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Design and Optimization of Energy-Efficient Wireless Access Networks Power by Renewable Energy Sources

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Abstract

Currently, data traffic on the Internet is growing rapidly and the Wireless Access Network has a key role in this context. Communication Network is in charge of providing seamless connectivity and great quality of service (QoS) to the end-users, and a large amount of energy is involved to accomplish this task. Besides network performance, energy efficiency becomes an important matter. The price of energy from fossil fuel is continuously rising, the risk for depletion in the future is concrete, and the energy provisioning from hydrocarbon has an impact on global CO_2 emission. In this context, carbon-low impact alternatives, like renewable energy supply, represent a possible solution.

In this thesis, strategies and algorithms to manage the renewable energy accounting and to ensure good energy and network performance are investigated. The deployment tool simulates an LTE-A network, that implements energy-saving techniques and is provided of energy provisioning and storage system. Solar, wind, and geothermal contribute to energy production and the sources are managed in a centralized manner. Two implementations of the energy management system are proposed and compared. On the one hand, regardless of the network consumption, a static energy system guarantees the participation of all the available resources to the energy generation. For example, if the system is equipped with solar panels and wind turbines, the centralized management system will statically use the whole available capacity even if the network does not need a large amount of energy to be fed. On the other hand, in dynamic energy system, a heuristic search algorithm based on the current energy consumption of the network will choose the most suited energy provisioning system layout.

The study demonstrates that the reduction of energy consumption is effective in the drop in the amount of bought energy, but the choice of energy supply resources is fundamental to achieve the goal. The results are promising to further investigation and implementation.

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Chapter 1

Introduction

Nowadays the worldwide population is increasingly becoming *internet addicted* and Information and Communication Technologies (ICT) are an integral part of our lives. Smartphones and other mobile devices, such as laptops, tablets, and smart things are affordable for everyone and they all need to be interconnected through the Internet.

The wireless access network is in charge of this task: it runs from the service provider's facilities to the end-user installations and it must provide seamless connectivity and great quality of service (QoS). Besides network performance, today energy efficiency is one of the main goals to achieve. The number of users is constantly increasing and wireless access networks are playing a more and more important role in global greenhouse emission since the amount of energy for ICT is rising dramatically. The increasing number of wireless devices that are accessing mobile networks worldwide is one of the primary contributors to global mobile traffic growth. Each year several new devices in different form factors and increased capabilities and intelligence are introduced in the market. In 2015, global mobile devices and connections grew to 7.9 billion, up from 7.3 billion in 2014. Globally, mobile devices and connections will grow to 11.6 billion by 2020 [2]. Regionally, North America and Western Europe are going to have the fastest growth in mobile devices and connections with 22% and 14% from 2015 to 2020, respectively (Fig. 1.1). We see a rapid decline in the share of nonsmartphones from 50% in 2015 (3.9 billion) to 21% by 2020 (2.4 billion). The most noticeable growth is going to occur in Mobile-to-Mobile (M2M) connections, followed by tablets. M2M mobile connections will reach more than a quarter (26%) of total devices and connections by 2020.

Mobile devices and connections are not only getting smarter in their computing capabilities but are also evolving from lower-generation network connectivity (2G) to higher-generation network connectivity (4G or LTE). Combining device capabilities with faster, higher bandwidth and more intelligent networks leads to wide adoption of advanced multimedia applications that contribute to increased mobile and Wi-Fi traffic. Service providers around the world are busy rolling out 4G networks to help them meet the growing end-user demand for more bandwidth, higher security, and faster connectivity on the move.

In this work, the wireless access network will be analyzed, and in particular, the attention will be focused on LTE-A technologies and power consumption handling and smart energy provisioning through different renewable energy systems.

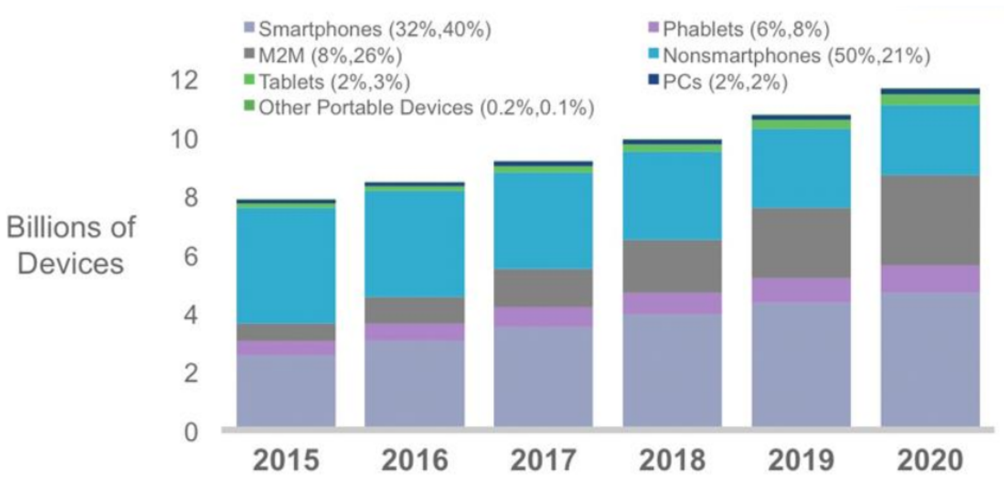


Figure 1.1: Global Mobile Devices and Connections Growth

1.1 Technological overview

The access network is the *"last leg"* of the telecommunication network, and it allows the communication between users' equipment and the whole network. Access networks can be categorized into two main types: wired if the link with customers relies on physical equipment like twisted pairs, coaxial cables or optical fiber, and wireless if the information is transmitted through the air using electromagnetic waves.

This thesis focuses on the analysis of a wireless broadband communication network for mobile devices, that works on LTE-A (Long Term Evolution- Advanced) technology. LTE provides high data rates and low latency and its network architecture has been designed to support packet-switched traffic with seamless Internet Protocol (IP) connectivity and great quality of service, without any disruption to the end-users' applications during mobility. LTE network is organized as a cellular network: it is distributed over areas called cells, each served by at least one transceiver. The high-level network architecture of LTE is comprised of the following three main components, as shown in Figure 1.2:

- Evolved Packet Core (EPC)
- Evolved Universal Terrestrial Radio Access Network (E-UTRAN)
- User Equipment (UE)

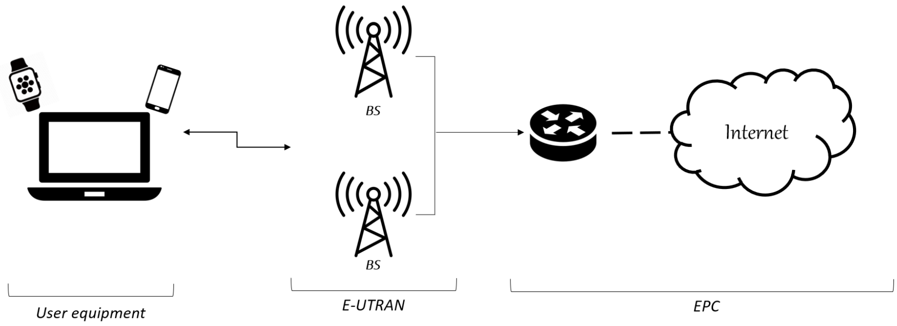


Figure 1.2: LTE architecture

Evolved packet core (EPC)

The evolved packet core is a framework to track and route data packets through the network, manage quality of service (QoS) and support deep packet inspection. The big enhancement introduced by EPC is the unification of voice and data on an Internet Protocol (IP) service architecture, in contrast to previous 2G and 3G network architectures.

E-UTRAN

The E-UTRAN handles the radio communication between the mobile and the evolved packet core and has just one component, the Base Stations. Each Base Station (BS) or Base Transceiver Station covers a cell. Different set of frequencies are typically used among neighboring cells, to avoid overlapping signals and interference. Based on the desired coverage area, different Base Station types are defined according to its output power:

- Macrocell Base Station: it provides the largest coverage area (from 5 Km to 32 Km of Coverage Radius) and for this reason can be often found along highways;
- Microcell Base Station: it provides a smaller coverage area than a macrocell Base Station (from 1 Km to 2 Km of Coverage Radius) and is typically used in densely populated areas such as historical city centers, metro stations, etc.;

- Small cell Base Station (femtocell or picocell): it provides the smallest coverage area (from 10 m to 200 m of Coverage Radius) and it is mostly placed indoor in offices and in large buildings to provide indoor coverage.

According to [1] power consumption of a macrocell base station is 4.4 times higher than the microcell base station due to the higher input power and the higher power consumption of its air conditioning. However, the energy-efficiency of macrocell base stations is greater than microcell base stations: the power consumption in the same area is about 4 to 18 times lower for a macrocell base station than for a microcell base station.

User equipment (UE)
The User Equipment is the equipment designed for consumer use. It is any device used by an end-user such as a smartphone or other mobile device, laptop, or tablet equipped with a mobile broadband adapter. Nowadays such devices become more and more widespread. Among all, smartphones which entered our lives since the end of '90, when the first mobile phone was marketed for both commercial and private purpose. In the early beginning, it was only capable of phone calls. Today smartphones are very powerful devices, performing many activities like reading/writing emails, watching streaming videos, sending messages and visiting social networks. This increasing trend results in higher traffic demands than before due to the large number of users, doubled by the introduction of the Internet of Things (IoT), and the greater data rate required to perform heavy activities like video-streaming or video-calls. As a consequence, it is expected [2] that the amount of bytes will be more than triplicated in 2022 with respect to 2017, as shown in Figure 1.4.

1.2 Renewable resources outline

More and more often, we hear about climate change debate and renewable energy is in the spotlight. The well known renewable energy sources include wind power, solar power, hydropower, geothermal energy, biofuels and the renewable part of the waste. The use of renewable energy has many potential benefits, including a reduction in greenhouse gas emissions, the diversification of energy supplies and a reduced dependency on fossil fuel markets, as well as some disadvantages like its virtually inexhaustible in duration but limited in the amount of energy available per unit of time. Due to the rising renewable energy popularity, in the recent decade, we have witnessed significant technological developments and rapid falling of renewable power generation costs.

In this work, three main energy sources will be examined:

Solar power

Solar resources are available in every country and both solar photovoltaic (PV) and concentrating solar power (CSP) technologies can be used to convert this solar resource into electricity. Solar PV can use both direct and diffuse sunlight to create power, while CSP relies on direct sunlight. Solar PV is more common than CSP: in fact, solar PV deployment reached 291 GW at the end of 2016, while the deployment of CSP is still in its infancy at 5 GW [3]. In this work, the focus is on photovoltaic solar panels.

Photovoltaics, also called solar cells, are electronic devices that convert sunlight directly into electricity. Their modular size means that they are within the reach of individuals, co-operatives, and small businesses who want to access their own generation. PV technology offers a number of significant benefits, including:

- Solar power is a renewable resource that is available everywhere in the world.
- Solar PV technologies are small and highly modular and can be used virtually anywhere
- Solar PV has no fuel costs and relatively low operation and maintenance (O&M) costs.
- PV, although variable, has a high coincidence with peak electricity demand.

There is a wide range of PV cell technologies on the market today, using different types of materials. First-generation PV systems are mainly used for commercial reasons and fit with the purpose of this thesis. Typical materials employed in the construction of the modules of this technology are crystalline silicon (c-Si) technology, either single crystalline (sc-Si) or multi-crystalline (mc-Si). This analysis will focus on crystalline silicon modules and its efficiency ranges from 14% to 19%. They are the ones that dominate the market thanks to their low costs and the best commercially available efficiency.

