetic Algorithm deployed in [6] will be taken into account when choosing the final amount of resources of each RES (solar, wind and geothermal) that will fed the network of the proposed scenario presented above. Remember that the algorithm criteria to choose the most suitable combination of resources is done in order to optimise three metrics: LCOE, cost of energy bought and cost of overproduction. These results obtained by the Genetic Algorithm were the following (Figure 13):

- Winter:

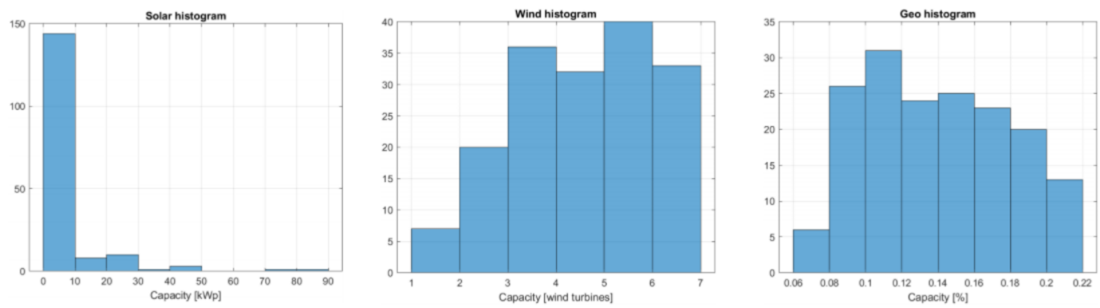


Figure 13: Histogram of the average energy system size chosen by the optimization costs algorithm for solar, wind, and geothermal during winter when undertaking no action.

The number of timestamps in a week is 168, as one timestamp corresponds to one hour. The histogram shows that in most of the time slots, solar energy is not chosen or is chosen but in small capacities (between 0-10 kWp). The explanation for this behaviour of the algorithm is simple: in winter, solar energy production is small. That would lead to larger PV modules to fed the network, which can be translated into more costs. Wind energy is always picked, as winter is the best season to produce wind energy. The most repeated option is to choose 5 windmills, as the histogram shows. Regarding geothermal energy, it seems to be the most suitable option, as it shows almost uniform trend in the range between 0.10% and 0.20%. Geothermal energy can always be a solution, but with limited percentage, as its production is almost constant over all the year.

- Summer:

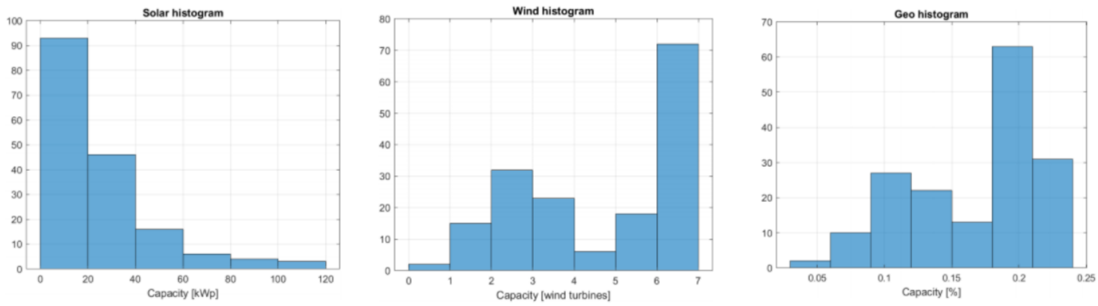


Figure 14: Histogram of the average energy system size chosen by the optimization costs algorithm for solar, wind, and geothermal during summer when undertaking no action.

The situation changes drastically in summer (Figure 14), where the histograms change significantly with respect to the previous ones. In summer, daytime is mainly covered by PV modules energy production. However, even if solar energy production is higher in summer, the algorithm prefers to choose small capacities for photovoltaic panels (between 0-40 kWp). This is due to the overproduction caused by big peaks of solar energy production during sunlight hours, leading to energy wasting. Wind is still a suitable option and most of the timestamps 7 wind turbines are activated. Finally, high percentages of geothermal energy are elected, due to the irregularity of the production of solar and wind energy.

Taking into account this useful information about which are the feeding systems that the algorithm considers optimal for summer and winter, an intermediate approach between both seasons (Figure 15) is elected to be fixed as the proposed scenario for this work:

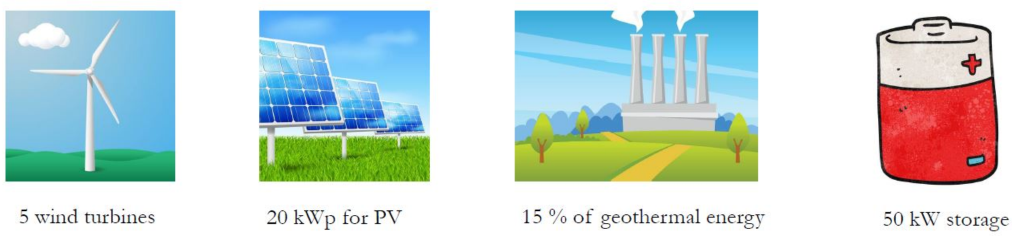
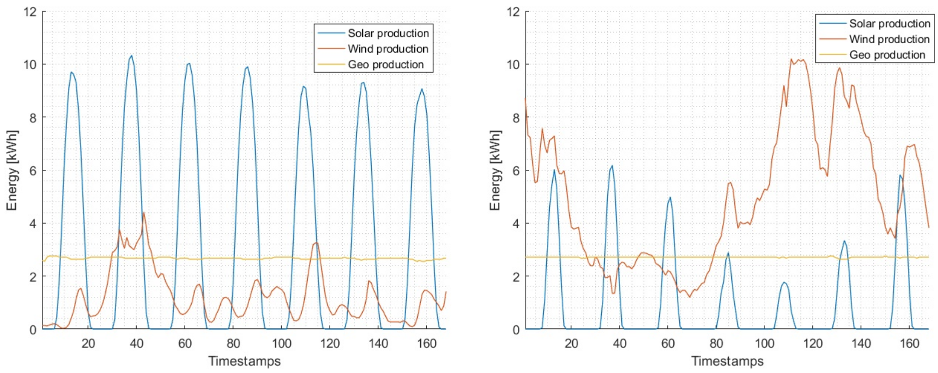


Figure 15: Resources considered for the proposed scenario.

During simulations: 5 wind turbines, 20 kWp for PV and 15% of geothermal energy will be considered as feeding system.

As in previous works, the system is provided of energy storage of 50 kW wide and the batteries are assumed completely charged at the beginning of the simulation. Note the difference that now **there is no backup connection with the traditional power grid**. Batteries are of type lead-acid and any losses when charging and discharging or when transferring energy are ignored.

Energy production data provided by the Italian operator and that will be used to calculate available energy in the system are showed in Figure 16:



(a) Summer week (June 10th-16th). (b) Winter week (December 23rd-29th).

Figure 16: Energy production

Huge differences can be noticed in RES production between summer and winter. In summer, energy produced comes mainly from PV panels, reaching energy peaks up to 10 kWh per kWp. But these peaks only occur in the middle hours of the day, when the sun shines at maximum intensity. At nights, for obvious reasons, there is not solar energy production. Regarding wind energy, it is unpredictable and the range of energy produced goes from zero in some timestamps till a maximum of four but most of the time is less than 2 kWh per windmill (in the proposed scenario, 5 windmills are considered). Geothermal energy production remains constant for all timestamps and for both seasons slightly higher than 2 kWh for the whole plant (in our case, multiplied by 0.15).
In winter, solar energy production drops by more than half with respect to summer and the opposite behaviour is detected in wind energy production: it rises up to 12 kWh in some timestamps and in all of them overcomes the production in summer. However, wind production remains irregular and it varies significantly along the week.

3.3 Optimization strategies

Even though results obtained in [6] and [7] are quite good results, they encourage to further investigation and improvements. This work will implement two new optimization strategies that aim to make the network more energy efficient and profitable: implementation of buy and sell approach and deactivation of some sectors of the macrocells.

3.3.1 Buy and sell approach

Energy market has been always complicated and, as it is experiencing huge changes with the introduction of renewable sources of energy, rules and policies change quickly and a new concept of market is emerging.

Energy price varies during the day, depending on the energy production, and on the consumption of the users. The energy production strongly depends on the weather conditions (for PV and wind, geothermal is constant as it has been mentioned before). Peak hours of user demand of the day have a higher energy price than, for example, night hours. In addition, if we have a cloudy or a windy day, it will affect PV and wind energy prices, respectively.

With this change of paradigm, a new energy supply model in the recent years. Self-consumption is increasingly being encouraged, and the users are not anymore passive consumers of electricity but they are also small producers of energy: they take (and buy) energy from the electrical grid but also they can inject (and eventually sell) energy into it. These kind of users are called *prosumers*.

The buy and sell approach that will be implemented here as a new feature with respect to previous works exploits the fact that the feeding network of the base stations can be a prosumer.

It can perform two actions: to buy energy in advance and to sell energy to the electrical grid. For both of them a very important parameter is taken into account: **the time window.**

The time window is a fixed number of hours that is used to extend the time period which is taken into consideration when buying and selling energy. Without time window, decisions would be taken immediately and only taking into account the current energy demand and energy production of the network.

When considering time window, better decisions are taken due to the wider vision of the network's forecast. This makes possible to act beforehand and to avoid possible shortages. For example, if a shortage is predicted, for a certain time interval, in the following timestamps within the considered time window, energy-saving strategies are applied in the current timestamp and not in the one with the predicted shortage, when it might be too late. In [7], effects of time window

variation are investigated and it concludes that a time window of 6 hours performs well, so is the one considered for this work.
As it has been mentioned, this approach implements two different actions: buy and sell energy. For each time stamp, one of them, both or none of them can be applied.

- Buy in advance: it takes advantage of the variation of the energy price during the day. If not extra energy is needed for a certain timestamp, but a minimum energy cost is detected within the considered time window, this energy can be bought in advance if the forecast predicts that it will occur an energy shortage for the following timestamps belonging to the time window.
  The amount of energy bought is the minimum space available in the storage during the considered time interval, in order to avoid that the energy produced by the feeding system that should be stored in batteries is wasted. In case the energy bought is not enough, the remaining amount is purchased at the beginning of the current timestamp, but probably at a higher price than if we buy it in advance.

- Sell energy: this strategy exploits that prosumers can inject extra energy into the power grid in order to obtain profits. If the network is not in a critical situation (energy-saving strategies are not needed), the amount of energy remaining in the storage for all the time window period can be sold. In this way, immediate purchase and sale of energy is avoided, because of the use of the time window and due to the fact that base stations are not switched off when no energy-saving strategy is applied.
  The amount of energy sold is equal to the minimum amount of energy remaining in the storage for the time slots belonging to the time window. So it is the quantity of electricity that exceeds during the considered time period. This energy is sold at a 90% of the purchase price. In addition, when energy is bought in advance because of its cheaper price, it can not be sold.

3.3.2 LCOE

There are numerous metrics that can be used for quantify electricity price, but the most common is *LCOE (Levelized Cost of Electricity)*. Figures in section 2.4 of this work and taken from [4] showed the LCOE for solar, wind and geothermal energy for the last few years. For this work, during simulations, the most recent values of the graphs (year 2019) will be used and they are listed in Table 2:

LCOE	USD/kWh	€/kWh
PV panels	0.068	0.05613
Wind energy	0.053	0.04375
Geothermal energy	0.073	0.06026

Table 2: Table LCOE

The LCOE of renewable energy technologies varies by technology, country and project, based on the renewable energy resource, capital and operating costs, and the efficiency/performance of the technology. The formula used for calculating the LCOE of renewable energy technologies in IRENA report is showed in Figure below (17):

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

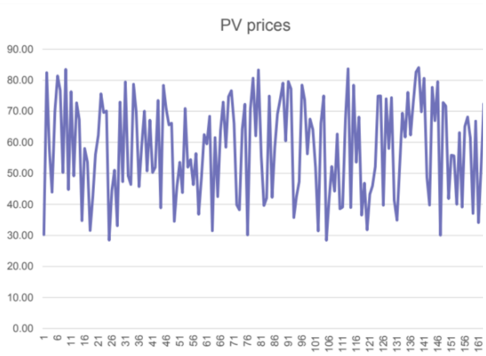
Figure 17: LCOE formula

Where:

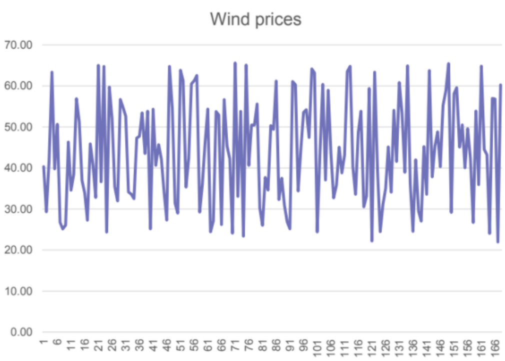
- LCOE = the average lifetime levelized cost of electricity generation.
- I_t = investment expenditures in the year t.
- M_t = operations and maintenance expenditures in the year t.
- F_t = fuel expenditures in the year t.
- E_t = electricity generation in the year t.
- r=discount rate.
- n= life of the system.

Life of the system has been considered 25 years for the three energy sources and Operation and Maintenance Costs (O&M) are showed as well in section 2.4.
LCOE is a complex metric that depends on many factors and that can vary significantly due to multiple reasons. For the algorithm to work and analyse price variations in order to take buy and sell decisions, we need not a constant but a variable LCOE value for each energy source and for each timestamp. Otherwise, the algorithm would take

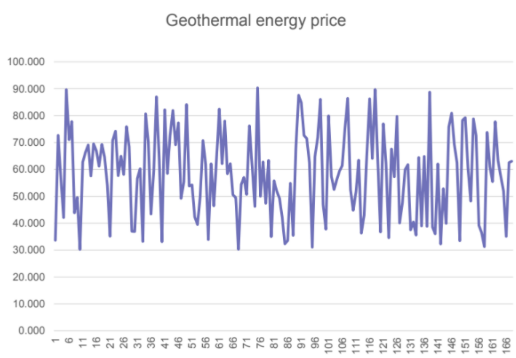
always the same source: the one with the cheapest LCOE showed in the table above (in this case, wind energy).
For this purpose, random variations to the base LCOE of each energy source are introduced in order to obtain a variable LCOE for the simulated week. The obtained results for energy price per MWh are showed in Figure 18:



(a) PV LCOE (MWh)



(b) Wind LCOE (MWh).



(c) Geothermal LCOE (MWh)

Figure 18: Energy prices

Once energy is purchased at these prices, if it is stored, it cannot be sold at the LCOE prices showed above, as the energy stored in batteries is treated as homogeneous energy and no distinctions are made between solar, wind or geothermal energy. Selling price is determined by 90% of the electricity price in Belgium in each timestamp. This information has been collected from Belpex webpage for the concrete weeks analysed in this work [10].

3.3.3 Deactivate some sectors of the macrocells

The optimization strategy just explained above is an economical strategy, and it aims to provide benefits to the feeding system operator.
The optimization strategy of this section, to deactivate some sectors of the macrocells, is not an economical strategy but an energy-saving strategy that can be combined with the ones explained in section 2.3.3. However, to save energy implies that less energy is consumed by the network and, if the production is the same, it means more energy is stored in batteries as well as the amount of bought energy decreases. Thus, this measure also has positive economic impacts.
This optimization strategy exploits the fact that macrocells and microcells have different power consumption patterns. All the strategies applied in previous works and mentioned before in this work focus on the microcells: undertake no action, deactivate all of them or deactivate some of them. However, no attention is payed to the macrocell base stations power consumption.
Macrocells consume much more energy than microcells, due mainly to two reasons: they have a higher input power and 3 different sectors (microcells only have one sector).
Higher input power is because of macrocells have higher capacity to cover a larger number of users and more coverage range than microcells. In addition, they are in charge of control tasks and are responsible of the baseline coverage in their relevance area. This parameter cannot be modified. Otherwise, quality of service of the network would be negatively affected.
Regarding sectors, they have a huge impact in power consumption, as all the calculations done in order to obtain it are finally multiplied by the number of sectors that the base station has.
The effect of deactivating sectors of the macrocell will be analysed in this work. This technique will be applied at the beginning of the simulation and it will be combined with the three strategies implemented in previous works and mentioned in section 2.3.3. In addition, the buy and sell approach is considered.

3.4 Metrics analysis

During simulations,two types of metrics will be considered to analyse network's behaviour: performance metrics and costs metrics. All of them will be explained in detail in this section.

3.4.1 Performance metrics

- Energy consumed (kWh): is the amount of energy that the network needs in order to provide service to the active users in each timestamp. It has been calculated using traffic files generated in the first step of the algorithm, taking into account users distribution and traffic per user. In addition, it needs the power consumption files for both microcells and macrocells to be computed. One value per timestamp is calculated.

- Energy bought (kWh): is the amount of energy the algorithm decides that needs to be bought per timestamp. As it has been mentioned before, this energy could come from three different energy sources: solar, wind or geothermal (depending on the cheapest one at the time interval that energy is purchased)

- Energy produced (kWh): amount of energy in kWh that the feeding system composed by RES produces per each timestamp. Is the sum of the energy produced by solar panels, windmills and the corresponding percentage of geothermal plant. It has been calculated using the energy production files provided by the Italian operator.

- Energy stored (kWh): amount of energy that is stored in batteries per timestamp. Is the surplus of energy that occurs when the feeding system produces more energy than needed by the network. This extra-energy will be used for future shortages of energy or in order to sell it if a critical situation is not predicted in the following timestamps.

- Energy sent (kWh): amount of energy that the buy and sell approach considers that can be sold per each timestamp. In order to sell, it needs to be stored in batteries and the network can not be involved in a critical situation in the timestamps belonging to the elected time window. Energy is sold at 90% of the purchase price.

- Energy available (kWh): amount of energy that is available to use in order to satisfy the demanded energy coming from the network. Is the sum of the energy produced and the energy stored just mentioned above.

- User coverage (%): percentage of active users that are successfully covered by the network in each timestamp, achieving quality of service requirements.

3.4.2 Costs metrics

- Solar Cost: is the cost per timestamp spent in buying energy coming from PV panels if this energy source is the one elected to be purchased.

- Wind Cost: is the cost per timestamp spent in buying energy coming from windmills if this energy source is the one elected to be purchased.
- Geothermal Cost: is the cost per timestamp spent in buying energy coming from geothermal plant if this energy source is the one elected to be purchased.
- Spent Cost: total amount of money that is spent buying energy at each timestamp. This value can come from solar, wind or geothermal energy purchased.
- Earned Cost: total amount of money earned if energy is sold at each timestamp.
- Total Cost: total cost earned minus total cost spent both just mentioned above. If it is positive, we will have benefits in that timestamp. Otherwise, if this value is negative, we will have losses.

4 Proposed scenario results

In this chapter, results obtained by simulations are presented and analyzed. The algorithm explained in section 2.3 is used, integrating the scenario proposed in section 3.1, and extending the algorithm with the optimization strategies detailed in section 3.3.
Simulations for winter and summer are performed and for each season different energy-saving strategies are applied. For all of them the buy and sell approach is implemented and both costs and performance metrics are discussed for each concrete situation.
Finally, when all cases have been analysed, the worst and the best simulation are compared between them in order to quantify the total improvement of the network performance.

4.1 Summer-Undertake no Action

Fist simulation is performed during the considered summer week (June 10th-16th).No energy-saving strategy is applied and, for the moment, all sectors of the macrocells are turned on. Buying and selling approach is in addition implemented for all simulations. This case is the reference case, as not energy-saving strategy is being used. All the following simulations aim to improve the results of this one. First graph (Figure 19) compares: consumed, bought, produced, stored and sold energy (all of them given in kWh).

Figure 19: Energy consumption-No Action.

It can be noticed firstly that energy consumed and energy produced follow a similar pattern. This is due to the main contributor of energy production for summer: solar panels. Peak hours of users demand coincide with the mid-hours in where sun is brightening the most and producing more energy.
However, energy produced overcomes energy consumed when both reach maximum values and the opposite happens when they go down to their minimum values: energy produced is lower than energy consumed. In the timestamps where this happens (mostly at nights) an energy shortage has to be solved. That is the reason of the red line peaks (bought energy) that appear when energy production is not enough for feeding the network. Energy needs to be purchased everyday at night hours, when the sun goes down (a mean of 6 kWh). Regarding stored energy, it increases gradually at the same time as the energy production is rising, as the extra amount that the network does not need is being stored in batteries. When energy production starts to decrease, but the network's demand is still exigent, energy stored starts to fall down because it is being used for backup of the feeding system. When energy stored is null, the line of bought energy starts to grow, because batteries are running out of energy. Finally, sold energy can be only appreciated when energy production is maximum. At these concrete timestamps, small quantities of energy (most of the days around 3 kWh) are sold, as the algorithm does not predict any energy shortage within the time window (they happen later, outside time window). In addition, as batteries are supposed to be full of energy at the beginning, this energy is sold at timestamp 1, when critical situations are not predicted to happen.

The following graph (Figure 20) shows clearly when the network faces with critical situations, as it represents available energy (stored plus produced) versus consumed energy. In all timestamps when available energy is lower than consumed energy, energy needs to be purchased. This happens in 100 timestamps over 168 timestamps (one week), which is 59.5238% of the time. To depend more than half of the timestamps of the week on the bought energy is not a desirable result, and it will be improved in the next simulations.
It can be noticed too that the available energy decreases drastically during the first timestamps, when the stored energy in batteries is sold.

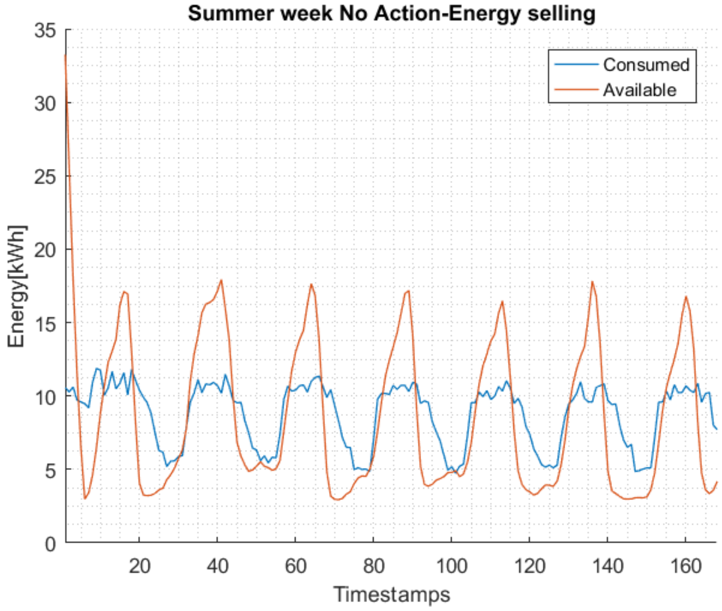


Figure 20: Energy available vs consumed-No Action.

When energy needs to be bought, remember that it can come from three sources: solar, wind and geothermal energy. In order to decide which one to choose, prices described in 3.3.2 are considered.

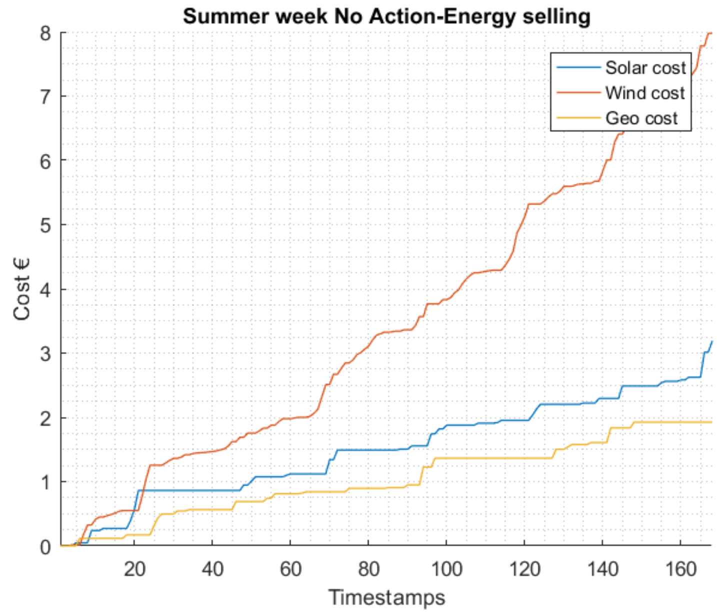


Figure 21: Energy bought-No Action.

Figure 21 represents in euros the amount of money spent in each energy source for all the previous timestamps and the current one, in an accumulated way. Most of the energy purchased comes from windmills, but at some points energy coming from PV or geothermal plants is also bought. This is due to the lower base LCOE of the wind energy, that makes more likely to have lower prices of this energy source when introducing random variations. Solar cost and Geo cost in the graph remain constant for large periods of time while Wind cost is constantly increasing. The total spent cost in wind energy for the week is 7.9761€, for solar energy is 3.1931€ and 1.9258€ are spent in geothermal energy.

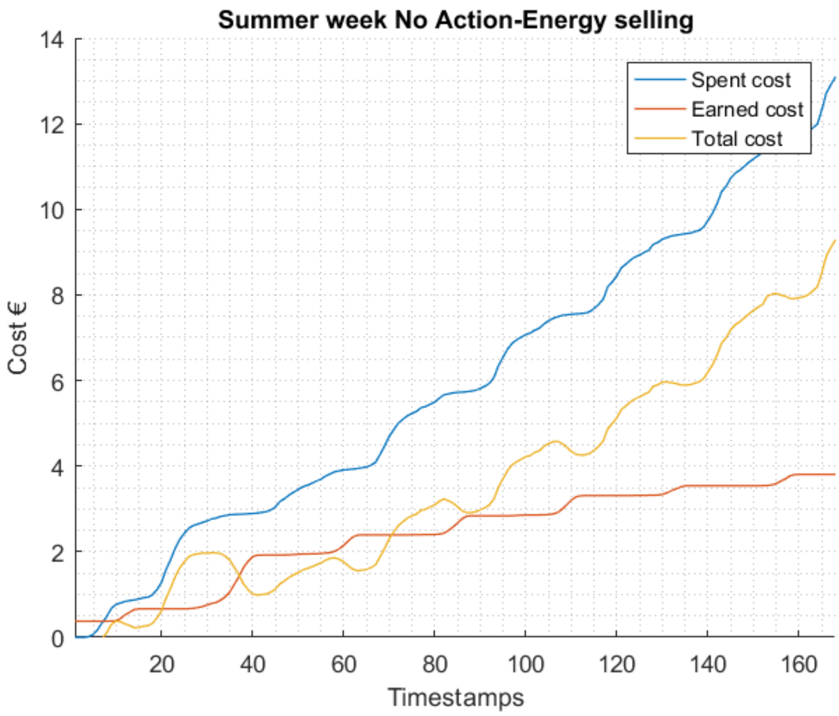


Figure 22: Total Costs-No Action.

Regarding total costs, they are summarised in Figure 22. Spent Cost always overcomes Earned Cost. This is easy to understand when looking at the first graph presented for this simulation: peaks of bought energy (red line) are much higher than peaks of sold energy (green line). The network has never large amounts of extra energy to sell as the demand is exigent and periods of shortage occur every night.
Total Spent Cost is 13.0950€, total Earned Cost is 3.8051€ and this makes a total outgo of -9.29€ for summer week without applying energy-saving strategies.

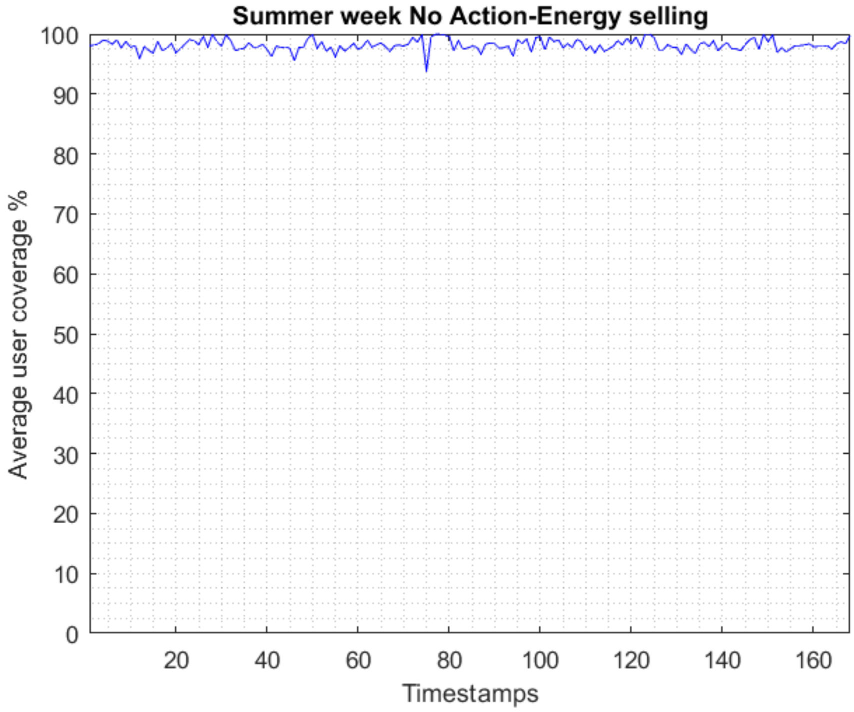


Figure 23: Average user coverage-No Action.

Regarding user coverage, which is the metric used to measure Quality of Service of the network, this simulation is providing quite good results, looking at the graph above (Figure 23) which represents the user coverage in % for each timestamp. Minimum value is 93.8690 %, maximum value is 100%, and mean value is 98.1573%. In 167 timestamps, user coverage is higher than 95%.