Wind power

Wind power technologies have two main characteristics: the axis of the turbine and the location. The axis of the turbine can be vertical or horizontal and the location can be onshore or offshore. The current average size of grid-connected wind turbines is around 1.16 MW, while most new projects use wind turbines between 2 MW and 3 MW. [4] The utility-scale market for wind technologies uses almost exclusively horizontal axis turbines. The amount of electricity generated by a wind turbine is determined by nameplate capacity (in kW or MW), the quality of the wind resource, the height of the turbine tower and the diameter of the rotor. Wind turbines typically start generating electricity at a wind speed of 3-5 meters per second (m/s), reach maximum power at 11-12 m/s and generally cut out at a wind speed of around 25 m/s. [5]

Wind power can be divided mainly into two categories: onshore wind turbines and offshore. Offshore wind power is related to wind energy generation over open water, usually in the ocean. Wind farms are constructed in bodies of water where higher wind speeds are available. Onshore wind power refers to turbines that are located on land and use the wind to generate electricity. They are generally located in areas where there is low conservation or habitat value. The cost of onshore wind farms is relatively cheap, allowing for mass farms of wind turbines.

Wind power has experienced a somewhat unheralded revolution since 2008-09. Between 2008 and 2017, improved technologies, such as higher hub heights and larger areas swept by blades, have increased capacity factors for a given wind resource. At the same time, installed costs have fallen as wind turbine prices have declined from their peak in 2008-09. With these factors all spurring increased deployment. [4]

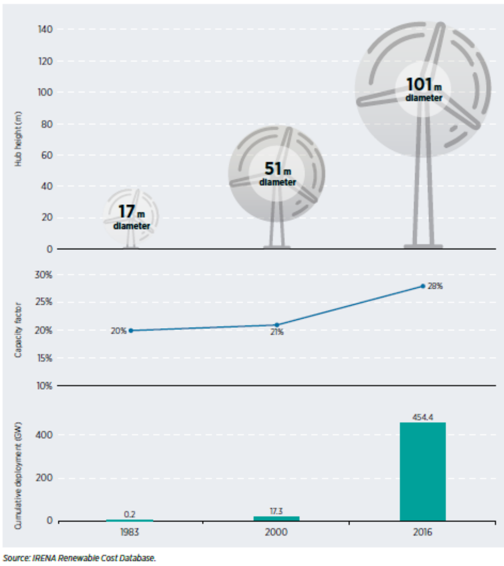


Figure 1.3: Global weighted average hub height, rotor diameter and capacity factors, and cumulative capacity for onshore wind, 1983-2016

Geothermal energy

Geothermal resources are found in the Earth's crust, in active geothermal areas on or near its surface and at huge depths. These resources consist of thermal energy, stored as heat in rocks of the Earth's crust.

Depending on its characteristics, geothermal energy can be used for heating and cooling purposes or be harnessed to generate clean electricity. However, for electricity generation, high or medium temperature resources are needed, which are usually located close to tectonically active regions. Reach this distance needs expansive techniques. Extensive geothermal resource mapping can reduce the costs of development, by minimizing the uncertainty about where initial exploration should be conducted. Poorer than expected results during the exploration phase might require additional drilling or wells may need to be deployed over a much larger area to generate the expected electricity. Once productivity at existing wells declines, there might also be a need for replacement wells to make up for the loss in productivity.

Three types of geothermal power plants are in operation today:

- *Dry steam plants* use steam directly from a geothermal reservoir to turn generator turbines. The first geothermal power plant was built in 1904 in Tuscany, Italy, where natural steam erupted from the earth.
- *Flash steam plants* take high-pressure hot water from deep inside the earth and convert it to steam to drive generator turbines. When the steam cools, it condenses to water and is injected back into the ground to be used again. Most geothermal power plants are flash steam plants.
- *Binary cycle power plants* transfer the heat from geothermal hot water to another liquid. The heat causes the second liquid to turn to steam, which is used to drive a generator turbine.

In this thesis binary cycle power plants are considered, since they allow cooler geothermal reservoirs to be used than is necessary for dry and flash steam plants. They are more expensive but allow to apply the technology widely.

1.3 Renewable Energy in Wireless Access Network

ICT is increasingly becoming an integrated part of people's daily activities, and advanced mobile networks (LTE) reached almost half of the world population. In the least developed countries, mobile access was on average significantly cheaper than fixed broadband access [6].
The exponential growth of transmitted data corresponds to a huge quantity of consumed energy. In 2012, close to 15% of the world's total electrical energy that is being produced was consumed by ICT, amounting to around 150,000 TWh. Power consumption has an impact also on pollution. ICT technologies release into the atmosphere roughly 1.7% of the total CO_2 emissions [7]. These numbers are

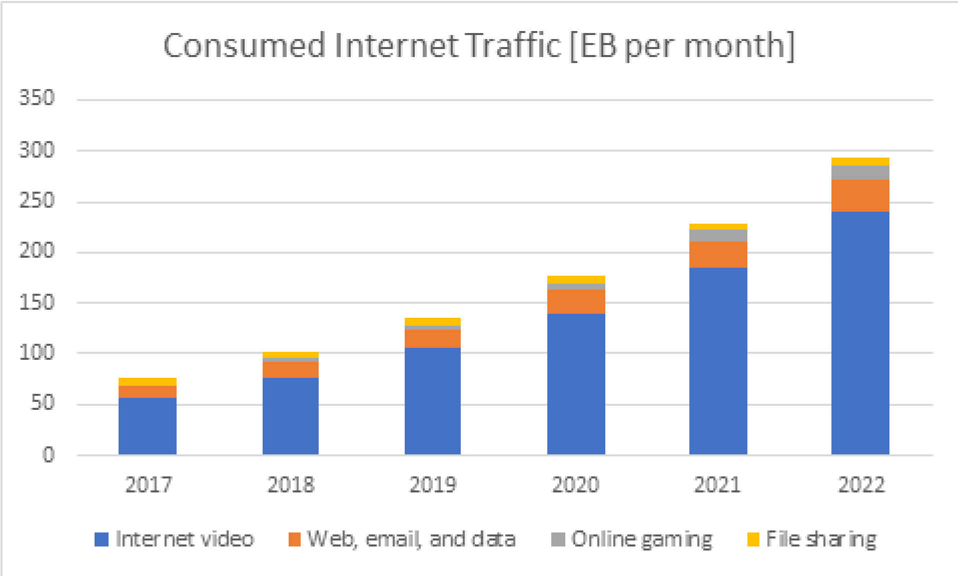


Figure 1.4: Global consumer internet traffic from [2], 2017–2022

growing, although the improving energy efficiency of ICT equipments leads to a slower growth of these metrics. Even though mobile broadband connections hold great potential for positive social impacts, estimated increase in mobile networks energy consumption requires attention. This issue has become an important matter for both the planet and the wallet. Several projects and organizations, such as Energy Aware Radio and Network Technologies (EARTH), have been set up to develop more energy-efficient architectures and techniques. Therefore, workshops have been organized at many international conferences, such as ICC and GLOBECOM [8].

Traditionally, fossil fuels are consumed for energy supply in a number of ways, including transport, heat and electricity production. In the chart we see the relative share of coal, natural gas and oil in electricity mixes across the world over the last few decades. At the global level we see that coal is the dominant electricity source accounting for approximately 40% of total electricity production. This is followed by natural gas at approximately 22%, oil at only 4% [9].Overall, the share of fossil fuels in global electricity production has not changed significantly over the decade from 2005-2015 (Fig. 1.5. Comparing these numbers to the years pre-2000, the share of fossil fuels in the global electricity mix has in fact increased slightly, despite the need for energy decarbonisation. Burning fossil fuel in fact has an impact on climate change, then some of this stagnation in progress can be explained by the offsetting of an increase in renewable electricity. Moreover, recent years have seen dramatic reductions in renewable energy technologies' costs

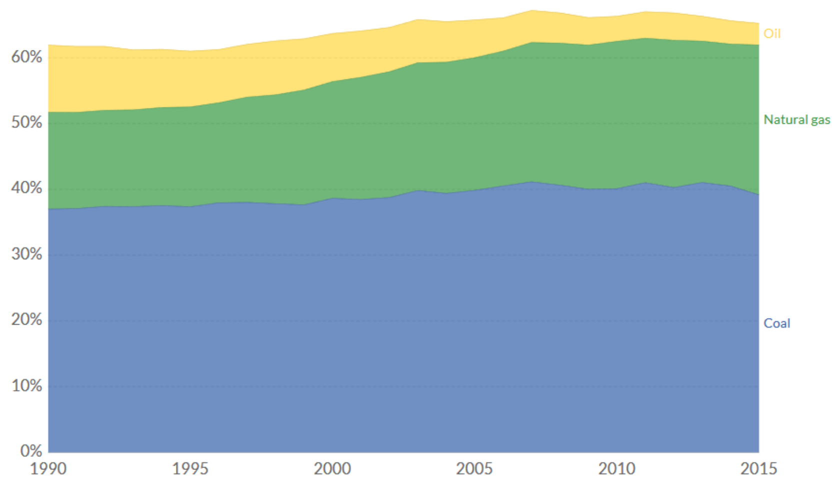


Figure 1.5: Share of electricity production from fossil fuels all over the World

as a result of accelerated deployment, for this reason renewable energy has gone mainstream.
In this scenario, renewable power generation can help to meet sustainable development goals through the provision of access to clean, secure, reliable and affordable energy. Besides that, supplying wireless access network through renewable energy sources can be a successful policy in remote areas, where the main power grid is not always reliable.

1.4 Goal of the thesis

The final goal of this master thesis is to analyze the behavior of the wireless access network powered by renewable energy sources. The optimality of technical requirements and energetic performance will be investigated. Besides solar generation, wind and geothermal energy will be integrated into the power supply system, and the energy optimization will be done based on the minimization of total installed costs and operational and maintenance costs. This would encourage investment from telecommunication companies.

1.5 Thesis organization

These are the topics treated in each chapter.

Chapter 2: State of the Art

This chapter discusses the most important studies from the literature that can be useful for the thesis. Attention is paid in particular to the energy-efficient access network tool proposed by WAVES, a research group from Ghent University. It implements a capacity-based network and minimizes energy consumption through specific energy strategies that are explained in this chapter. It is used as the starting point of this study and for this reason, its operation is described in detail. The chapter ends with a detailed analysis of the RES costs trend in recent years. This information will be used in the following chapters for the techno-economic optimization of energy resources.

Chapter 3: Methodology and Settings

In this chapter, the proposed scenario and system configuration are described. The second part of the chapter focuses on the illustration of the strategy used to minimize the total bought energy and wasted power. Parameters that can be affected, such as the capacity of the network, the user coverage, etc. are discussed as well as costs metrics used in the techno-economic analysis.

Chapter 4: Simulations and Results

In this chapter, the results obtained are presented and analyzed for each proposed scenario. Results are not presented in terms of network performances only, but also in terms of cost parameters introduced in Chapter 3.

Chapter 5: Conclusion

Conclusions and considerations based on the results mentioned in Chapter 4 are discussed. Possible future works are mentioned.