4.2 Summer-Deactivate All microcells

Second simulation is performed during summer week and, the strategy applied when energy shortage is detected, is to deactivate all microcells and reconnect the users to the macrocells. The network in this simulation will consume less energy than in the previous one and it will provide benefits, as it will be showed in the graphs of this section. First graph (Figure 24) compares: consumed, bought, produced, stored and sold energy (all of them given in kWh). What first catches the attention of the graph are the abrupt peaks of the purple line (stored energy), that seem to have a repetitive pattern along the week.
The effects of the energy-saving strategy applied can be clearly noticed in the consumed energy data (represented in blue), that is much lower that in the previous simulation. Mean energy consumption was

8.7976 kWh when undertaking no action regarding energy efficiency and now, deactivating all microcells in case of shortage, the mean energy consumption along the week falls to 5.7405 kWh. Energy production remains constant as we are analysing the same week. As a consequence of the decrease of the consumed energy by the network, the demand can be covered by the produced energy coming from the feeding network composed by RES and a large amount of it can be stored in batteries as backup energy. Only in 50 timestamps energy consumed is higher than energy produced, and, when it happens, energy from batteries is taken. Energy stored increases gradually and slightly shifted to the energy produced and it decreases when it is being used, i.e., when the sun goes down and PV panels stop extracting energy from the sun.
As the network is self-sufficient, we can notice that the bought energy remains constant along the week and its value is 0 kWh. Regarding sold energy, it varies along the week reaching its maximum values at the same time as the energy produced, when it is not needed to fed the network due to overproduction.

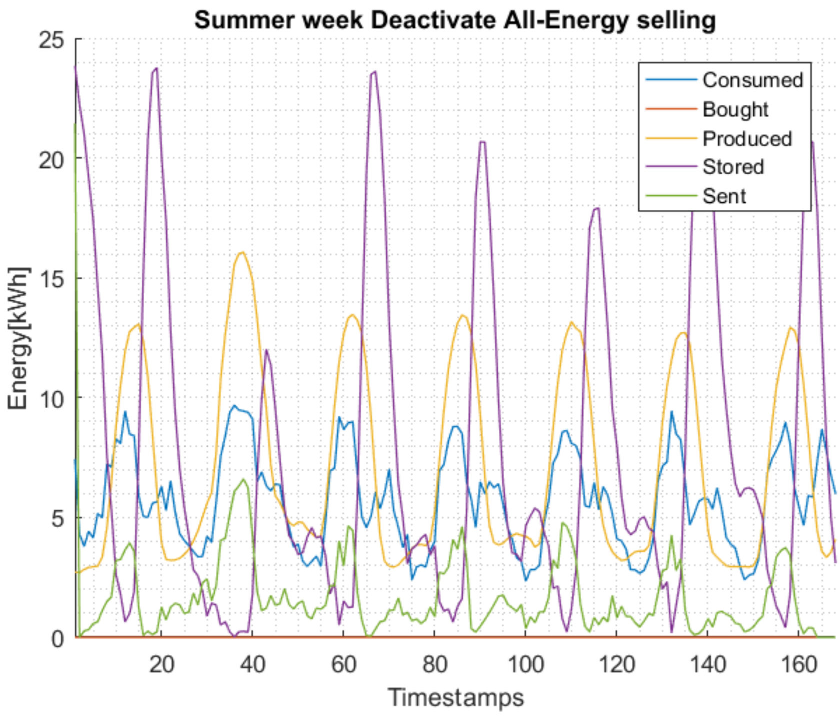


Figure 24: Energy consumption-deactivateAllMicro.

Figure 25 comparing energy available versus energy consumed looks quite different in this simulation comparing to the previous one. Without taking action, more than half of the timestamps occurred an energy shortage. In this case, as shown in figure below, the energy stored in batteries in addition to the one produced by the RES network is more than enough to cover the demand. At some timestamps, energy available is three times higher than the energy needed to provide service to the active users.

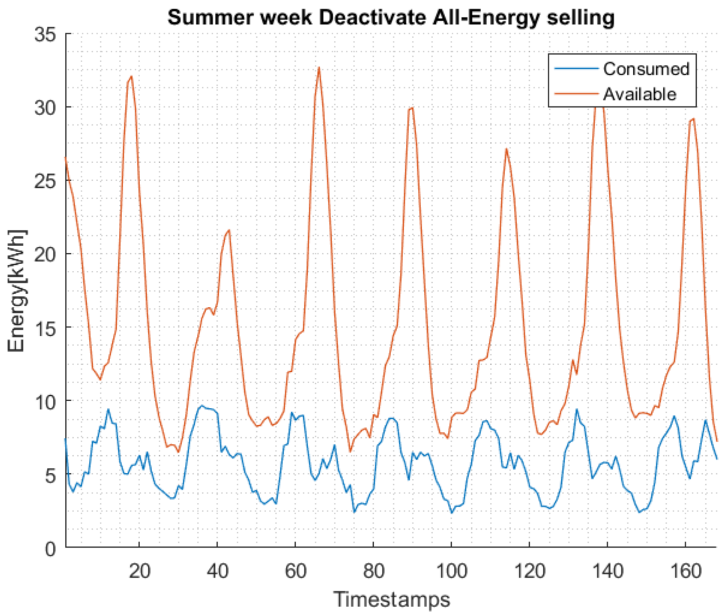


Figure 25: Energy available vs consumed-deactivateAllMicro.

In this case, as no energy is bought, the obtained graph for the cost spent in different energy sources is simple: solar, wind and geothermal cost remain constant to 0 kWh. (Figure 26).

In this manner, also Total Costs graph (Figure 27) changes drastically when applying energy-saving strategies. Total spent cost is zero and total earned cost is +8.9885€, which is equal to the total outgo.
Only in five timestamps the amount of sold energy is null. In the rest of them, some energy is injected to the power grid.

Total outgo of the previous simulation was -9.29€, so the fact of deactivating all microcells when energy shortage is detected has increased profits by 196.75%

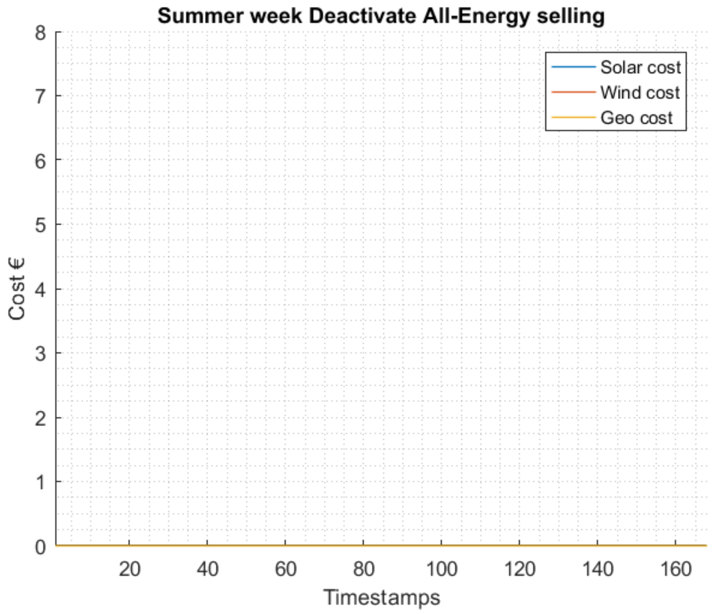


Figure 26: Energy bought-deactivateAllMicro.

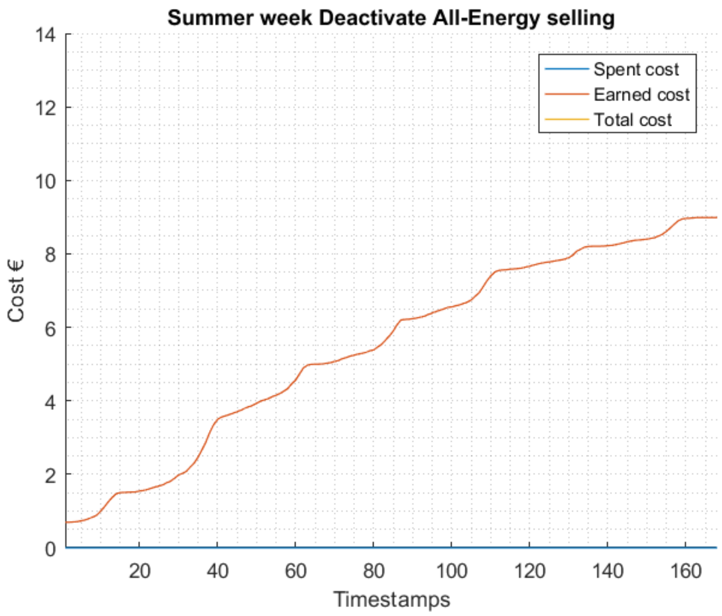


Figure 27: Total Costs-deactivateAllMicro.

Regarding user coverage showed in Figure 28, this simulation is providing also excellent results, looking at the graph below which represents the user coverage in % for each timestamp. Minimum value is 94.0357 %, maximum value is 100%, and mean value is 98.2172%. In 167 timestamps, user coverage is higher than 95%.

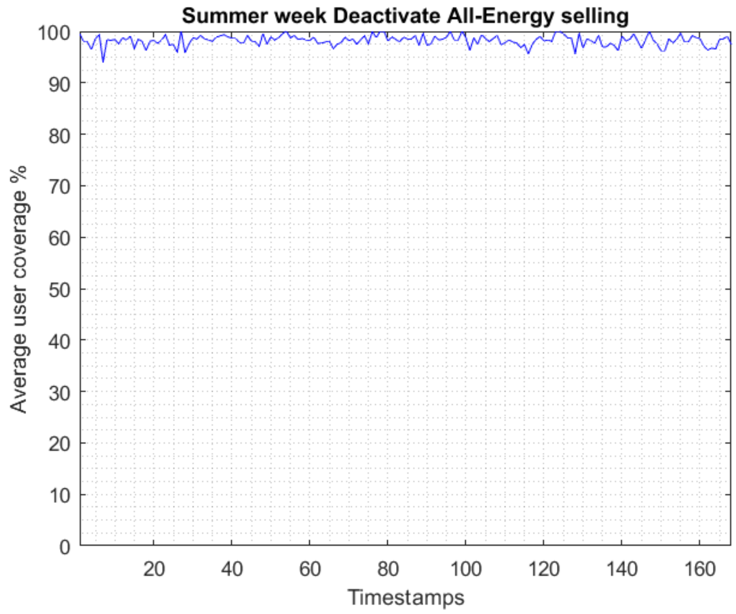


Figure 28: Average user coverage-deactivateAllMicro.

4.3 Summer-deactivate as much microcell BSs as needed (intelligent)

Still simulating in summer, in this simulation the third energy-saving strategy is applied. Remember that this strategy consists on deactivate a certain number of microcells (between 1 and 4) per macrocell, till the energy demand is satisfied.
Results are very close to the previous ones, but taking into account that to deactivate all microcells saves logically more energy than deactivating only some of them. This can be noticed in the graph below (Figure 29), where the outstanding peaks of stored energy disappear. Now, the extra amount of energy than can be stored in batteries is not as high as the previous case, but still everyday at mid-hours the amount remaining after feeding the network is saved to use it later or to sell it.
Mean power consumption per timestamp in the previous case, when deactivating all microcells, was 5.7405 kWh. In this case, it slightly rises up to 6.6027 kWh per timestamp.
Even if the power consumption has risen, the network still has enough energy with the energy produced and the energy stored in batteries to satisfy user's demand. This means that no energy needs to be bought along the week, so the red line remains flat in the graph. Finally, regarding sold energy, it follows exactly the shape of produced energy: rises when we have overproduction and falls down when the feeding system production does it.

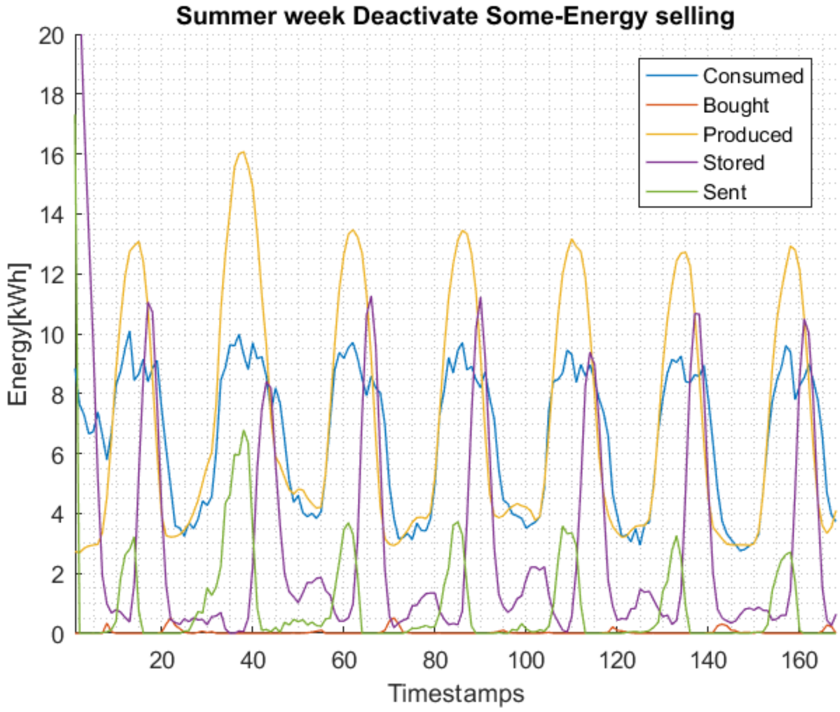


Figure 29: Energy consumption-deactivateSomeMicroIntelligent.

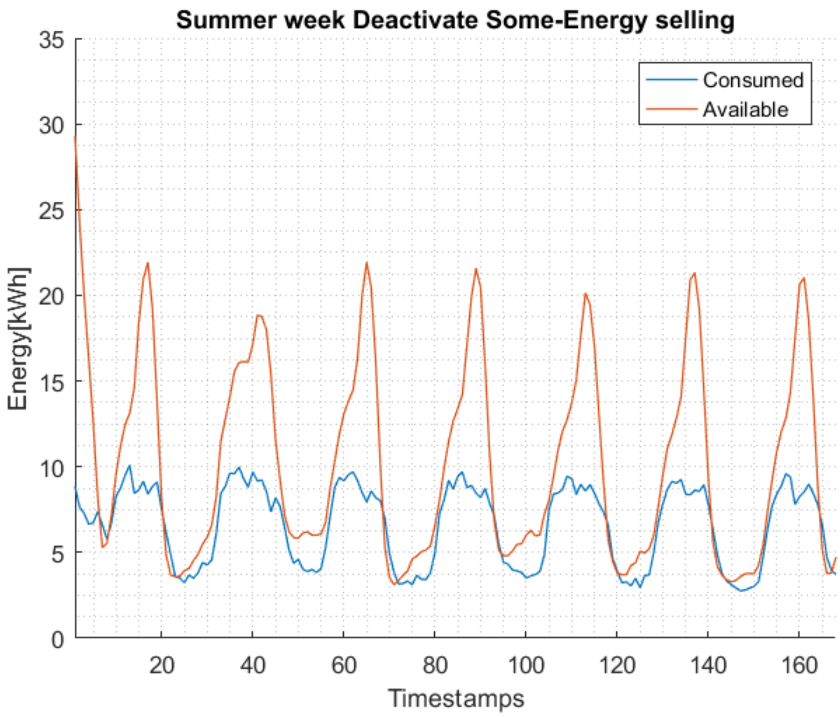


Figure 30: Energy available vs consumed-deactivateSomeMicroIntelligent.