Chapter 2

State of the art

2.1 Energy saving in wireless access network

Since their introduction in the late 1970s, the design objectives for cellular networks have been maximum throughput, spectral efficiency and meeting Quality of Service (QoS) requirements rather than energy efficiency. It is now widely acknowledged that cellular communication networks have greater economic and ecological impact: a mobile phone network may consume approximately 40-50 megawatts (MW), even excluding the power consumed by the users' handsets [11]. Reducing energy consumption may affect operating expenditure (OPEX) costs and capital expenditure (CAPEX) costs. Capital expenditure is incurred when a business acquires assets to make the system up running, for instance new equipment or buildings. Operational expenditure consists of those expenses that a business incurs to run smoothly every single day. They are the costs that a business incurs while in the process of turning its inventory into an end product. Boosting energy-savings will affect the OPEX since maintenance costs will be reduced, but improving the technologies to will have an impact on CAPEX.

In [10] different technological approaches to reduce energy consumption are classified in five distinct categories:

- *Improving energy efficiency of hardware components.* Most of the components have unsatisfactory performances: considering, for example, the power amplifier, the component dissipates more than 80% of the input energy as heat, and only around 5% to 20% of the input power is useful as output power [10]. In [11] Han et al. prove that improving the efficiency of the Power Amplifier (PA) increases the overall Base Station performance by at least 50%. One solution reduces inefficiencies by locating the PA next to the antennas in order to minimise the power lost in feeders cables. This architecture also further reduces the need for cooling. However, careful consideration in both operational and economical aspects by network operators is required before decisions on hardware replacement are made.

- *Turning off components selectively.* Usually, wireless access networks are dimensioned for peak hours traffic. Monitoring the traffic load during the day, it is possible to deactivate some resources (e.g. Base Stations (BS)) during off-peak hours, through sleep mode techniques. However, BSs deactivation can have some drawbacks, impacting QoS in the network. *Oh, et al.* in [12] discussed the dynamic operation of cellular Base Stations. They proved that during periods of low traffic, some redundant BSs can be switched off to provide significant energy savings.

- *Optimizing energy efficiency of the radio transmission process.* This optimization category works on physical or MAC layer: advanced techniques including MIMO technique, cognitive radio transmission, cooperative relaying, channel coding and resource allocation for signaling have been studied to improve the energy efficiency of telecommunication networks.

- *Planning and deploying heterogeneous cells, including micro, pico, and femtocells.* As explained in [10], this implementation reduces energy consumption in the network by shortening the propagation distance between nodes in the network and utilizing higher frequency bands to support higher data rates. Meanwhile, the major constraint of these approaches is the extra small cells bring additional radio interferences as compared to conventional homogeneous macrocell networks, which might negatively affect user experience.

- *Adopting renewable energy resources.* The power supply at minimal cost and with low emissions is an important issue when discussing future energy concepts. In [13, **?**] *Mereia et al.* presented the modeling and optimization for UMTS/GSM Base Station powered by a stand-alone hybrid energy system. The system consists of photovoltaic (PV) panels and a wind turbine as renewable power sources, a diesel generator for back-up power and batteries to store excess energy and to improve the system reliability. This research infers that the largest part of the energy is produced by the wind turbine (49%). Energy generated by the PV panels has a share of 29% and the diesel generator contributes 22%.

2.2 Energy-efficient wireless access network by WAVE

This thesis considers as a reference system the energy-efficient wireless access network studied by WAVES, a research group from Ghent University. They propose a capacity-based tool, that responds to the instantaneous bit rate required by the users active in the considered area [14]. This deployment tool simulates LTE-A technology, which involves the use of *sleep mode techniques*, and performs three main functionalities:

- *Carrier aggregation*, whereby the bit rate is increased by letting the Base Stations transmit at multiple carriers up to a total bandwidth of 20 MHz
- *Heterogeneous deployments*, whereby macrocell and microcell Base Stations can be mixed in one network
- *Multiple-Input-Multiple-Output (MIMO)*, which in this case will be used to enhance the coverage of the Base Station by using multiple antennas on one Base Station (spatial diversity).

In [15], WAVES deploys the enhanced version of the tool, focusing on LTE-Advanced wireless network powered by solar panel system and equipped with batteries as energy storage. To minimize the energy bought from the traditional electricity grid during a renewable energy shortage, the deployment tool proposes energy-saving strategies. Depending on the chosen strategy, up to 72% less energy should be bought compared to the fully operational network for a worst-case scenario and a period of one week. However, network performance is influenced by the chosen strategy.
The tool used in [15] is reused in the thesis as the starting point of the work. For this reason, in this chapter it is explained in detail how it works.

Tool development

The tool can be split logically into three steps (Figure 2.1).

Step 1: Traffic generation
The network is designed for a certain area under analysis. The tool must receive as input a shapefile describing in detail the area to be covered (e.g. buildings location, shape, height, etc.). Traffic usually varies over the day and for each hour traffic distribution is determined based on the following three components:

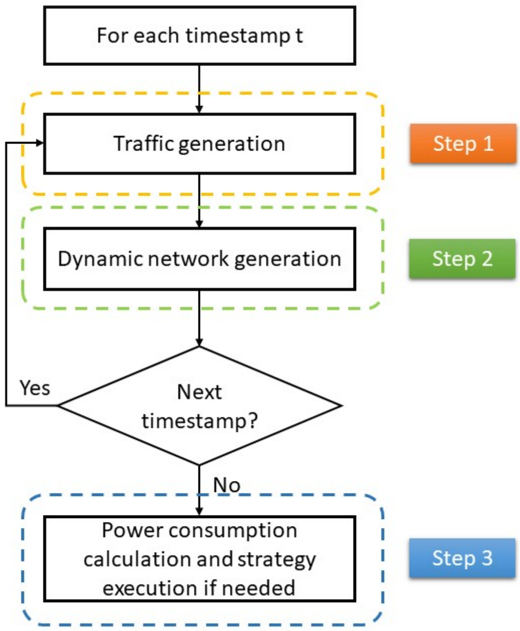


Figure 2.1: Tool block diagram illustration

- *User distribution:* the user distribution determines the maximum number of active users in the considered timestamp. It depends on the population density of the area under analysis and evolves during the day. The distribution proposed in [14] is here considered, which takes into account data provided by a Belgian operator.

- *Location distribution:* location distribution is in charge of determining the position of the users in such an area. In the tool is considered to be uniform, as in [16].

- *Bit rate distribution:* the bit rate distribution establishes for each user individually the bit rate the user requests. For a certain timestamp, users are making a voice call request 64 kbps and users are transferring data requests 1 Mbps.

All these data are combined and stored in traffic files, that later are provided as input of the following algorithm phases (Figure 2.2). Due to the distributions described above, multiple simulations need to be executed for each time interval. According to [16], in the considered case study, the number of simulations needed

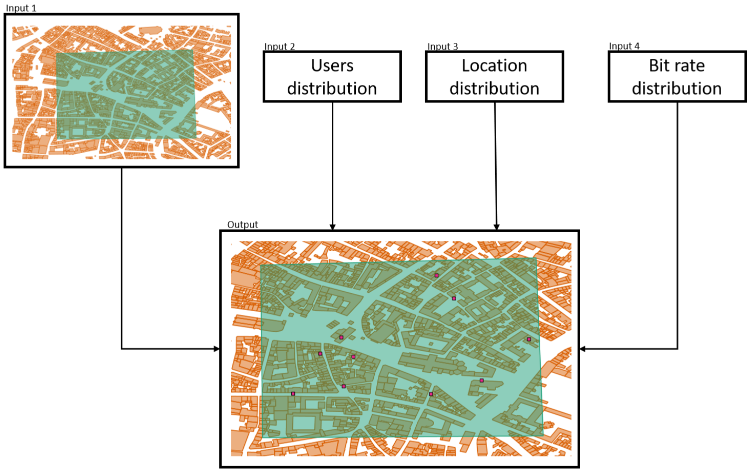


Figure 2.2: Traffic generation diagram

is 40. So for each time interval, 40 traffic files are generated and the average value is considered.

Step 2: Dynamic network generation

Once the traffic files have been created, the algorithm can go forward with network generation. In addition to the traffic files (Figure 2.2), a file containing the Base Station's location and characteristics is provided as input. To define the heterogeneous access network, the tool will add 4 microcell BSs for each macrocell BS, placing them around it. As well as a shapefile describing the environment and the buildings of the considered area is needed so that it is possible to consider obstacles in the propagation of the signals.

For each active user in the area, a list of possible BSs, both active and by waking up, to which the user can connect is created. This list is generated taking into account three requirements.

(i) The experienced path loss must be lower than the maximum allowable. To determine the path loss the straight line between the user and the BS is calculated and the receiver SNR (Signal-to-Noise-Ratio) is used.

(ii) The bit rate that such a Base Station can ensure to the user must be at least equal to the bit rate requested by the user.

(iii) The Base Station must ensure coverage to the user. When it cannot, the input power of the antenna is increased of 1dBm until the user coverage or the maximum allowable power is reached. If the second option is the case the Base Station is deleted from the list.

To determine which is the best solution in the list, a fitness function is applied: this function examines how well the system performs in terms of power consumption and exposure. For every user, the Base Station with the highest fitness function value is chosen. Note that if the list is empty, it means that there is no Base Station available to connect this user with and we can proceed with the next user. Moreover, the algorithm will check if users already connected by other BSs can be transferred to this BS to experience a lower path loss from it.

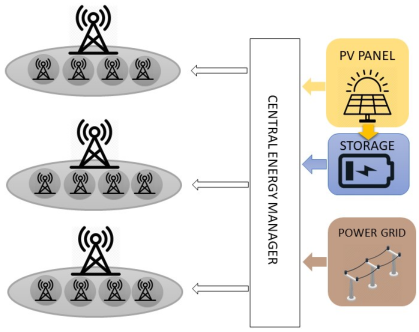


Figure 2.3: Wireless access network equipped with energy storage and powered by PV panels and power grid

Step 3: Energy production and energy-saving strategy

As mentioned in [15], the implemented scenario consists of a wireless access network powered by solar panels and a traditional power grid and equipped with batteries, as shown in (Figure 2.3). The system can use directly the energy produced by the PV panels or it can draw energy from the storage. Whenever no renewable energy neither energy from the batteries is available, the Base Stations drain the energy from the grid.

In case of extra-production from the PV panel, the energy generated is fed into the batteries. In the algorithm, the PV modules and the batteries are treated as they are a unique module. Furthermore, storage losses are neglected, occurring both during battery charge and discharge and in energy transfer and transmission. This system is combined with green energy-saving strategies and it aims at proposing ways to reduce the amount of energy bought from the main power grid during critical shortage period. If the network consumes less energy than the amount of energy stored and produced, no energy reducing strategy should be applied. Otherwise, if the network consumes more energy than the amount of energy available, microcell BSs are switched off. The decision of putting into sleep mode microcell

Base Stations rather than the macrocell Base Stations is because the macrocell Base Stations are responsible for the baseline coverage in their relevance area, whereas the microcell Base Stations provide additional capacity for peak time, rather than extended coverage. The criterion of first switching off the least loaded BSs is adopted, and when BSs are switched off their traffic is moved to a neighboring macrocell Base Station (Fig.2.4). One of the following energy reducing strategies can be applied:

- *Undertake no action:* this strategy does not apply any adjustment on the network. Keeping the network fully operational, the needed amount of energy is completely bought from the traditional electricity grid. This scenario can be considered the starting point of the study, the reference to compare other results with.

- *Deactivate all microcell BSs:* when this strategy is applied and an energy shortage is detected, all the microcell BSs are turned off. The decision is based on the network's energy demand, energy stored and energy produced by the PV panels. If a microcell BS is switched off all the users connected to that BS need to be reconnected to an active macrocell BS.
  It might happen that the available renewable energy is still not enough, then at least the macrocell Base Stations are kept up and running buying the energy from the traditional grid. Vice versa, in case there is no extra amount of renewable energy when the microcell Base Stations are switched off, it is harvested in the battery for future usage.