Differences between available energy and consumed energy (Figure 30) are not as huge as in the previous case and, when they reach maximum values, the available energy approximately doubles the consumed energy.
However, in 20 timestamps, energy demand overcomes energy produced but the difference is negligible. This difference explains the minimum quantities of bought energy that appear in the graph below (Figure 31), but they can be neglected.

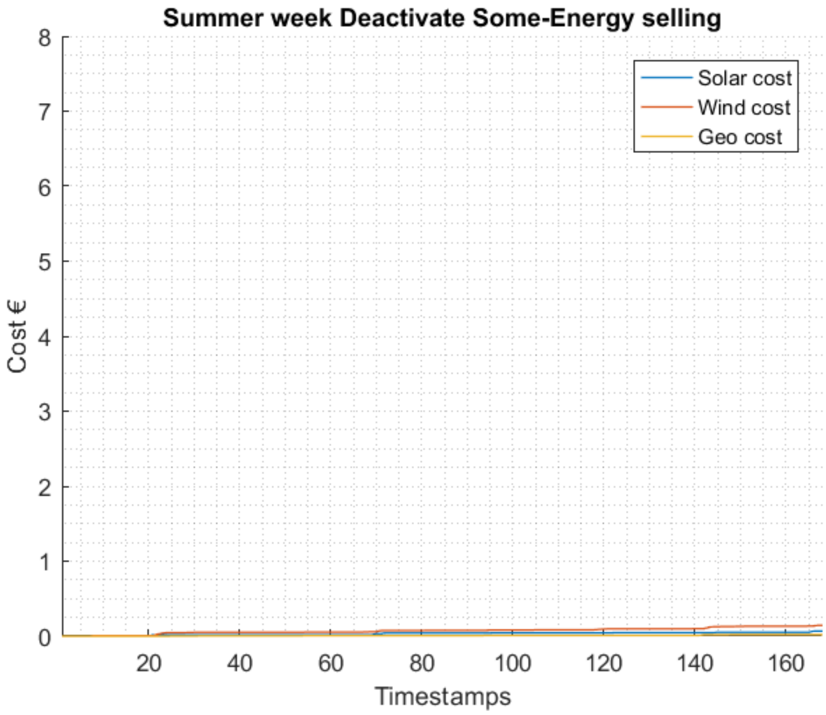


Figure 31: Energy bought-deactivateSomeMicroIntelligent.

Total Spent Cost (Figure 32) is 0.4426€, total Earned Cost is 5.2517€ and this makes a total outgo of +4.8091€ , 46.5% lower that in the previous case.

Regarding user coverage (Figure 33), looking at the graph below, minimum value is 95 %, maximum value is 100%, and mean value is 98.3529%. In 167 timestamps, user coverage is higher than 95%.

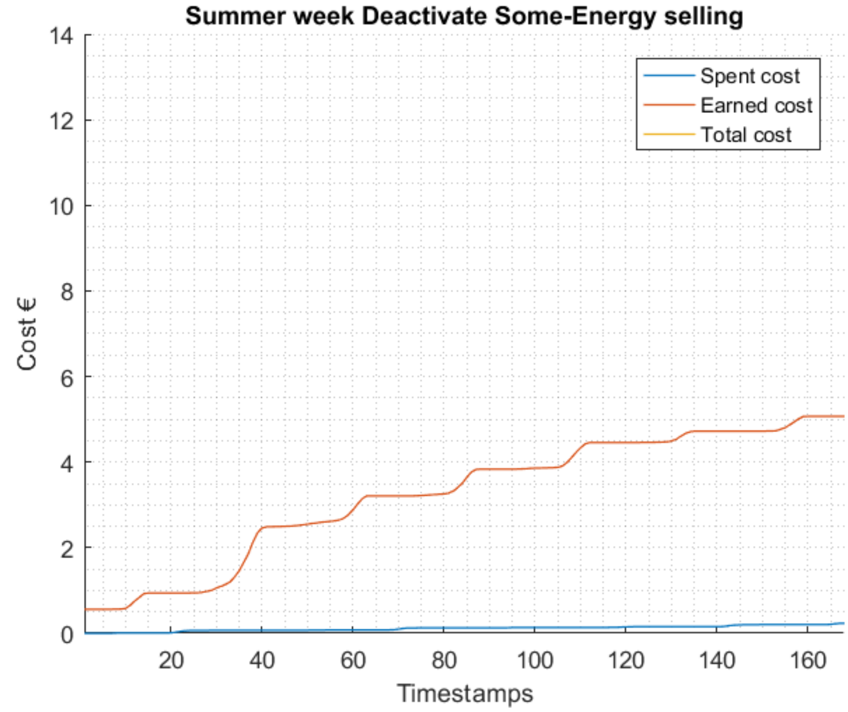


Figure 32: Total Costs-deactivateSomeMicroIntelligent.

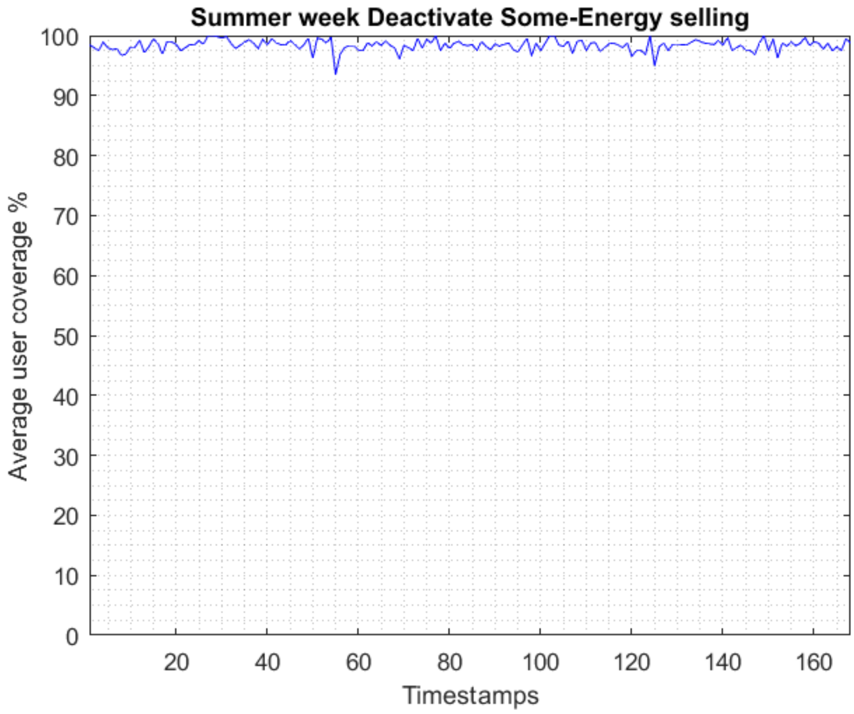


Figure 33: Average user coverage-deactivateSomeMicroIntelligent.

4.4 Summer-Deactivate All microcells + deactivate some sectors of the macrocells

Remind that, as a new feature of this thesis, in addition to the strategies already mentioned, some sectors of the macrocells are going to be deactivated, in order to improve the performance of the buying and selling approach and to save energy.
The performance of the strategy consisting on deactivate all microcells at critical situations when powering off 1 or 2 sectors is going to be analysed in this simulation in terms of energy consumption, benefits obtained and user coverage, which are the most important parameters to prove efficiency.
Energy consumption behaviour is shown in the graph below (Figure 34). It gradually decreases as more sectors are being deactivated. The shape of the three curves is the same and the power consumption is inversely proportional to the number of sectors considered.

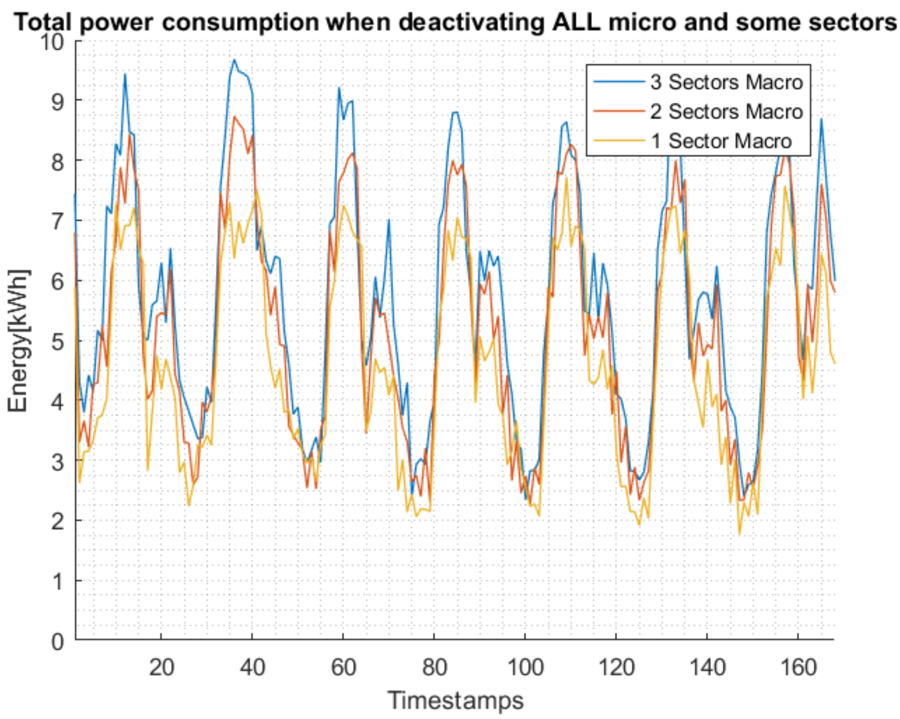


Figure 34: Energy consumption-deactivateAll+SomeSectors.

Mean energy consumption per timestamp when macrocells have 3 sectors is 5.7405 kWh. When we deactivate one sector and still 2 of them are available, mean energy consumption per timestamp is 5.1943 kWh. Finally, when only 1 sector is powered on, mean energy consumption falls to 4.6157 kWh. This can be translated into an energy save of 19.59% between the worst case and the best case.

Regarding total costs variation, they are represented in Figure 35. For the three simulations with different number of sectors, 'negative' costs are obtained, which are profits. This benefits are higher as more sectors are powered off.

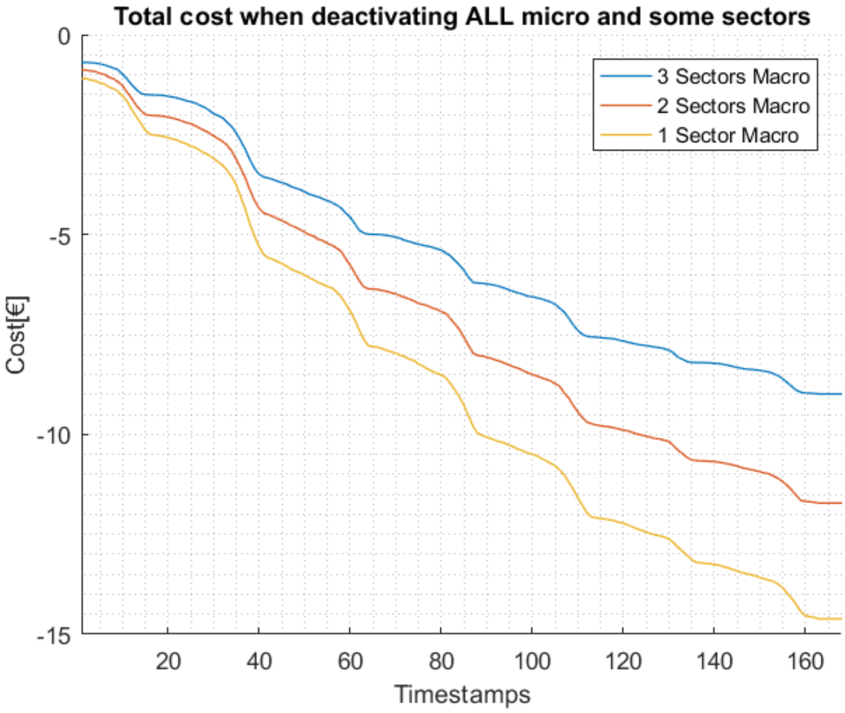


Figure 35: Total Costs-deactivateAll+SomeSectors.

The final amount of earned money is 8.9885€ with 3 sectors per macrocell. When two of them are available, this value rises up to 11.7200€. And, when only one sector per macrocell is working, profits increase till reach the amount of 14.6152€. This means that, when applying sectors deactivation, a 38.50% increase in profits is obtained. Till now, this strategy is providing good results both from the energetic and the economical point of view. However, is this energy reduction affecting quality of service of the users?
The answer to this question is in Figure 36 below and it is clearly no. This graph represents the percentage of users covered by the network per timestamp and for the three different situations considered: one sector, two sectors or three sectors per macrocell. For all of them, users are covered in all timestamps and it is proven that to deactivate sectors of the macrocells does not affect quality of service, saving energy and increasing benefits.

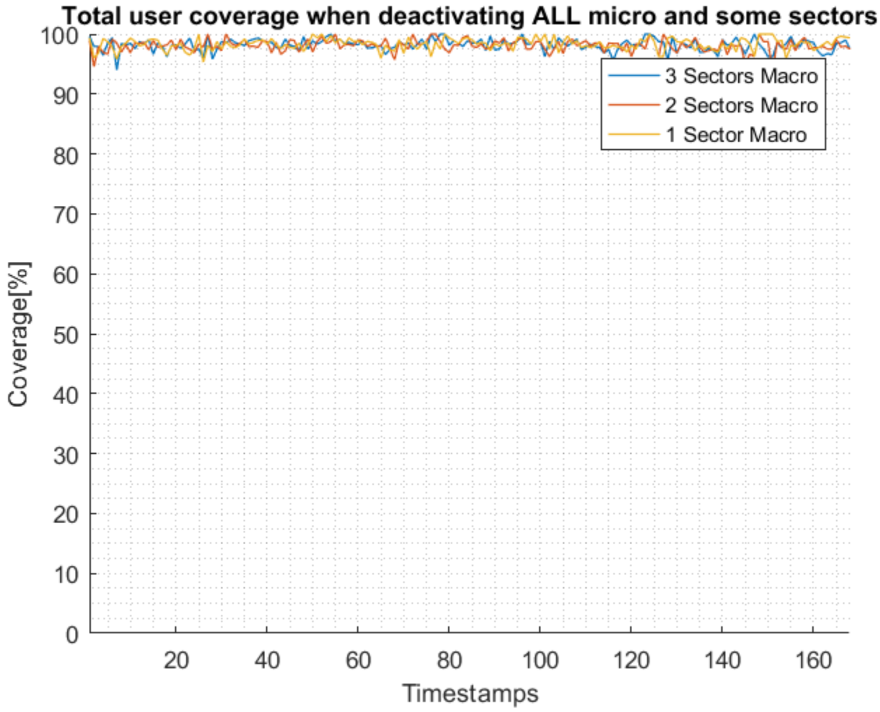


Figure 36: Total user coverage-deactivateAll+SomeSectors.

4.5 Summer-deactivate as much microcell BSs as needed (intelligent) + deactivate some sectors of the macrocells

The strategy of deactivating as much microcells per macrocell as needed is also analysed when it is combined with deactivating some sectors of the macrocell.
Observing values for power consumption below (Figure 37), a decrease of 20.47% of the energy consumption is achieved when deactivating two sectors comparing with the reference macrocell (3 sectors powered on). This percentage is slightly higher than the one obtained in the previous simulation.
Regarding total costs showed in Figure 38, the obtained profits are 4.8091€ when no sectors are turned off. For the best case, when only one sector per macrocell is working, they rise up to 11.8770€, that means an increase of 59.51% (21% more than in the previous case).
This simulation has provided the best results for summer week. The cooperation between the feeding system composed by RES, in addition to deactivate some microcells in a intelligent way when energy shortage is detected + deactivate two sectors of the macrocells + buying and selling approach is a suitable configuration in order to obtain profitable results at both economical and energetic level.

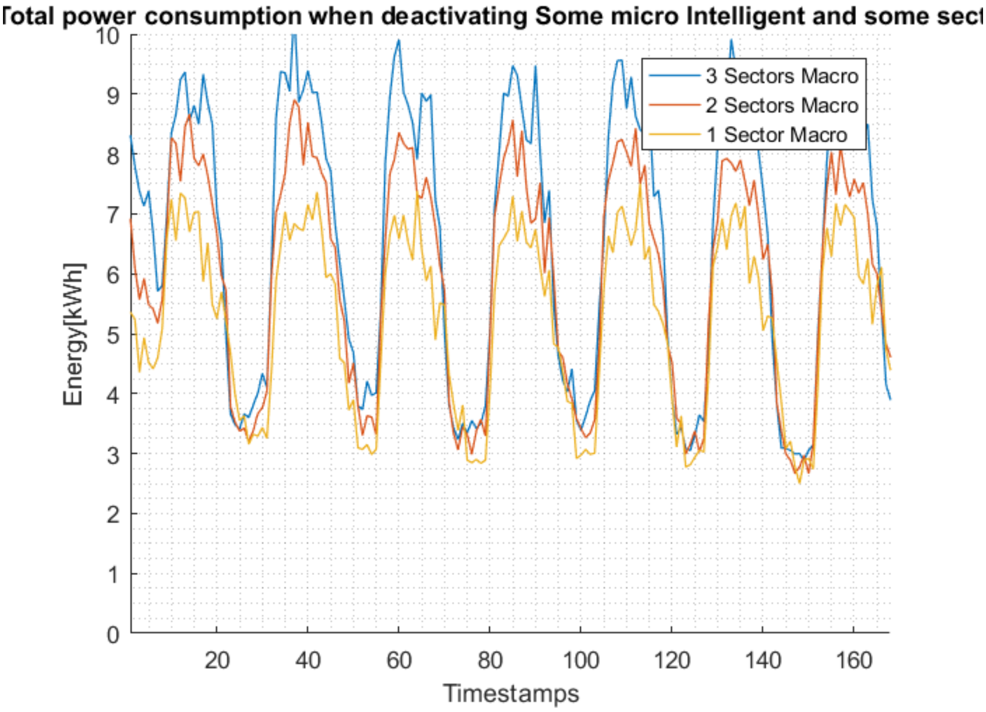


Figure 37: Energy consumption-deactivateSomeMicroIntelligent+SomeSectors.

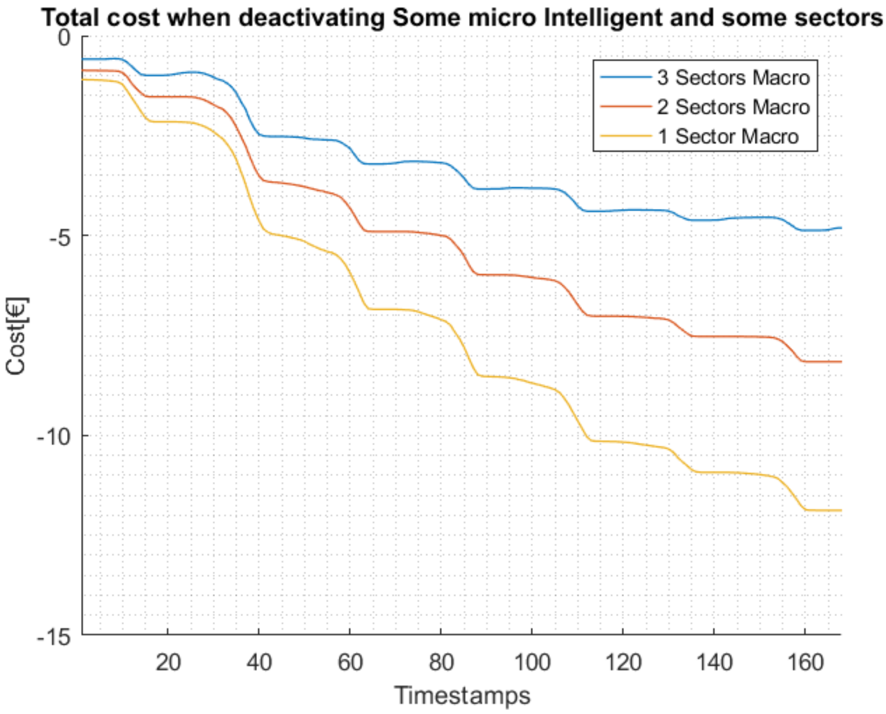


Figure 38: Total Costs-deactivateSomeMicroIntelligent+SomeSectors.

Figure 39 proves once more, as in the previous case, that to deactivate sectors (in this case, combined with deactivating some microcells in a intelligent way) does not have a negative impact on user coverage.

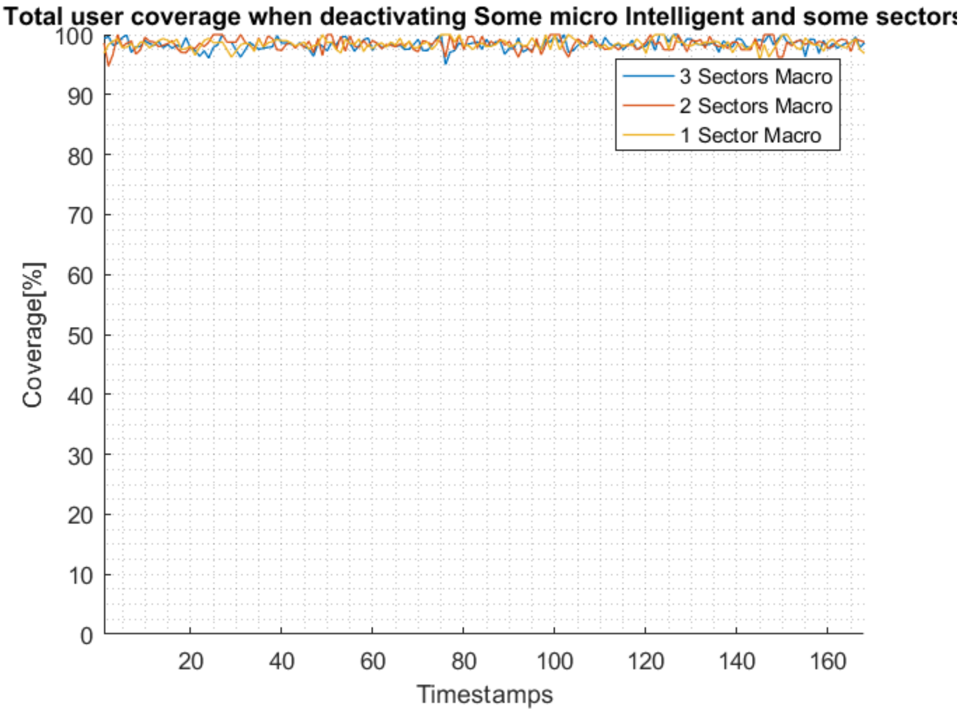


Figure 39: Total user coverage-deactivateSomeMicroIntelligent+SomeSectors.

4.6 Can macrocells be deactivated?

Motivated by the good results obtained when deactivating sectors of the macrocell, this simulations aims to explore a new strategy: to deactivate the whole macrocells (3 sectors) when energy shortage is detected.
Regarding total costs graph (Figure 40), it can be appreciated that no energy is bought during the week (spent cost remains flat). That means that total outgo is equal to earned cost, obtained from selling energy. This cost is slightly higher than 8€. From energetic point of view, the network is performing well, as it has extra-energy that can be sold.
However, quality of service is strongly affected by applying this strategy, as it is noticed in Figure 41. At some points, user coverage reaches minimum values of around 10%. When it rises, the network covers almost 100% of the users. The irregularity of this curve is not allowed for providing a good quality of service.

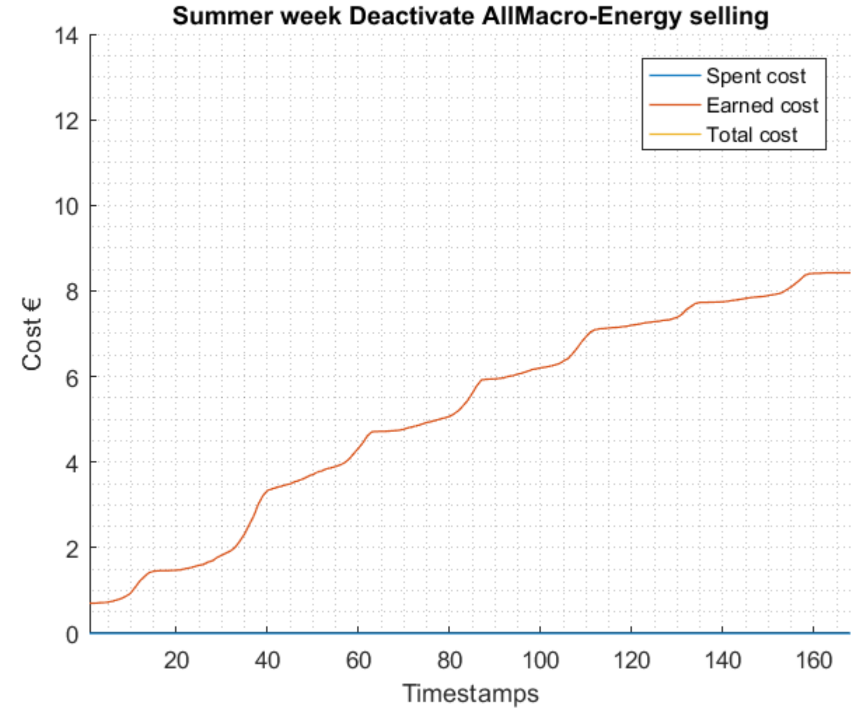


Figure 40: Total Costs-deactivateAllMacro.

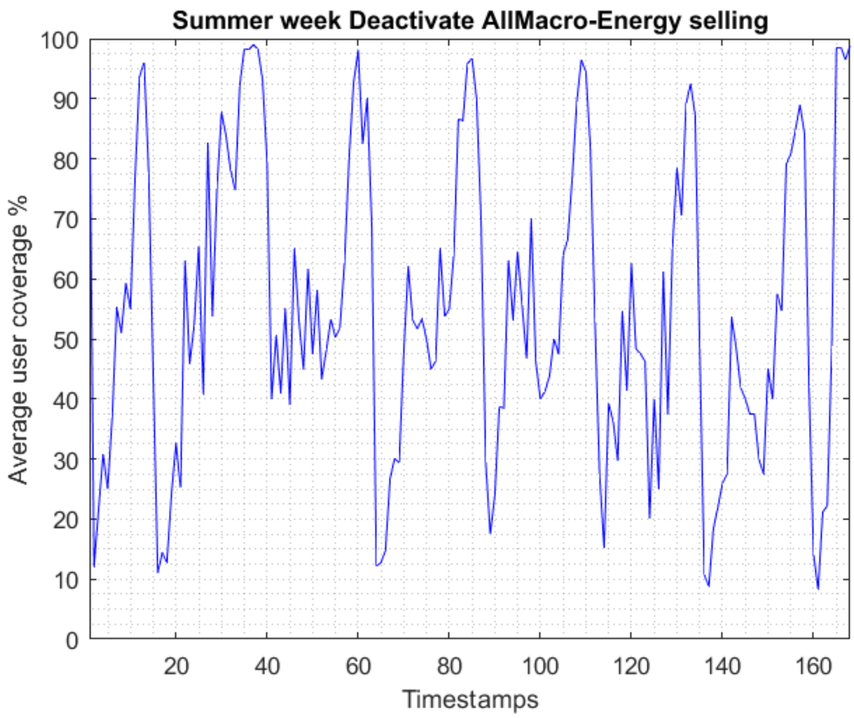


Figure 41: Average user coverage-deactivateAllMacro.

Using only microcells when energy shortage is detected is not enough to cover the users properly in most timestamps, due to the limitations of microcells regarding maximum input power, path loss and bit rate. In addition, macrocells are in charge of control tasks that cannot be delegated to microcells. This strategy could not be implemented in a real scenario.

4.7 Winter-Deactivate All microcells + deactivate 2 sectors of the macrocells

As energy production changes drastically from summer to winter, this last season needs to be analysed too. The most energy restrictive case is going to be considered, as it could be the case in where quaility of service could be affected. If the network performs well when 2 sectors of the macrocells are deactivated, it will be also showing a good performance when only one or none sectors are deactivated.
This simulation will analyse the scenario during winter week when 2 sectors of the macrocells have been deactivated and combined with the strategy of deactivating all microcells when energy shortage is detected.