- *Deactivate as much microcell BS as needed:* the last strategy is a variation of the previous. In this case, if the produced energy and the stored energy are not enough to feed the system, the algorithm chooses how many microcell BSs to turn off from 1 to 4. They will be deactivated gradually: the algorithm evaluates the network energy consumption when 1,2 or 3 microcell Base Stations are switched off per macrocell Base Stations. As soon as the network's consumption becomes lower than the amount of available renewable energy, we know how many microcell Base Stations per macrocell Base Station turn off. Obviously, in the worst case, this strategy matches the second one.
  Similarly to the previous strategy, we need to reconnect all users connected to the sleeping microcell Base Stations to the best extent possible. In case of any extra production, it is harvested in the battery for future usage.

The last two strategies can be combined with a prediction time window TW, expressed in hours. Without considering the time window, the network's energy demand and energy production for the current time interval are considered and an

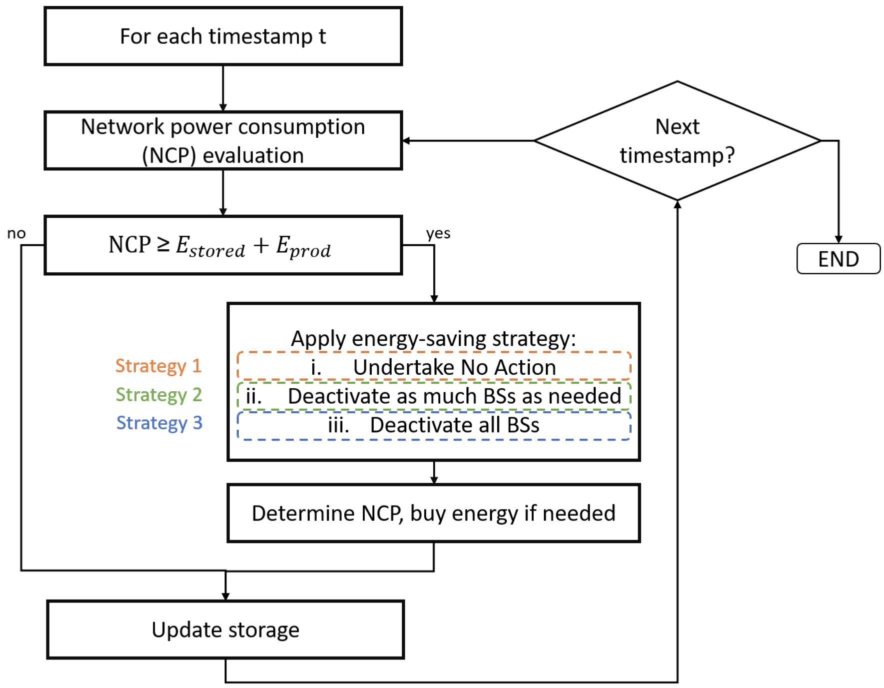


Figure 2.4: Block diagram of the energy management

energy strategy is applied in case of energy shortage.
When considering a time window, any energy shortage in the next few hours is taken into consideration. In particular, assuming a given time interval TI and a given time window TW, if an energy shortage is predicted between TI and TI+TW (boundaries included), microcell Base Stations are switched off from TI on.
The network prediction can be sufficiently accurate since the traffic patterns during the day tend to be repetitive and rather predictable. Moreover, Base Stations' energy consumption is very little traffic proportional: the small fluctuation of traffic load corresponds to little impact on consumption.

2.3 Renewable Energy costs trend

As already mentioned, wireless access networks have an important economic impact, due to the continuously rising energy consumption. In this scenario, renewable power generation can help countries to meet their sustainable development goals through the provision of access to clean, secure, reliable and affordable energy.
In the previous section, strategies and techniques that can be applied to save en-

ergy in a wireless access network were the main focal point. Now more attention is paid to the renewable energy system used to power the network. Investigations around the equipment costs, total installation costs, *capacity factors*, operation and maintenance (O&M) costs, as suggested in [17], can guide in a techno-economic analysis. This thesis looks in particular at three sources: solar, wind and geothermal. Per each of them, three main aspects will be examined and summarized in Table 2.1:

- *Total installed costs*, which refer to the costs to develop and provide durable assets for the system, including machinery or intellectual property. They are not fully deducted in the accounting period they were incurred but amortized over their lifespan.

- *Capacity factor*, which is defined as the actual electricity production divided by the maximum possible electricity output of a power plant over a period of time.

- *Operation and maintenance costs(O&M)*, that consists of those expenses that a business incurs to run smoothly every single day. They are fully deducted in the accounting period they were incurred.

Photovoltaic panel

PV modules prices in Europe decreased by 83% from the end of 2010 to the end of 2017 [17]. Though solar PV technology has matured and more and more countries are starting to deploy solar PV at a large scale, regional cost differences persist. Different domestic market maturity levels, as well as differences in local labor and manufacturing costs, can influence competitiveness. Sometimes adopting policies that aim to reduce the administrative hurdles associated with gaining incentives can bring down soft costs. Between 2010 and 2017, the weighted average total installed cost of the newly commissioned PV project decreased by 68% [17]. In the commercial sector (up to 500 kW of capacity), solar PV cost ranges between the lowest 1100 EUR/kW in Germany and China to the highest 3650 EUR/kW in California.
The global weighted average capacity factor of PV systems increased by 28% between 2010 and 2017, from an average of 13.7% to 17.6%. This has been driven mainly by (i) the trend toward greater deployment and (ii) the increased use of tracking and improvements in the performance of systems.
Historically solar PVs operation and maintenance costs have not been considered a major challenge to their economics. Yet, with the rapid fall in solar PV module prices and installed costs, the share of O&M costs has climbed significantly. O&M costs have been reported to be between 10 EUR/kW and 18 EUR/kW per year [17].

Wind turbine

The total installed costs of a wind project is driven by:

- Turbine cost: Rotor blades, gearbox, generator, nacelle, power converter, transformer, and tower.
- Construction works for the preparation of the site and foundations for the towers
- Grid connection: Includes transformers and substations and connection to the local distribution or transmission network.
- Planning and project costs.
- Land

In the past 30 years, onshore wind installed costs have declined significantly, according to IRENA's database [17]. On average, in Europe total installed costs of wind farms range from 1200 EUR/kW to 2600 EUR/kW [17].
The capacity factors of wind projects are determined by the quality of the wind resource and the technology employed. The global weighted average capacity factor for onshore wind increased from around 20% in 1983 to around 29% in 2017 [17].
Operations and maintenance costs, both fixed and variable, are a significant part of wind power cost. O&M costs measured as initial full-service contracts are less expensive than full-service renewal contracts. Initial full-service contracts varied from 14 to 30 EUR/kW per year between 2008 and 2017, while full-service renewal contracts varied from 22 EUR/kW to 44 EUR/kW per year [17].

Geothermal power plant

Geothermal power plants are, with respect to other technologies, relatively capital-intensive. Extensive geothermal resource mapping can reduce the costs of development, by minimizing the uncertainty about where initial exploration should be conducted.
The total installed costs of a geothermal power plant consist of:

- Exploration and resource assessment costs
- Drilling costs for production and re-injection costs
- Field infrastructure, the geothermal fluid collection, and disposal system, and other surface installations;
- Costs of the power plant

- Project development and grid connection costs.

The characteristics of the geothermal field are key to what type of power plant can be used for a given site. The total installed costs of recent conventional binary geothermal power generation projects are between 2250 EUR/kW and 5500 EUR/kW [17].
The capacity factors of geothermal power plants vary from around 60% to more than 85% [17].
It's important to note that geothermal power plants need active management of the reservoir and production profile to maintain production at the designed capacity factor. O&M costs are the main component in the overall cost and they are around 110 EUR/kW per year [17].

Source	Installed Cost [EUR/kW]	O&M [EUR/kW/year]	Capacity factor [%]
Solar	1100 - 3650	10 - 18	Up to 17.6
Wind	1200 - 2600	22 - 44	Up to 29
Geothermal	2250 - 5500	110	Up to 85

Table 2.1: Renewable Energy Cost Trend Summary

2.4 RES costs optimization in wireless access network

In Chapter 1, renewable energy sources (RES) were proposed as a possible alternative to power cellular BSs. RES can be supportive not only to reduce the global greenhouse gases (GHG) emission but also to solve the problem for areas where it is difficult or impossible to get connectivity to the power grid. Finally, renewable energy can be seen as a source of revenue by the operators, e.g. by selling the excess energy to the grid.
Different optimization algorithms have been proposed in the literature to optimize the energy consumption and energy costs in wireless access networks. In [18], the planning of cellular networks equipped with RE sources is investigated. The study takes into account satisfying the users and reducing the CapEx and OpEx. Each BS belonging to the system is connected to RE sources and the problem is to select the subset of candidate BSs with minimum cost (sum of CapEx and OpEx). The problem is shown to be NP-hard, and thus a heuristic search is applied for cellular planning. The solution consists of two phases, QoS-aware BS deployment, and

energy balancing connection. In the first phase, the authors assume that there is no power connection between RE sources, and solve the problem based on the QoS constraints. The second phase starts with a fully connected RE source topology and then removes the connection with minimum amount of transferred energy until no cost saving is achieved. In terms of the network capital and operational expenditure, the authors conclude that savings can be made by enriching cellular infrastructure with energy harvesting sources, in comparison to traditional deployment methods.

The authors of [19] propose an optimization of an off-grid hybrid PV-Wind-Diesel system with different battery technologies using Genetic Algorithm. The system has been modeled and implemented in Matlab/Simulink and data of irradiation, wind speed and air temperature from Aachen (Germany) and Quneitra (Syria) have been used. The load is assumed to be that of a rural UMTS/GSM Base Station for telecommunication. The optimization through a Genetic Algorithm is done for six different scenarios with different system configurations. The results show that combining the batteries with renewable energy systems is effective, economically and ecologically, and using only redox-flow batteries is the best solution. However, using a combination of more than one battery technology as energy storage (PV, wind turbine, diesel, and batteries) is not favorable.

Chapter 3

Methodology and Settings

3.1 Scenario

The considered scenario consists of a group of base stations powered with renewable energy systems, equipped with batteries, and connected to the traditional energy grid for back-up power. The enhancement with respect to the prototype described in Chapter 2 is the introduction of new energy generation plants, like wind farms and geothermal power plants, besides the photovoltaic system. Energy from renewables follows *first-use-then-harvest* principle, meaning that it is used to feed the network and in case of extra production is stored into the batteries. The base stations are assumed to share the renewable energy generator systems and energy management decisions are taken based on the total available energy and the total power demand, in a centralized way for the whole group of base stations. As regards energy generation, data collection from Terna S.p.A. is considered. Terna S.p.A. is a transmission system operator (TSO) that manages the Italian energy production. Data regarding hourly production from renewable energy sources and information about the total installed capacity (Figure 3.1) on the Italian territory are reported on its official website [20]. The adopted traces report data about the power output obtained per installed capacity. The values of renewable energy production are then referred to as production per kWh.
Concerning period and area under analysis, simulations have been performed considering two weeks, one during summer and the other one in winter, to compare best and worst cases. Since we are using a renewable energy-based provisioning system, the season influences particularly the production: summer would be the best case with solar energy systems, while winter would be the worst one. Viceversa with wind energy, which ensures higher production during winter and smaller in summer. Geothermal energy instead is not involved in seasonal variation. All data are referred to the year 2017: summer period goes from June 10th to June

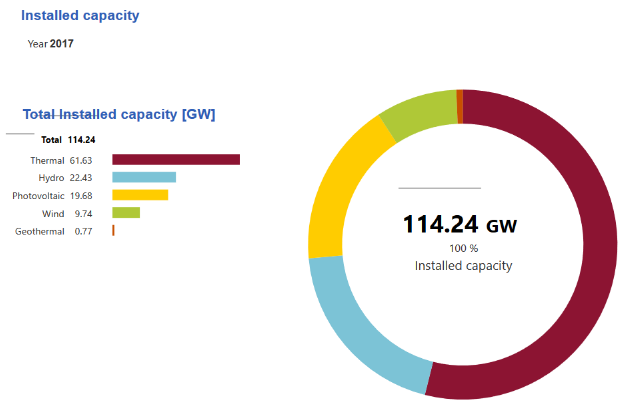


Figure 3.1: Total installed capacity on the Italian territory managed by Terna S.p.A.