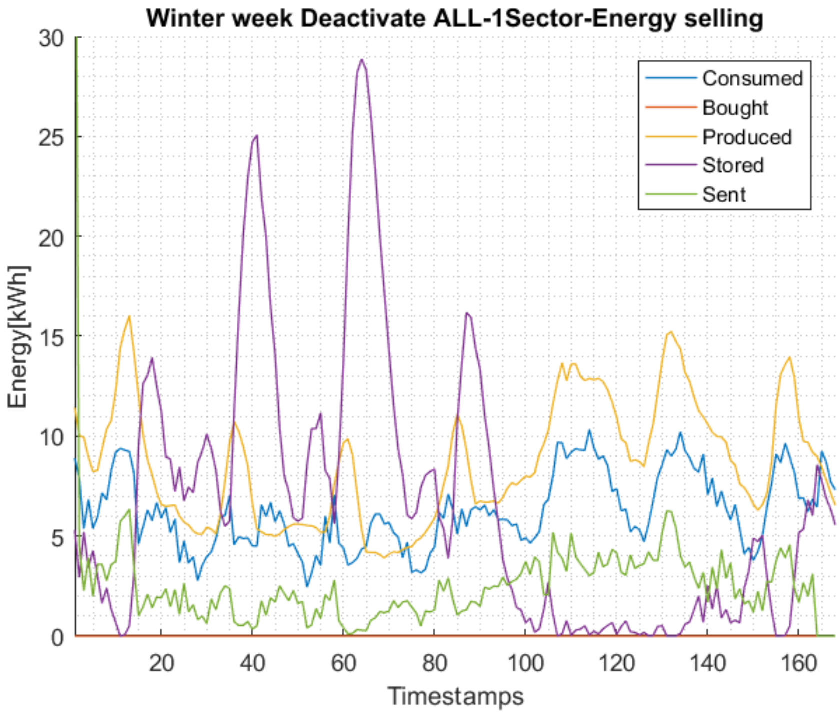


Figure 42: Energy consumption-deactivateAll+2SectorsMacro.

Graph above (Figure 42), as in previous cases, compares: consumed, bought, produced, stored and sold energy. Mean energy produced was, for summer week, 7.2246 kWh. Now, when switching to the data provided by the italian operator during the winter week, mean energy production is 8.6424 KWh.

As more energy is produced, winter scenario will work better than summer scenario regarding the economical aspect, as more extra energy can be sold.

This can be noticed observing the graph. Red line (bought energy) remains flat during all the week, so no energy needs to be purchased. Paying attention to sold energy line (in green) most of the timestamps is not zero, so the network always has extra energy and no energy shortages are detected within the timewindow.

Energy consumption is quite low (average 6.2525 kWh) due to the energy-saving strategies applied. Now, energy produced does not follow a "sinusoidal" shape, because PV panels are not the main contributor to the feeding energy system but windmills, whose production is more irregular.

As in previous cases, when we have overproduction, energy is stored in batteries.

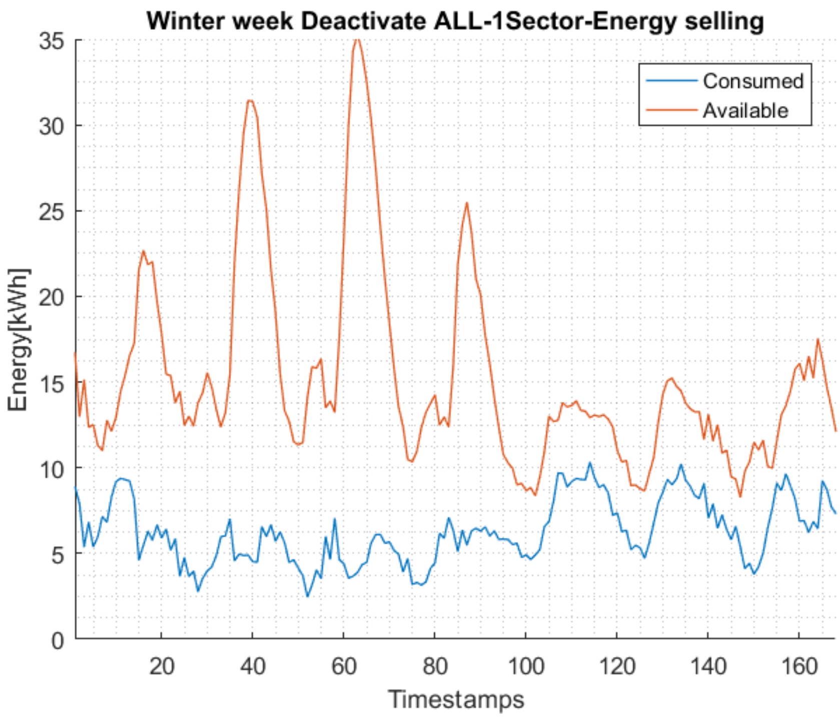


Figure 43: Energy available vs consumed-deactivateAll+2SectorsMacro.

Energy available versus energy consumed graph (Figure 43) shows clearly that not energy shortages will happen. In average, the energy produced plus the energy stored in batteries is 59.21% higher than the energy consumed.

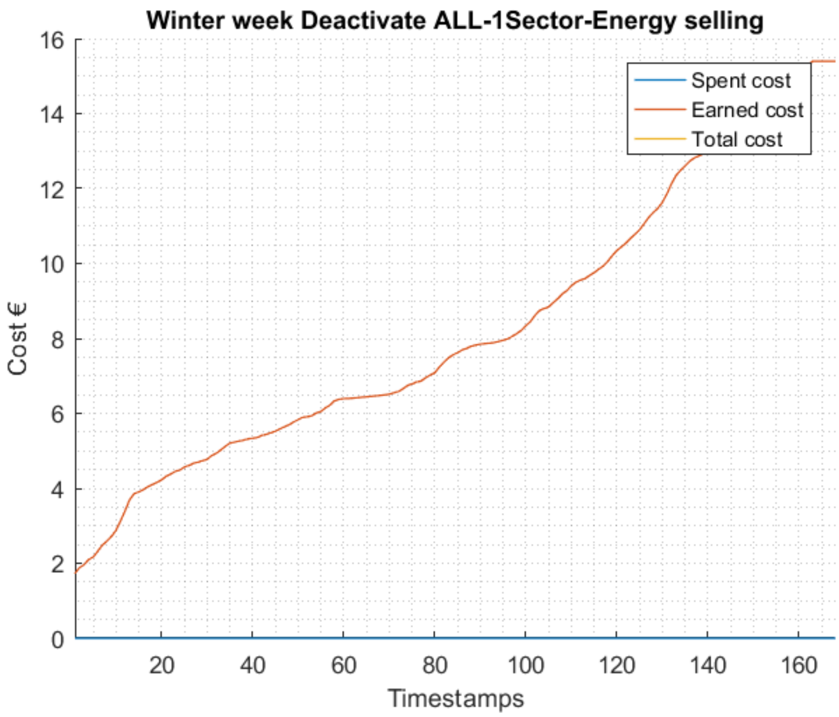


Figure 44: Total Costs-deactivateAll+2SectorsMacro.

In terms of costs, represented in Figure 44, as no energy is bought, the total earned cost is equal to the outgo, and only benefits are obtained.
Concretely, the total amount of earned money at the end of the week is 15.3954€. For the same energy-saving strategies applied in summer, this quantity was 14.6152€, so no big improvements have been achieved.
No major changes can be appreciated in Figure 45 below either regarding to user coverage. Minimum value is 95.4762 %, maximum value is 100%, and mean value is 98.2030%. In all timestamps, user coverage is higher than 95%.

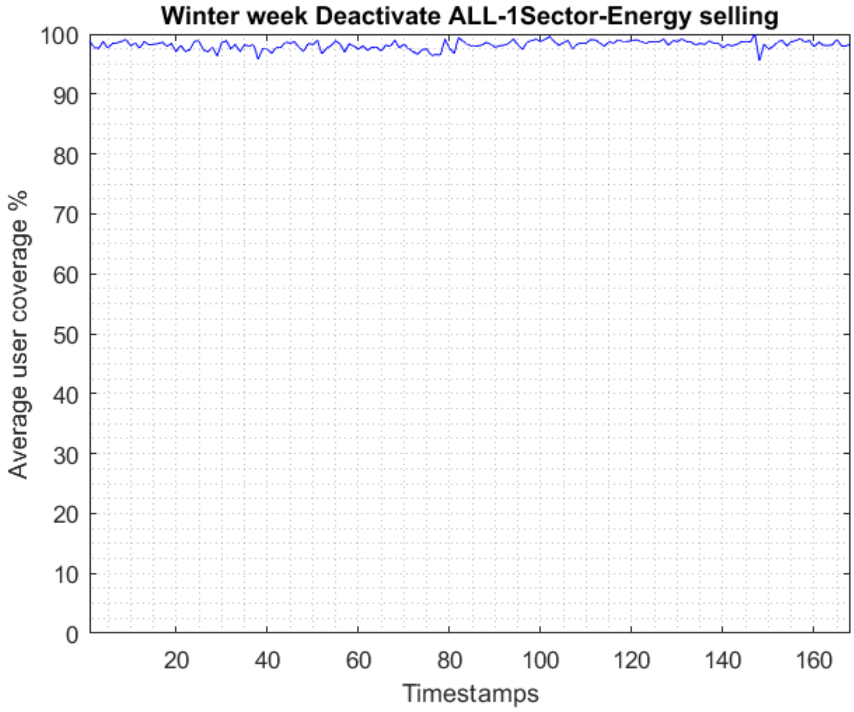


Figure 45: Average user coverage-deactivateAll+2SectorsMacro.

4.8 Winter-deactivate as much microcell BSs as needed (intelligent) + deactivate 2 sectors of the macrocells

To finalise winter simulations, the last energy-saving strategy, consisting on deactivate as much microcells as needed, is analysed when deactivating 2 sectors of the macrocells.
Graph below (Figure 46) shows that, applying this strategy, mean energy consumption has decreased to 5.4224 kWh, which is a reduction by 16.45% with respect to the previous case. Bought energy is still 0 kWh per all timestamps, as the feeding system in addition to the batteries are capable of providing to the network the required amount of power without purchasing extra energy.
As energy consumption is low, the overproduced energy can be sold most of the timestamps, when it does not need to be stored in batteries. Only in 8 timestamps out of 168 energy sold is zero, which means that almost all the week some energy is being injected to the power grid daily.

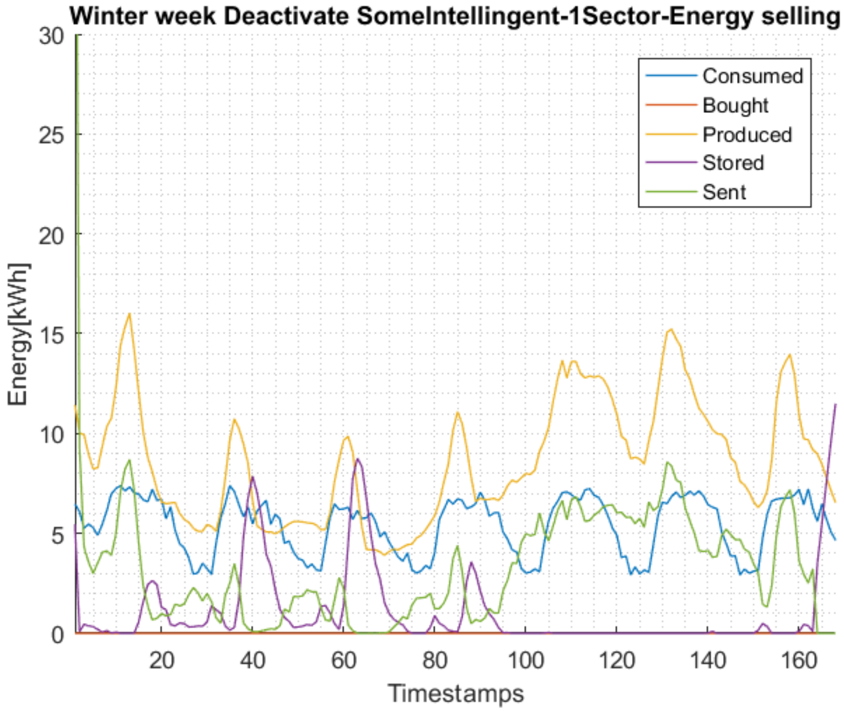


Figure 46: Energy consumption-deactivateSomeMicroIntelligent+2SectorsMacro.

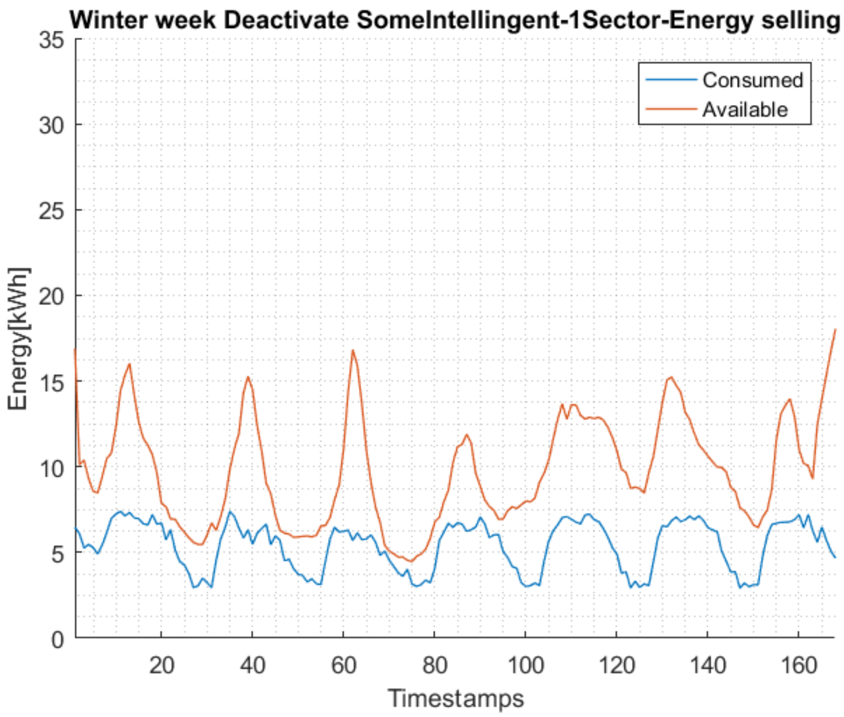


Figure 47: Energy available vs consumed-deactivateSomeMicroIntelligent+2SectorsMacro.

In this case, energy available is 44.54% higher than energy consumed, and it is never below the requirements of the network (Figure 47).
Regarding total costs (48), this simulation provides the best results according to profits, as they are 20.6729€ per week. This value is 25.52% higher than in the previous case, and it rises specially at the end of the week. From timestamp 100 onward, high peaks of energy produced are encountered and large amounts of energy can be sold.