16th, while the winter period from December 23rd to December 29th. An area of 0.3 km^2 consisting of only residential houses of the city center of Ghent, in Belgium, is studied. That area is covered by 8 macrocell Base Stations, each equipped by 4 microcell Base Stations (Figure 3.2). The location of the 8 macrocell Base Station is the location in the real network from a mobile operator in that area. The microcell base stations are regularly generated around the macrocell base station. To avoid an over-dimensioned network for the considered amount of traffic, the support is limited to 4 microcell Base Stations per macrocell Base Station. To model the user traffic, realistic data from an operator is considered. The users are assumed to be uniformly distributed over the area and 64 kbps for voice calls and 1 Mbps for data calls are proposed for the user bit rate requirements.
Furthermore, LTE Advanced is considered as wireless technology at a frequency of 2.6 GHz. Table 3.1 lists all the relevant link budget parameters for the assumed framework. The power consumption of the macrocell and microcell base stations is modeled as proposed in [21]. It is assumed that during sleep mode, the base station does not consume any power.

3.2 Energy Production and Storage System

Besides the connection to the traditional electricity grid, the network is provided by an energy production and storage system. This equipment for the energy provisioning is designed to be shared among all the active base stations: it might be physically co-located with the base stations or it might be concentrated in a few larger sites that provide power supply for the whole group of base stations. The energy production system is made up of three sources: solar, wind and geothermal.

Figure 3.2: The considered suburban area of 0.3 km^2 (orange box) of the city center of Ghent, in Belgium, with macrocell Base Stations (purple points) and microcell Base Stations (pink points)

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 3.1: Link budget parameters for the LTE-Advanced

Table 3.2 lists details about the costs for each of them, referred to as data reported in [17].

Source	Installed Cost [EUR/kW]	O&M [EUR/kW/year]	Capacity factor [%]
Solar	2375	15	16
Wind	1900	30	29
Geothermal	3700	110	85

Table 3.2: Summary of RES costs

The energy production system comes in combination with an energy storage system. For energy harvesting, lead-acid batteries represent a common technology adopted in renewable energy systems. A set of lead-acid battery units, each with a capacity of 200 Ah and voltage 12 V, is hence assumed as storage in this work. Any loss occurring during the (dis)charge of the battery and the energy transfer or transmission are neglected.
To handle the centralized management of this system, a central controller will be available at the cluster. Concerning scalability issues, some clarification should be provided. Even in the case of a larger network, a single controller would be sufficient to run the algorithm over the whole network. The limited computational complexity does not require significant computational power to run the implemented strategies and no significant delay would be experienced in the information exchange since the decisions are taken every hour. However, about the renewable energy transfer within a larger network area, there might be slightly higher transfer losses due to the larger size of the network. Hence centralized management could be not suited in renewable energy production when this energy is not produced and consumed locally. The transfer losses would be not rather limited in the case of larger networks.

3.3 Optimization strategy

In the second part of the analysis, the main goal is to minimize the total amount of bought energy and wasted energy. Therefore, the developed algorithm and strategies are presented in this section.
The decision is taken according to a *load proportional criterion*: based on the amount of energy required to fed the network a heuristic search is applied to establish how many RESs are needed. Per each timestamp, once the traffic and the network itself have been generated, the energy production system is produced too, Figure 3.3.

To figure out the most suited arrangement, a heuristic search among the possi-

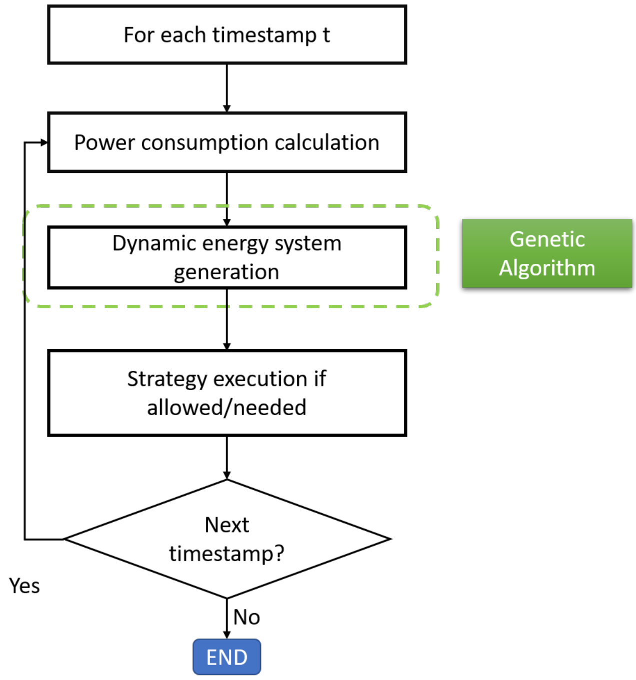


Figure 3.3: Block diagram of the tool combined with the optimization algorithm

ble solutions is done through a Genetic Algorithm: it has been chosen because of its balance between exploration and exploitation, that can be achieved by setting the parameters properly.
Genetic Algorithm is inspired by Darwin's theory of natural evolution, it explores the search space using principles of selection and evolution to produce several solutions to the problem. The input to the GA is a set of potential solutions to that problem, encoded in some fashion, and a metric called *fitness function* that allows each candidate to be quantitatively evaluated. The optimization algorithm can be split into four steps, as shown in the pseudocode below [Algorithm 1].

Algorithm 1 Dynamic energy system generation

Input: Network power consumption

```
for all timestamp t do
    Initialize random population
    while generationounter < MAXiter do
        Find fittest solution
        Evolve population
    end while
end for
```

Step 1: Initialization

The process begins with a set of individuals called *population*. In this case study, the population has one hundred individuals randomly generated. Each individual represents a possible solution to the problem. An individual is made up of a set of parameters, known as *genes*. Genes are joined into a string to form a *chromosome*. Usually, binary values are used. The system needs to represent three renewable energy sources and for each of them, maximum capacity is set. Therefore per each capacity value, three binary values are associated with. In total each chromosome is composed of nine genes: subgroups of three genes represent a specific renewable source, Figure 3.4.

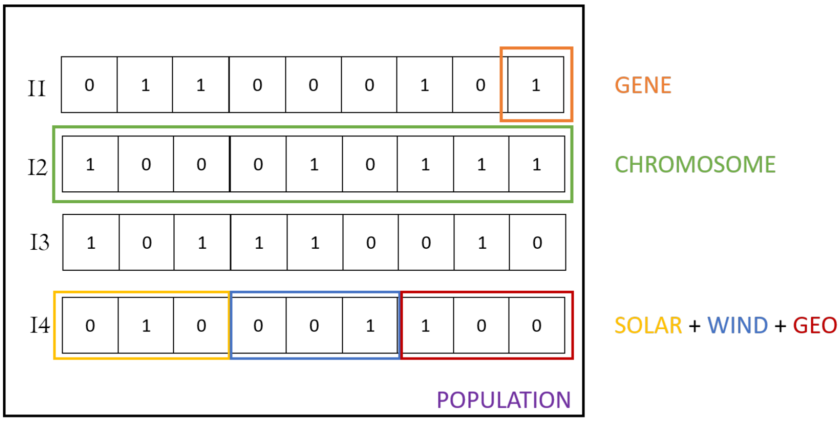


Figure 3.4: Summary of the population pattern

Assuming that each source is represented by three bits, each source can have 8 different capacity values. In Table 3.3 the possible values are summarized.

Source	Capacity interval	Step
Solar	From 0 to 100 [kWp]	12.5 [kWp]
Wind	From 0 to 7 [wind turbine]	1 [wind turbine]
Geothermal	From 0 to 21 [%]	3 [%]

Table 3.3: Summary of allowed capacity in renewable energy systems

Step 2: Fitness Function

The fitness function determines how fit an individual is: thanks to this function each candidate is quantitatively evaluated. The candidate with good fitness has a high probability to get selected. These promising candidates are kept and allowed to reproduce.
The goal of the fitness function in this work is to select individuals that minimize the energy cost and energy wasting. This means basically to minimize three components that influence the overall costs:

(i) *Renewable Energy System Costs*, computed through Levelized Cost Of Energy (LCOE). This quantity allows to compare different electricity generation sources on a consistent basis, taking into account total costs to build and operate a power generating asset with respect to the amount of energy produced. 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. How to estimate the LCOE and those parameters needed to evaluate it are listed and explained in Subsection 3.4.2.

$$RES\ COST = LCOE \times produced \tag{3.1}$$

(ii) *Cost of the Energy Bought from the Electricity Grid* evaluated taking into account the average electricity price in Europe, amounting to 0.29 EUR/kWh. If the assets are not able to cover all the energy request, the missed amount of energy will be bought from the grid:

$$GRID\ POWER\ COST = 0.29 \times (needed - produced) \tag{3.2}$$

(iii) *Money Wasting due to Overproduction*, quantified as the amount of money that the network owner is paying to maintain the system up working and producing the surplus.

$$GRID\ POWER\ COST = LCOE_{mean} \times (produced - needed) \tag{3.3}$$

Step 3: Genetic Algorithm

To explore as well as possible the solutions space, the algorithm follows three main steps:

a) Selection

The idea of the selection phase is to choose the fittest individuals and let them pass their genes to the next generation. There are many different techniques which can be used to select the individuals:

- *Elitist selection*: the fittest members of each generation are guaranteed to be selected.
- *Fitness-proportionate selection*: more fit individuals are more likely, but not certain, to be selected.
- *Roulette-wheel selection*: the chance of an individual to be selected is proportional to the amount by which its fitness is greater or smaller than its competitors' fitness.
- *Tournament selection*: subgroups of individuals are chosen from a larger population, and members of each subgroup compete against each other. Only one individual from each subgroup is chosen to reproduce.

Applying one or more of these techniques two pairs of individuals (*parents*) are selected based on their score.
In this implementation, elitism selection, and tournament selection are implemented. Thanks to elitism selection, the fittest individual is selected for sure and inserted in the new generation. The other members of the population are generated by applying the tournament selection. Subgroups of 10 individuals are randomly picked from the main population. At a later stage, the fittest member of these subgroups is extracted. Tournament selection is applied twice to choose two individuals, which will become the main characters of the following step.

b) Crossover

Crossover is the most significant phase of GA. Once the individuals have been selected, the algorithm will produce the *offspring*, which is the new individual born from the fusion of the parents. For each pair of parents to be mated, a crossover point is chosen. Usually, the most common crossover type is a single point: a locus at which the alleles are swapped from one parent to the other is chosen.
In this case, since each source has to be mixed, crossover points are as many as genes in a chromosome. Crossover technique is applied on each gene and based on the crossover rate the gene i is picked by individual 1 or individual 2. Crossover rate is here chosen equal to 0.5: the probability to pick one gene from parent 1 or parent 2 is uniform.

c) Mutation

In certain new offspring formed, some of their genes can be subjected to a mutation with a low random probability. This implies that some of the genes can be flipped.
Mutation occurs to maintain diversity within the population and prevent premature convergence. The probability of mutation is usually between 0.01 and 0.02 and I choose 0.015 for this case study.

Step 4: Termination

Terminating condition is established based on the number of iterations. During the simulations, it turned out that 10 iterations are enough before the convergence.

3.4 Technologies analysis

In this work, to evaluate the behavior of the system both performance metrics and cost metrics are taken into account.

Performance metrics

In the first part of this study, the influence of different energy and performance-related parameters on the energy production and storage system are investigated using the following metrics:

- *Total consumed energy (in Wh)*: This parameter describes how much energy (renewable energy and energy bought from the traditional grid) is consumed over the whole simulation period.
- *Total bought energy (in Wh)*: This parameter shows us how much energy should be bought from the traditional grid during the whole simulation period. Furthermore, we consider also ΔP, which represents the relative improvement or deterioration of the total energy bought compared to the reference scenario.
- *Total wasted energy (in Wh)*: This parameter corresponds with the total amount of energy that the energy system is overproducing during the whole simulation period.
- *Average user coverage (as a percentage)*: express how many users on average are covered by the developed networks over the whole simulation period.

- *Average network capacity (in Mbps)*: shows how much capacity is offered by the developed networks on average over the whole simulation period and can not be harvested in the storage system.

In the second part of this study, the evolution of the system over time frames will be investigated, considering the following metrics:

- *Power consumed by the network*: This parameter shows how much energy the network is currently consuming.
- *Power produced by RESs*: This parameter tells us how much energy is currently produced by each renewable energy source.
- *Wasted power*: This parameter shows how much renewable energy is currently wasted by the system, due to surplus production.

Costs metrics

Electricity generation can incur different costs based on the source we are considering. The costs are typically given per kWh or MWh and it includes the initial capital, discount rate as well as the cost of operation, fuel, and maintenance.
The *Levelized Cost of Energy (LCOE)* is a measure that allows comparison of different methods of electricity generation consistently. It is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime [22].
While calculating $LCOE$, several cost factors have to be considered:

$$LCOE = \frac{(CRF \times ICC) + AOE}{AEP_{net}} \tag{3.4}$$

where:
CRF= Capital Recovery Factor
ICC= Installed Capital Cost
AOE = Annual Operating Expenses
AEP_{net} = Annual Energy Production

The costs include equipment costs (e.g. PV modules, wind turbines, etc.), total installed costs, fixed and variable operating and maintenance costs (O&M), fuel costs. The analysis of LCOE can be very detailed, but for comparison purposes, the approach here has been simplified.
Below the components that affect the LCOE are depicted.

The **Capital Recovery Factor (CRF)** is a ratio used to calculate the present value of an asset. In other words, this quantity helps to understand today's value of revenues to pay back the initial investment [22]. The equation for CRF is:

$$CRF = \frac{d(1+d)^N}{(1+d)^N - 1} \tag{3.5}$$

This value, as shown in (3.5), is influenced by the *discount rate (d)*, that is the price put on time that an investor waits for a return on an investment, and the *number of years (N)*.

The **Installed Capital Cost (ICC)** includes one-time expenses incurred on the purchase of land, buildings, construction, and equipment used in the production of the asset. It can be associated with Capital Expenditure because it is the total cost needed to bring a project to commercially operable status.

The **Annual Operating Expenses (AOE)** covers all the costs incurred over a year to maintain the asset running. It can be compared to the Operational Expenditures.

The **Annual Energy Production (AEP)** is the total amount of electrical energy that a source is expected to produce over a year measured in kWh. This concept is strictly linked to the capacity factor, which is the ratio of an actual electrical energy output over a given period to the maximum possible electrical energy output over the same period.

Chapter 4

Simulations and results

In this chapter results obtained by the simulations are presented and analyzed. The following sections investigate how the power consumed by the network, the power produced by the RESs, and the power wasted evolve during one week while changing the structure of the energy provisioning system.
The tool described in Chapter 2 is used, integrating wind farm and geothermal power plant with photovoltaic modules already existing, and extending the algorithm with the energy costs optimization proposed in Chapter 3.
The analysis of the network will be carried out considering the case study in which no energy-saving strategy is applied as well as the ones in which all or as much as needed microcell BSs are deactivated. These strategies have been described in Chapter 2.
From now on the *reference scenario* will concern the framework in which no energy reducing strategy is applied, called sometimes *strategy 1*. In the following sections, I will refer to the energy-saving strategy that deactivates all microcell BSs as *strategy 2*, and to the strategy that switch off as much as needed microcell BSs as *strategy 3*.

4.1 Wind Only

Influence of the Wind Farm Size on Energy and Network Performance

When the system is provided only by wind energy system, the following settings are assumed:

- Nominal capacity of each wind turbine: 2.5 MW
- Size of the wind farm: varying from 1 wind turbine to 10 wind turbines in steps of 1

- Capacity of energy storage: 50 kWh, full at the start of the simulation
- Time window: 1h

The size of the wind farm will be evaluated for four different metrics: the amount of bought and wasted power, the user coverage, and the capacity offered by the network.

1. *Bought Power*: Comparing Figure 4.1a and Figure 4.2a, it is immediately evident that the curve trend changes according to the season. When the amount of wind energy is plentiful, the curve is almost exponential, while as the amount of energy available decreases, the curve becomes linear with the number of turbines. During the winter (Fig. 4.1a), an elbow is observed for 5 wind turbines, when strategy 1 is applied.
   The meaning of the total bought power is more clear if compared to the total amount of power consumed by the network. All over the week, about 1270 kW are absorbed by applying strategy 1. During winter, increasing the wind farm size, the total amount of bought power goes from 1058 kW to 138.6 kW. In summer, wind energy production becomes smaller and the expenses grow: the total bought power reaches 834.1 kW with 10 turbines, starting from 1194 kW with one turbine. Therefore, when the network is fed only by wind, up to 89% of energy less must be bought from the main grid during winter, and 65% in summer.
   The implementation of energy-saving strategies boosts the performance: up to 68.7% less energy must be bought from the traditional power plant during summer, and around 79% during winter. The choice between strategy 1 and 2 does not affect system performance: the energy lack is so evident that all microcell BSs are always switched off.

2. *Wasted Power*: Wind energy production is quite small during summer Figure 4.2b shows that the energy-wasting is null. Changing the season (Fig. 4.1b), wind turbines increase the production and the behavior of the wasted energy is exponential with the number of windmills: it is almost null up to 4 wind units, and it reaches 550 kW with 10 wind turbines. The choice of the strategy does not influence the energy-wasting.

3. *User Coverage*: In Figure 4.1c and 4.2c, the influence of the wind system dimension on the user coverage is shown for the three strategies. During summer, in Figure 4.2c, a slightly lower user coverage is obtained when energy-saving strategies are applied (about 1% both for strategy 2 and for strategy 3) and this does not depend on the number of the windmill. Even if

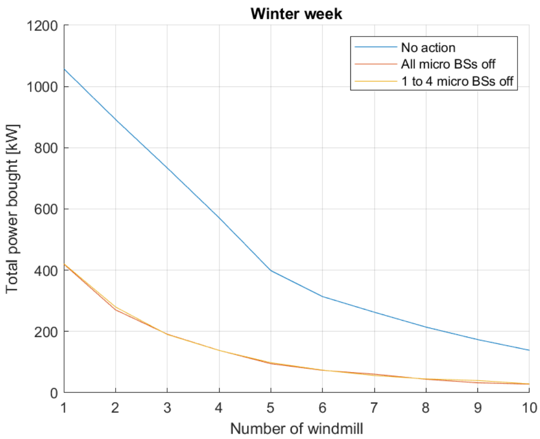
the number of turbines in the system increases, during summer wind production is not enough to feed as Base Stations as needed to keep all the users connected. When a microcell BS is turned off, all users connected to the sleeping Base Station need to be reconnected to the active ones, but this is not always possible as the capacity of these Base Stations is limited and it might already be used. There is no difference between strategy 2 and 3 since the number of Base Stations turned off with strategy 3 is equal to strategy 2 due to the lack of energy.
The influence of the wind farm size is more evident during winter (Fig. 4.1c): the reference scenario shows that 98.5% of the users are covered by the network while applying one of the energy-saving strategies user coverage starts from 97.6% and gradually increase with the number of wind turbines up to reach same performance of the reference scenario.

4. *Network Capacity*: Both in summer (Fig. 4.2d) and in winter(Fig. 4.1d), network capacity is not influenced by the number of wind turbines in the system when applying strategy 1. Huge influence on the network capacity is shown when applying the other two strategies: on average a reduction between 13% to 76% (depending on the considered wind farm size and season) is obtained and strategy 2 has slightly worse performance than strategy 3. On one side, during summer (Fig. 4.2d), performances do not significantly improve even increasing the wind farm size, going from a minimum of 52.5 Mbps with one turbine to 72.8 Mbps with 10 turbines. In winter the behavior is different: Figure 4.1d shows an ever-increasing trend with the number of turbines, reaching 201.4 Mbps with the maximum available size.

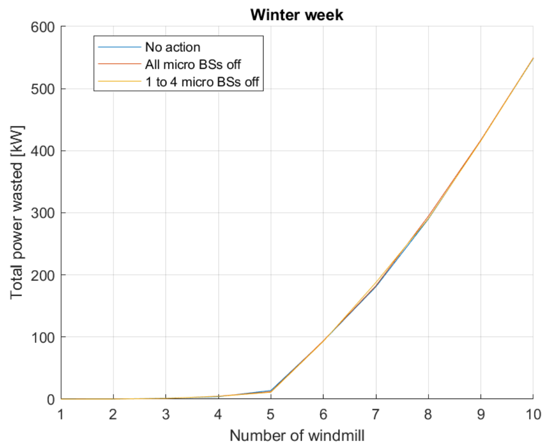
Evolution of the Energy Consumption, Production, and Wasting During the Week

Based on these results, to have a quite good performance on the overall behavior of the network, a reasonable number of wind turbines is 5. Both in summer and winter, it is the turning point in performance improvement. The total amount of power that the network buys from the traditional power plant is reduced, and the wasting is low. Furthermore, since the network under analysis covers a small area in the city of Ghent, a wind farm with limited size should be considered.
The size of a system is always established based on worst-case behavior, for this reason in this section summer season is examined.