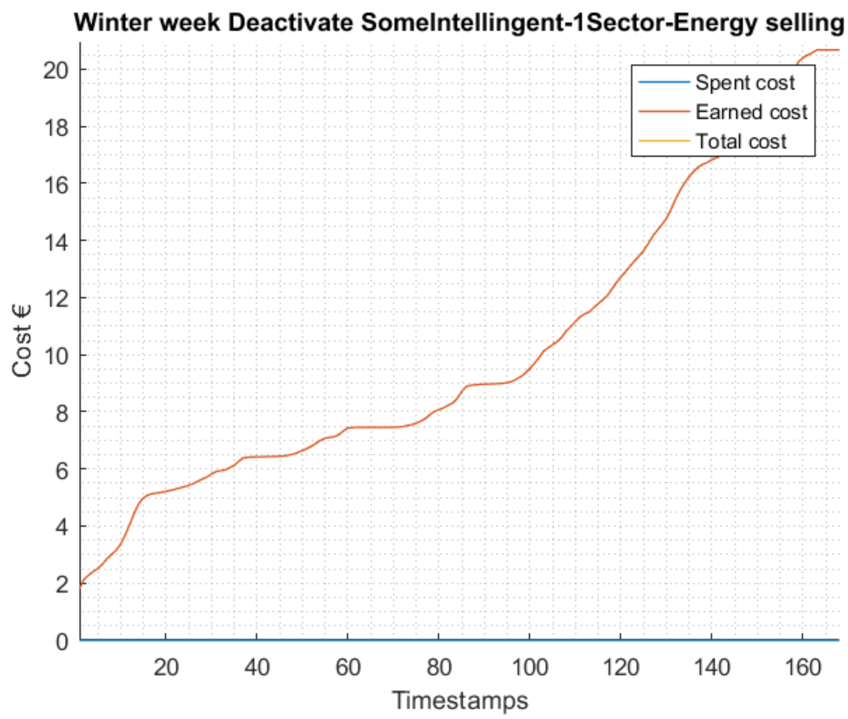


Figure 48: Total Costs-deactivateSomeMicroIntelligent+2SectorsMacro.

4.9 Best vs worst case summer

As a conclusion of all simulations performed in above sections, best case and worst case can be identified and compared in order to quantify the total improvements achieved when introducing all the new features developed for this work.
Worst case was the reference case: summer + undertake no action + 3 sectors per macrocell working. None of the optimization strategies is applied.
Best case is the case which obtained best results: summer + deactivate as much microcells as needed (intelligent way) + deactivate two sectors per macrocell. In the following graphs, they are compared in terms of energy consumption, total costs and user coverage.

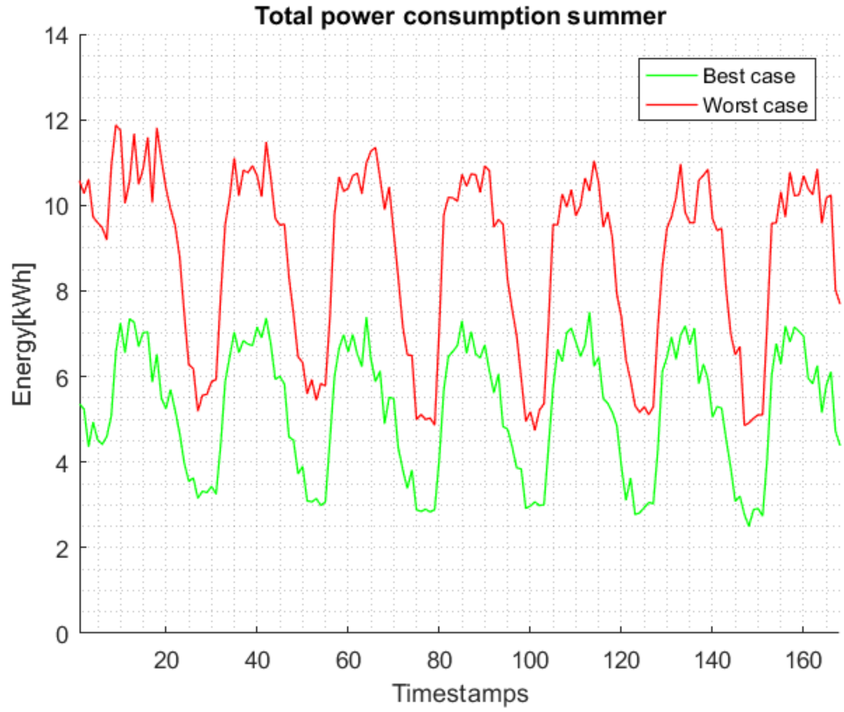


Figure 49: Energy consumption-summer best vs worst case.

Graph above (Figure 49) shows total energy consumption in summer week for both best and worst case. Maximum energy consumption in kWh for the best case is 7.5030 and for the worst case is 11.8735. Regarding minimum values, they are 2.4976 kWh and 4.7390 kWh for best and worst case respectively. Finally, a mean energy consumption of 5.2512 kWh for the best case is achieved, while for the worst case it is 8.7976 kWh.

	Maximum (kWh)	Minimum (kWh)	Average (kWh)
Best case	7.5030	2.4976	5.2512
Worst case	11.8735	4.7390	8.7976
Difference	-4.3705	-2.2414	-3.5464

Table 3: Total energy reduction in summer.

All the improvements just mentioned are summarised in Table 3. A reduction by **40.31%** is achieved in terms of average energy consumption during summer week when implementing two optimization strategies: to deactivate microcells selectively and to turn off some sectors of macrocells.

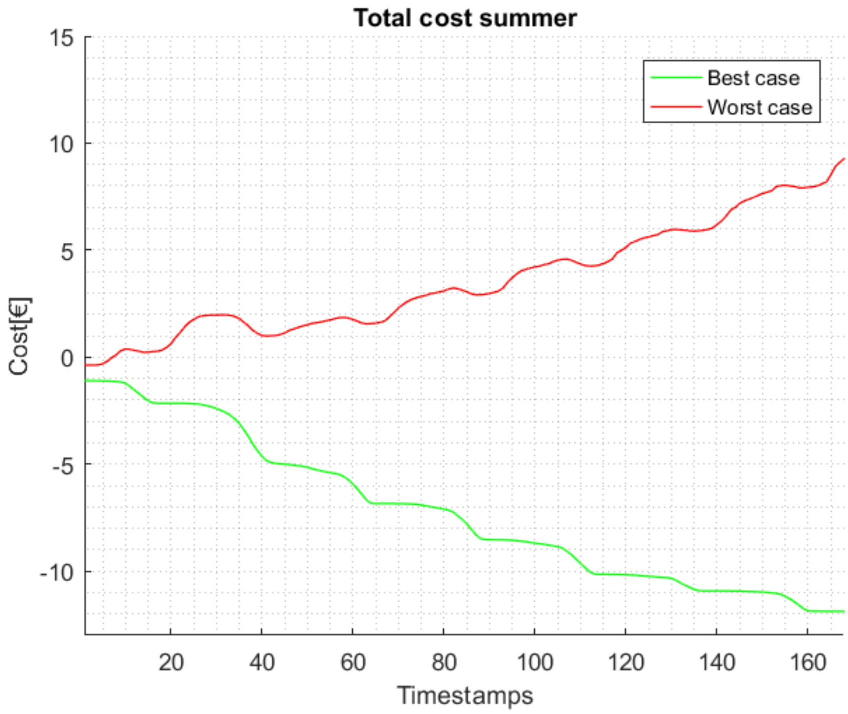


Figure 50: Total cost-summer best vs worst case.

When comparing total costs (50), clear differences can be noticed in the Figure above. Total outgo of the week follows a rising trend when the worst case is analysed and it is below zero only at the beginning when energy stored in batteries is sold. Then, only positive costs (losses) are obtained, reaching a total amount of money of 9.29€ at the end of the week.
However, total costs observed in the best case follow the opposite trend. As the week passes, more benefits are obtained and the total outgo is -11.8770€. This means an improvement of **227.85%** between the worst and the best case, when energy-saving strategies are applied.

	Total cost (€)
Best case	-11.8770
Worst case	9.2900
Difference	+21.167

Table 4: Total costs reduction in summer.

User coverage in the best case versus user coverage in the worst case is plotted in the graph below (Figure 51). Both of them are very similar and once more it is demonstrated that applying energy-saving strategies does not affect quality of service.

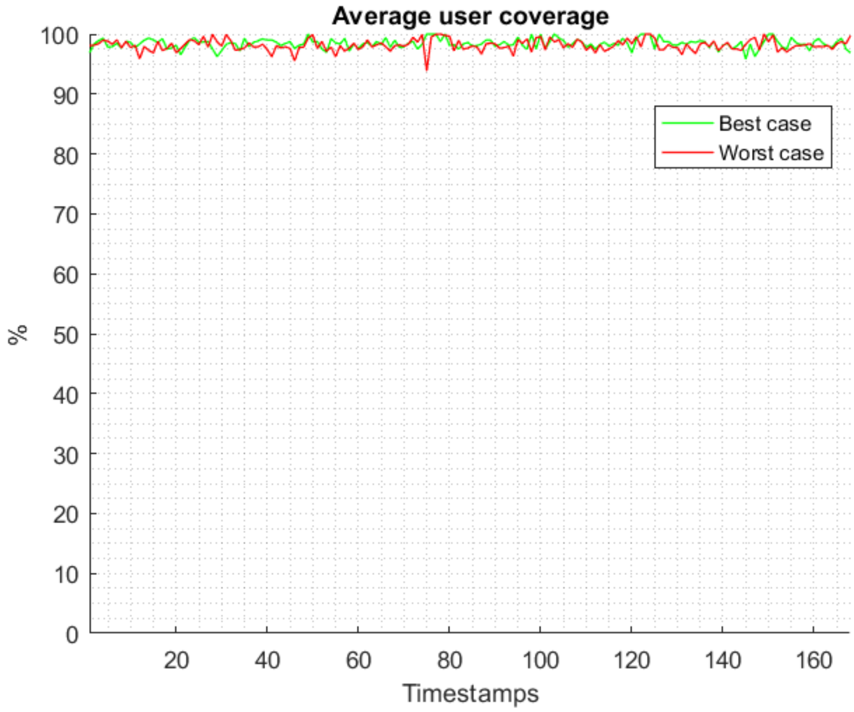


Figure 51: Average user coverage-summer best vs worst case.

4.10 Best vs worst case winter

Same comparison as the previous one is also performed for winter week between the worst and the best case.
Remember that for winter energy production data changed significantly and, due to that change, the network performed better than for summer week.
Graph below (52) shows total energy consumption in winter week for both best and worst case. Maximum energy consumption in kWh for the best case is 7.3971 and for the worst case is 12.5598. Regarding minimum values, they are 2.9159 kWh and 5.5438 kWh for best and worst case respectively. Finally, a mean energy consumption of 5.4224 kWh for the best case is achieved, while for the worst case it is 9.7684 kWh.

All the improvements just mentioned are summarised in Table 5. A reduction by **44.5%** is achieved in terms of average energy consumption during winter week when implementing two optimization strategies: to deactivate microcells selectively and to turn off some sectors of macrocells. This means an increase by 4.19% with respect to the summer week.

Figure 52: Energy consumption-winter best vs worst case.

	Maximum (kWh)	Minimum (kWh)	Average (kWh)
Best case	7.3971	2.9159	5.4224
Worst case	12.5598	5.5438	9.7684
Difference	-5.1627	-2.6279	-4.3460

Table 5: Total energy reduction in winter.

When comparing total costs (Figure 53), same situation as in the previous comparison occurs: both total costs follow the opposite trend. But, in this case, differences are even incremented and higher improvements are achieved.
For the worst case, only positive costs (losses) are obtained, reaching a total amount of money of 5.5071€ at the end of the week.
For the best case, the total outgo is -20.6729€. This means an improvement of **475.38%** between the worst and the best case, when energy-saving strategies are applied.

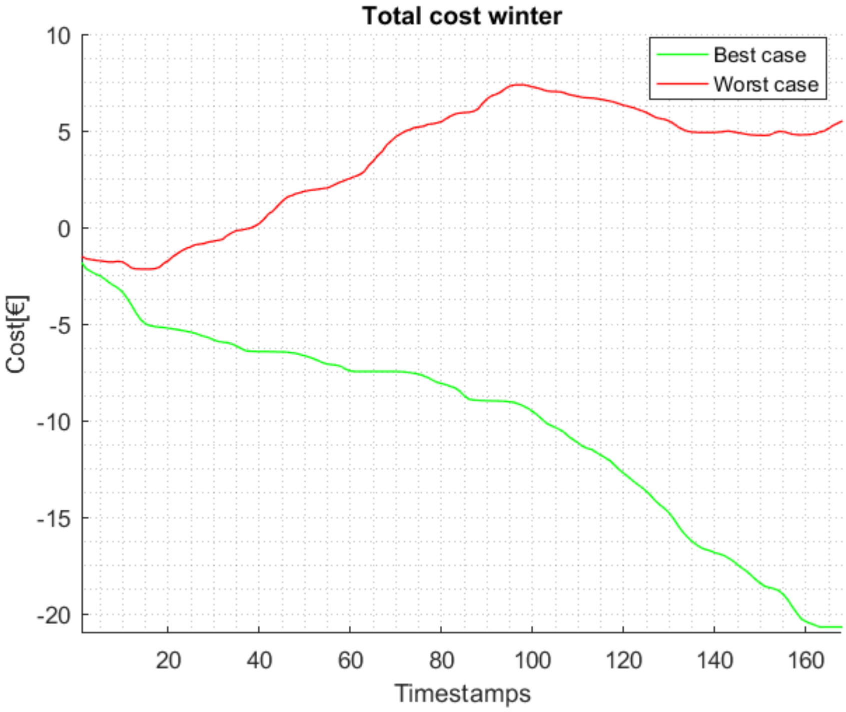


Figure 53: Total cost-winter best vs worst case.

	Total cost (€)
Best case	-20.6729
Worst case	5.5071
Difference	+26.18

Table 6: Total costs reduction in winter.

Costs improvements just mentioned are summarised in Table 6. User coverage is for both cases similar as in the previous comparison, so the graph has been omitted.

5 Other scenarios

Till now, for all performed simulations, the same feeding system has been considered. Remember that it was composed by: 20 kWp for PV panels, 5 wind turbines, and 15% of geothermal energy.
In this section, another scenarios with different feeding systems will be considered in order to explore how it changes the performance of the algorithm.
Two new simulations are performed: one considering only PV panels to feed the network and another one in which only windmills will provide power to the wireless access network.
Both of them will be analysed for the worst case, which means for the season in which they produce less energy.

5.1 Only PV panels

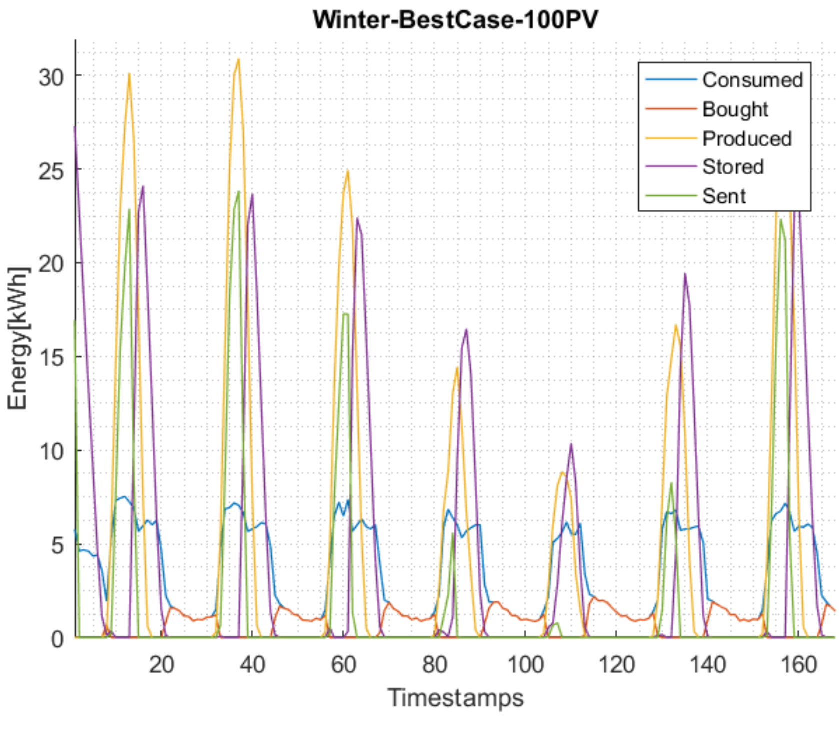


Figure 54: Energy consumption-winter-only PV panels.