Figure 4.3 shows how the network behaves over a summer week in energy consumption, purchased energy, and waste. Only wind energy system is not enough to



(a)



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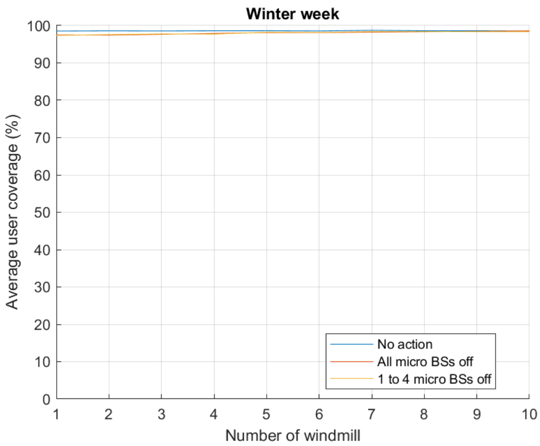
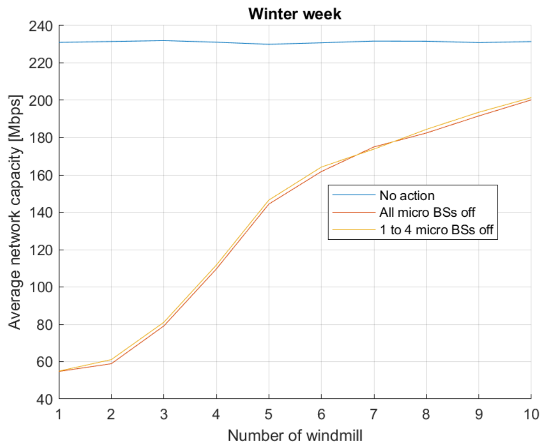
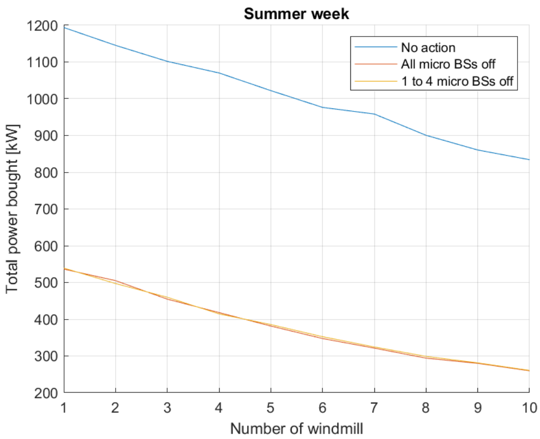


(c)

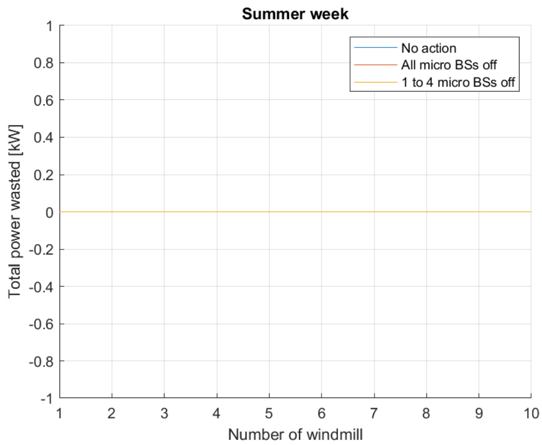


(d)

Figure 4.1: Comparison of the amount of bought power (a), the power wasted (b), the user coverage (c) and the network capacity (d) for the three different strategies as a function of the wind farm size during winter.



(a)



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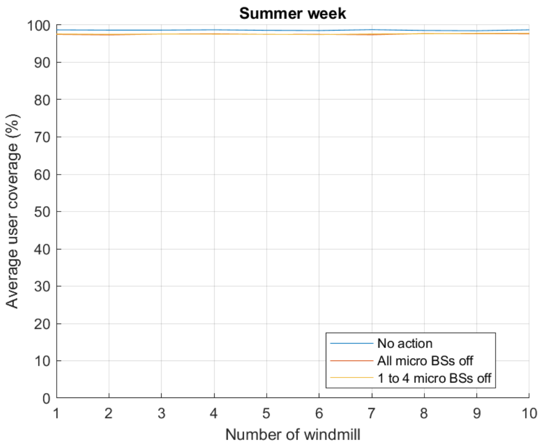

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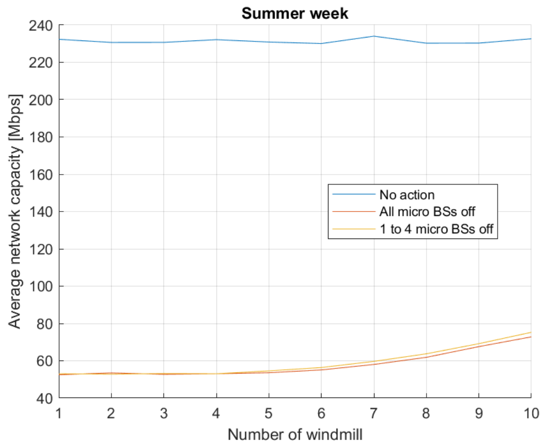
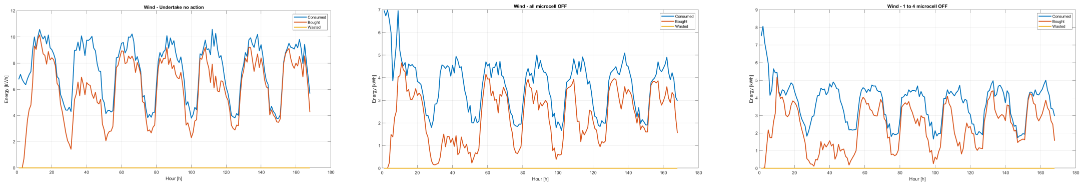


(d)

Figure 4.2: Comparison of the amount of bought power (a), the power wasted (b), the user coverage (c) and the network capacity (d) for the three different strategies as a function of the wind farm size during summer.



(a) (b) (c)

Figure 4.3: Evolution of the network's energy consumption, the energy bought from the traditional electricity grid, and the energy wasting during one summer week (168 hours) for the 3 considered strategies: no action (a), all microcell Base Stations off (b), and 1 to 4 microcell Base Stations off (c).

feed the whole system. Each hour it gets most of the energy needed from the main electricity grid. Energy reducing strategies are not effective on the performance: both strategy 2 (Fig. 4.3b) and strategy 3 (Fig. 4.3c) halve the consumption, but still, the wind energy source can not deal with it.

4.2 Geothermal Only

Influence of the Geothermal Energy Percentage on Energy and Network Performance

Geothermal energy is among the considered sources the only one that is not influenced neither by the hour nor by the season. In Figure 4.4, the comparison between summer and winter production is depicted. On average the amount of energy is the same during all the simulations, hence for the sake of simplicity here is reported the analysis of one of them.

Furthermore, the network is assumed to absorb only a percentage of the total energy produced by the geothermal power plant. Due to its small size, such a hypothesis is more likely. In the following phases as well, the optimization of the cost will take into account that the owner of the network will contribute to the expenses based on the percentage of energy he is using.
When the system is provided only by geothermal energy system, the following settings are assumed:

- Nominal capacity of the whole geothermal power plant: 21 MW
- Percentage drained: varying from 5% to 20% of the total energy in steps of 5%
- Capacity of energy storage: 50 kWh, full at the start of the simulation

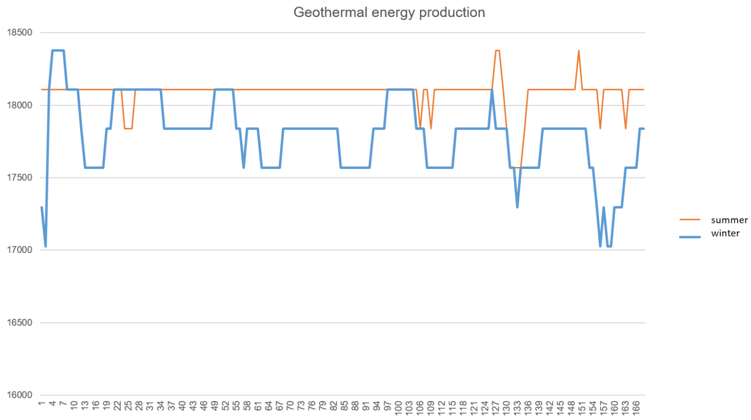


Figure 4.4: Geothermal energy production: comparison between seasons

- Time window: 1h

The amount of bought power, the amount of wasted power, the user coverage, and the capacity offered by the network are then individually analyzed.

1. *Bought Power*: Looking at figure 4.5a, the amount of bought power as a function of energy drained by the geothermal power plant is depicted. Taking into account the total consumption of the network, the system is not efficient at all when no action is undertaken: the amount of energy purchased decreases linearly from 84.7% to 50%. Thanks to strategies 2 and 3, power consumption is halved, and the network has to buy from the traditional electricity grid only 13% when the geothermal plant supplies the maximum power allowable.

2. *Wasted Power*: Focusing on wasting, Figure 4.5b shows the behavior of overproduction with respect to energy production system size. For percentage equal to 20%, the link between energy behavior and strategy is clear: when no action is undertaken, more energy is needed to feed the network since all the microcell BSs are up working. Strategy 2 allows saving more energy than strategy 3: energy wasting is higher when all microcell BSs are switched off because energy consumption is lower and energy storage gets full faster.

3. *User Coverage*: The influence of the amount of energy drained by the geothermal power plant on the user coverage is shown in Figure 4.5c. Similarly to the previous case, around 98.5% of the users are covered in the network when strategy 1 is applied, and the performance drops off by 1% with the other

two strategies. No meaningful differences come out by the energy-saving strategies implementation.

4. *Network Capacity*: Figure 4.5d compares the network capacity for the three considered strategies while varying the percentage of energy drained by the geothermal power plant. The results show that the reference scenario ensures capacity of about 230 Mbps to the users, and this value is not influenced by the energy system size. While applying energy-saving strategies, the network capacity is greatly reduced: compared to strategy 1, system performance drops between a quarter and a third based on the percentage chosen for the geothermal power plant. Differences among strategies behavior are more evident for higher values of percentage. Rising the amount of available energy, strategy 3 does not deactivate all the microcell BSs of the network as strategy 2. Hence, the amount of Mbps available increases, reaching 79.5 Mbps with strategy 2 and 83.7 Mbps with strategy 3.

Evolution of the Energy Consumption, Production, and Wasting During the Week

In this section the attention will be focused on the hourly evolution of energy consumption, energy bought, and wasted energy in the network powered only by geothermal source. Let's take into account the scenario in which 15% of the total geothermal production is taken to feed the system. Figure 4.6 shows how the system performs during winter applying three different strategies. Undertaking no action (Fig. 4.6a, more than 60% of energy must be bought from the main electricity grid, and the network is far from being self-sustaining.

At the beginning of the simulation, the energy storage is assumed to be full, and this influences the results. In Figures 4.6b and 4.6c, some peaks are recorded in the first 20 timestamps and a gradual decrease in consumption is observed afterwards. Due to the energy harvested in the batteries, the system does not detect any shortage and keeps the microcell BSs active. After a while, when this amount of energy is gone, energy-saving modes restrict the energy consumption, that is halved till the end of the simulation. This strong influence of the energy harvested in the batteries is due to the small amount of energy produced by the geothermal source. Nevertheless, the purchased energy decreases, reaching around 20% of the total with both strategy 2 and strategy 3.