For the case in which only PV panels are part of the feeding system, the worst case occurs during winter week, when solar production is much lower than in summer as it was shown in section 3.2 of this work. For this reason, the simulation will be performed for that week and, if the system works properly, it would also demonstrate a good

performance during summer week, when solar production increases significantly.
Note that we cannot just take the correspondent part of PV panels of the previous feeding system, which was only 20 kWp. Only this resource could not feed the network by itself and energy would need to be purchased too often.
Because of this, energy system generator will be composed by 100 kWp for this simulation. In addition, the best combination of energy-saving strategies is applied: to deactivate some microcells and to turn off two sectors per macrocell.
Figure above shows (54), as in previous cases, the comparison between: consumed, bought, produced, stored and sold energy. Produced and sold energy follow exactly the same tendency: both are narrow peaks produced during the mid-hours of the day. PV panels produce high amounts of energy that are more than enough for feeding the network, as the consumption is much lower than the production. For this reason, large quantities of energy can be sold everyday at peak hours. Once energy production is decreasing, it is being stored in batteries, in order to feed the network.
However, at nights, no spare energy remains stored in batteries and small quantities of energy need to be purchased.
The system is not completely self-sufficient.

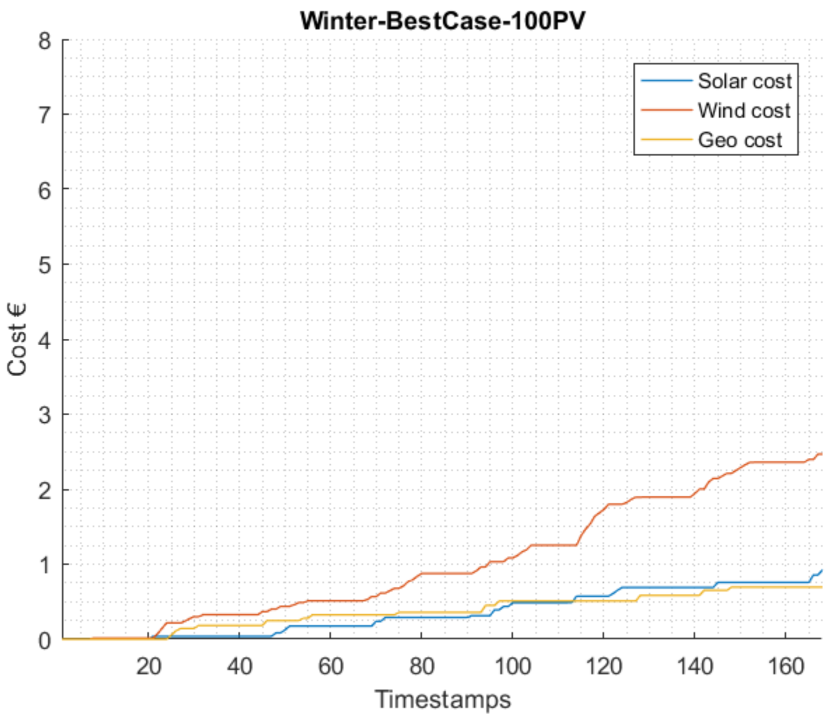


Figure 55: Energy bought-winter-only PV panels.

This bought energy at nights comes from the three sources showed in Figure 55. Once more, wind energy is the most bought due to its lower LCOE, but at some point energy is purchased also from another renewable energy sources.

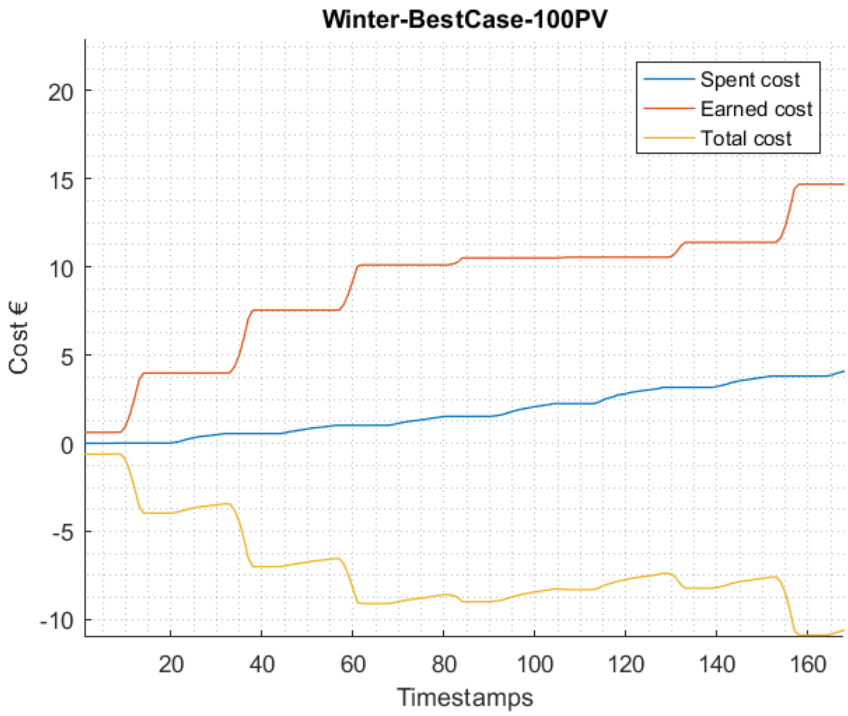


Figure 56: Total costs-winter-only PV panels.

Regarding total costs (56), as the amount of bought energy is significantly lower than the amount of sold energy, benefits will be obtained.
Total spent cost is at the end of the week 4.0870€ and the amount of earned money by selling energy is 14.6875€. This means a total weekly outgo of -10.60€ during winter when only feeding the system using solar energy.

5.2 Only wind energy

The last simulated scenario for this work consists on a situation in which the access network is totally powered by wind turbines. The feeding system will be composed by five wind turbines and the considered week is summer week, as it is the season when wind production is scarce (worst case).

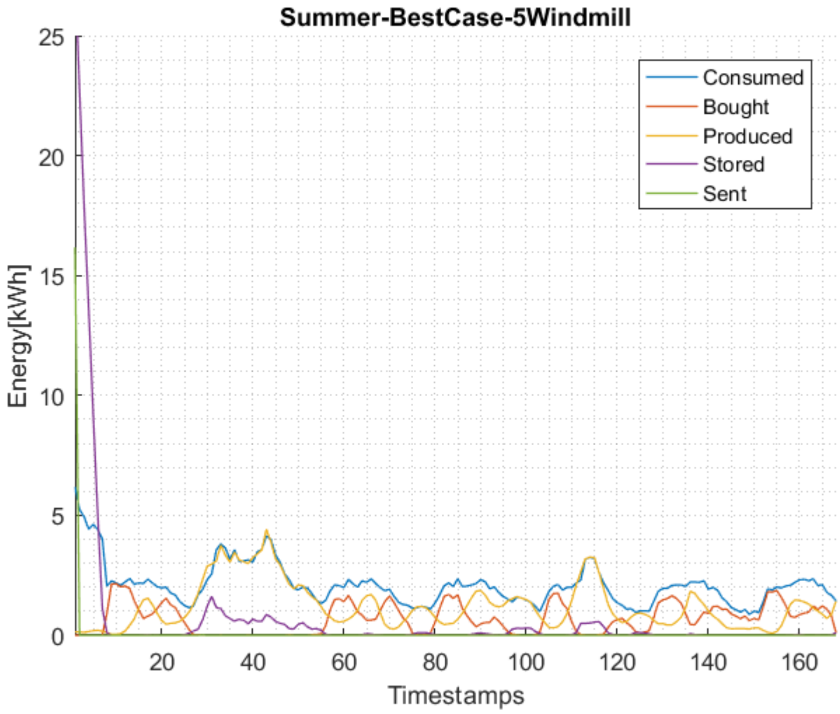


Figure 57: Energy consumption-summer-only windmills.

Figure 57 above shows that the algorithm's performance is not being good in this case. Wind production in summer is really low (average per timestamp is 1.2156 kWh) and it never overcomes consumed energy (average per timestamp 2.1016 kWh). This means that extra energy needs to be purchased most of the timestamps (162 out of 168).

As a consequence, sold energy is null along the week, as the same way as the stored energy. No spare energy is available neither for store or sell it due to the low energy produced by wind turbines.

This poor performance is in addition reflected in costs graphs below (58 and 59). In this case, no benefits but losses are obtained, as spent costs are higher than earned costs (only appear at the beginning, when energy stored in batteries is sold). The total outgo is 4.0273€ per summer week when only windmills are used. This scenario would not be suitable for implementation in a real case.

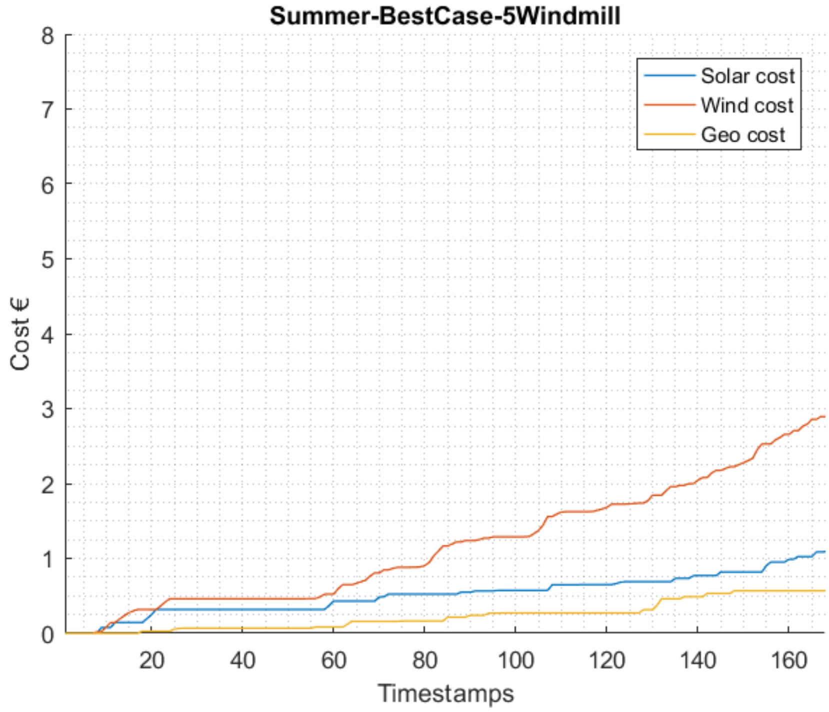


Figure 58: Energy bought-summer-only windmills.

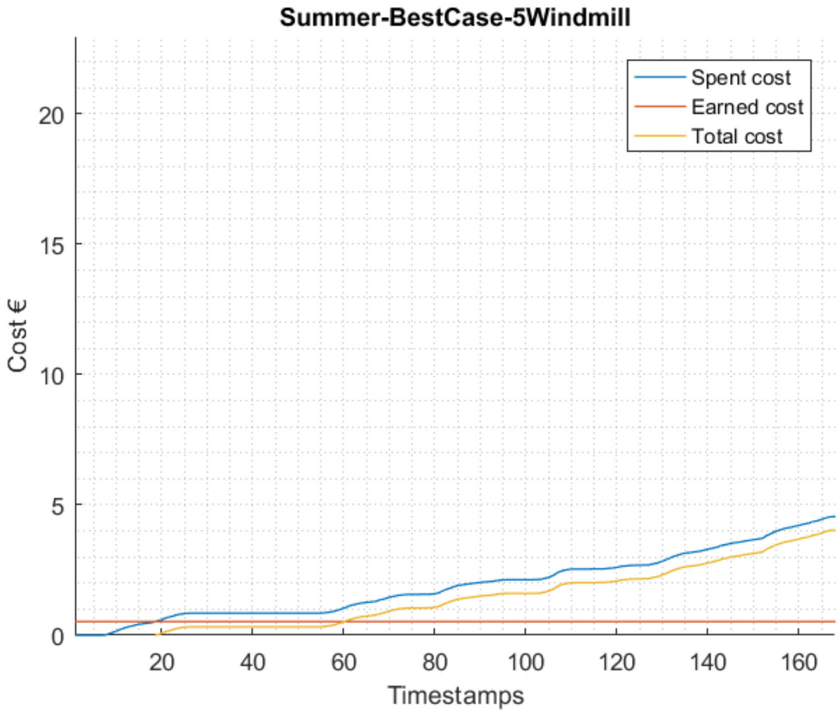


Figure 59: Total costs-summer-only windmills.

6 Conclusions

7 Bibliography

References

[1] SISTEMAS DE COMUNICACIONES MÓVILES: SEGUNDA, TERCERA Y CUARTA GENERACIÓN. Juan Pascual García, José María Molina García-Pardo,Leandro Juan Llácer, 2014, ISBN: 978-84-16325-03-0

[2] IEA, Global electricity generation mix, 2010-2020, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-electricity-generation-mix-2010-2020

[3] Lotfi Belkhir, Ahmed Elmeligi, Assessing ICT global emissions footprint: Trends to 2040 and recommendations, Journal of Cleaner Production, ISSN 0959-6526, `https://doi.org/10.1016/j.jclepro.2017.12.239`

[4] IRENA (2020), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi.

[5] Blume, Oliver & Zeller, Dietrich & Barth, Ulrich. (2010). Approaches to energy efficient wireless access networks. Proc of ISCCSP 2010. Limassol, Cyprus. 1 - 5. 10.1109/ISCCSP.2010.5463328.

[6] Silvia Bova, Design and optimization of energy-efficient wireless access networks powered by renewable energy sources. Politecnico di Torino, Corso di laurea magistrale in Ict For Smart Societies (Ict Per La Società Del Futuro), 2020

[7] Vallero, G.; Deruyck, M.; Meo, M.; Joseph, W. Accounting for Energy Cost When Designing Energy-Efficient Wireless Access Networks. Energies 2018, 11(3), 617; `https://doi.org/10.3390/en11030617`.

[8] M. Deruyck, W. Joseph, E. Tanghe, L. Martens, Reducing the power consump- tion in LTE-Advanced wireless access network by a capacity based deployement tool, Radio Sci. 49 (9) (2014)

[9] `https://www.terna.it/it/sistema-elettrico/transparency-report/renewable-generation`

[10] `https://my.elexys.be/MarketInformation/SpotBelpex.aspx`