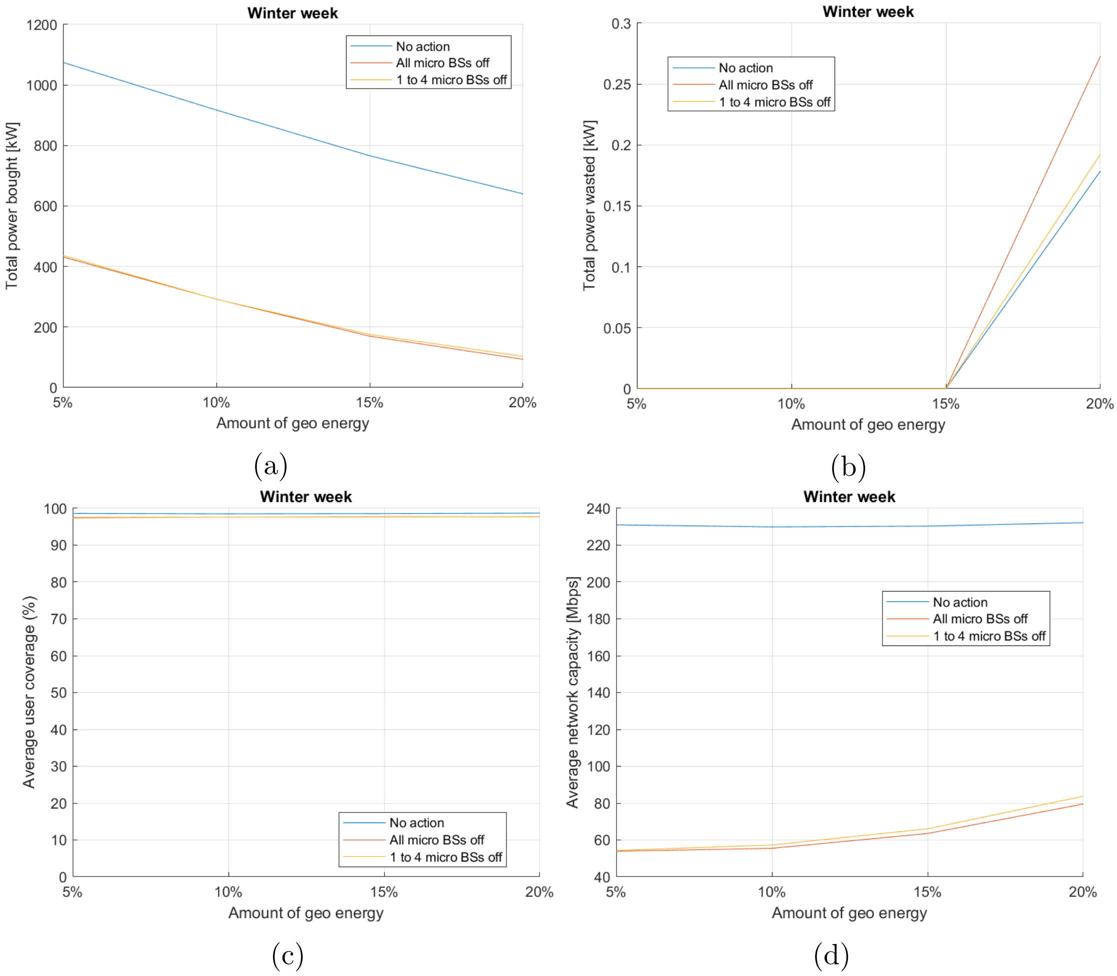
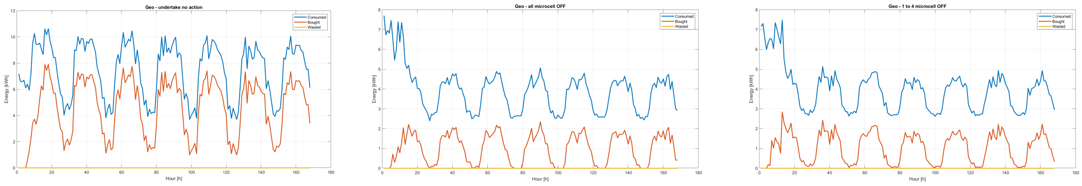


Figure 4.5: Comparison of the amount of bought power (a), the power wasted (b), the user coverage (c) and the network capacity (d) for the three different strategies as a function of the geothermal power plant percentage during winter.



(a) (b) (c)

Figure 4.6: Evolution of the network's energy consumption, the energy bought from the traditional electricity grid, and the energy wasting during one summer week (168 hours) for the 3 considered strategies: no action (a), all microcell Base Stations off (b), and 1 to 4 microcell Base Stations off (c).

4.3 Solar and Wind

Influence of the Wind Farm Size on Energy and Network Performance

As already mentioned this work is an extension of the tool described in Chapter 2, then the analysis is carried out starting from the solar system already existing and observing the influence of the wind system size.
The following settings for combined solar and wind energy system are assumed:

- Total capacity of PV panels: 100 kWp
- Nominal capacity wind turbines: 2.5 MW
- Size of the wind farm: varying from 1 wind turbine to 10 wind turbines in steps of 1
- Capacity of energy storage: 50 kWh, full at the start of the simulation
- Time window: 1h

Let's go deeper on the bought power, the wasting, the user coverage, and the network capacity.

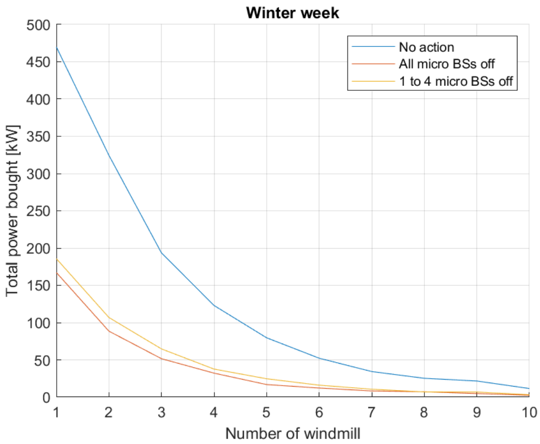
1. *Bought Power*: Figures 4.7a and 4.8a depict how the energy bought evolves with the number of wind turbines.
   With respect to the reference scenario, the bought energy goes from 470 kW to 11.53 kW in winter and from 119 kW to 21.8 kW in summer. This gap between seasons (more evident for small wind farms) is linked to the nature of the two renewable sources. During summer the amount of solar energy has

huge peaks in the central hours of the day and the intensity of solar radiation causes high production. Therefore, the network has great availability of resources and the amount of energy needed from the traditional power plant is cut. In winter, instead, the amount of energy produced by solar panels is halved and, although the level of wind energy increases, this is not enough to bridge the gap.
On the contrary, increasing the number of turbines, summer gets worst than winter. This is mainly due to the fast battery saturation. During the day renewable sources generate energy, filling the batteries in a short time and squandering the surplus; at night, when the production of energy decreases, the amount of energy stored in the batteries is not sufficient to power the network and therefore the purchased energy increases. In winter the production of energy is lower but more balanced, then the network buys less energy than summer when 10 wind turbines are involved.
As regards the strategy choice, reducing the number of active microcell BSs, the energy required to fed the network is reduced too. Moreover, the effect described before with strategy 1 is reflected also on strategy 2 and strategy 3, but the exponential curve is smoother.

2. *Wasted Power*: Wasting becomes a problem as soon as different renewable energy sources are combined. In Figure 4.7b the exponential curve shows the relationship between total wasted power and number of wind turbines during winter: starting from about 200 kW the squandering rises till more than 1200 kW. Summer case study (Fig. 4.8b) is even worse: wasting linearly increases from 1850 kW to 2100 kW with the number of windmills. Strategy choice has no influence: applying energy-saving modes, the wasted power increases as much as the reference scenario.

3. *User Coverage*: The combination of solar and wind energy allows to feed the network enough to experience great performance in users coverage, not heeding about the season (Fig. 4.7c and Fig. 4.8c. Even the choice of the strategy does not influence coverage, which is almost 98.5% all over the simulation. The amount of energy produced ensures to have as much active microcell BSs as needed: once users have been associated with a BS, they do not need to be reconnected to new BSs and this means that the capacity of each BS does not saturate, resulting in an optimal coverage of the network.

4. *Network Capacity*: The presence of microcell BSs in the system allows to have larger network capacity and handle a larger amount of traffic. When strategies to save energy are used, some of the microcell BSs are deactivated and consequently the network capacity decrease. Figure 4.7d perfectly describes this concept: if no action is undertaken, network capacity is quite



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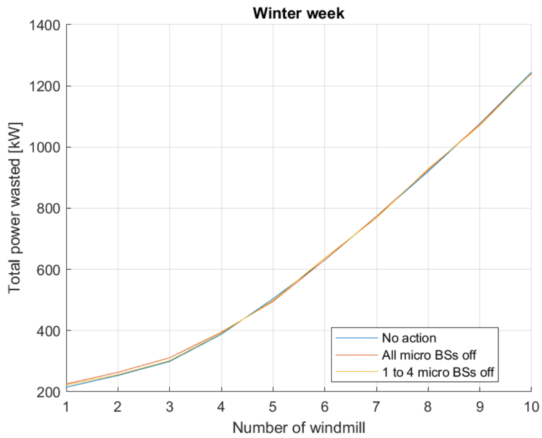

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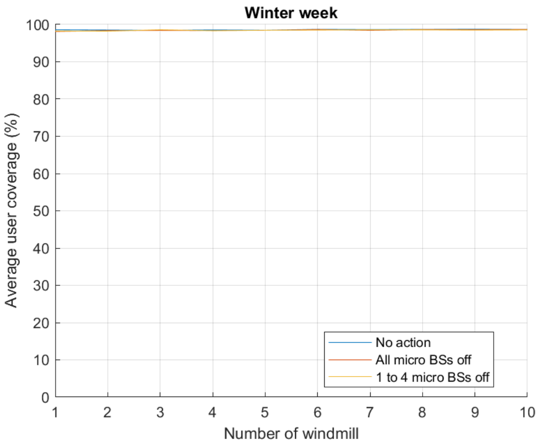

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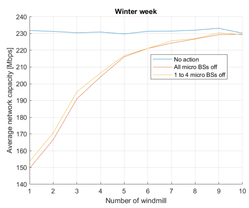


(d)

Figure 4.7: Comparison of the amount of bought power (a), the power wasted (b), the user coverage (c) and the network capacity (d) for the three different strategies in combined solar and wind energy system during winter.

constant around 230 Mbps; when strategy 2 and 3 are applied, it comes down up to 149.5 Mbps (strategy 2) and 153.6 Mbps (strategy 3) and then goes back up to the reference scenario at 230 Mbps with the growth of the number of windmills. Increasing the amount of available energy, the network does not need anymore to deactivate microcell BSs and hence the system behavior equals strategy 1.
During summer, in Figure 4.8d, the relationship between the variables is the same but it is less evident because the available energy is huge even for small wind farm size.

Evolution of the Energy Consumption, Production, and Wasting During the Week

The evolution of the network's energy consumption, the energy bought from the traditional electricity grid, and the energy-wasting during one week (168 hours) is compared in the best and worst case (Fig.4.9) in the reference scenario. The energy system is made up of 5 wind turbines and 100 kWp of solar modules.
The system is the most efficient among all the possible energy system alternatives. In the previous section, it was found that user coverage and network capacity have good performances. With this configuration of the energy system, the network needs from the traditional electricity grid 5.7% of the total consumed energy during winter, and 3% during summer. As expected, the energy is bought during the night, since solar is the one that contributes more. More attention has to be paid to the wasting: batteries always overflow during summer (Fig. 4.9b) due to the surplus produced by the PV panels, and 1.9MW are lost. During winter, the performance improves, falling to 511.7 kW.

4.4 Solar and Geothermal

Influence of the Geothermal Energy Percentage on Energy and Network Performance

As mentioned in the previous section, also in this case study the same solar modules size of the tool described in Chapter 2 will be used. Differently from Section 4.2, both seasons will be analyzed, since the influence of solar energy is fundamental in the system.
The network will be analyzed assuming the following settings for combined solar and geothermal energy system:

- Total capacity of PV panel: 100 kWp

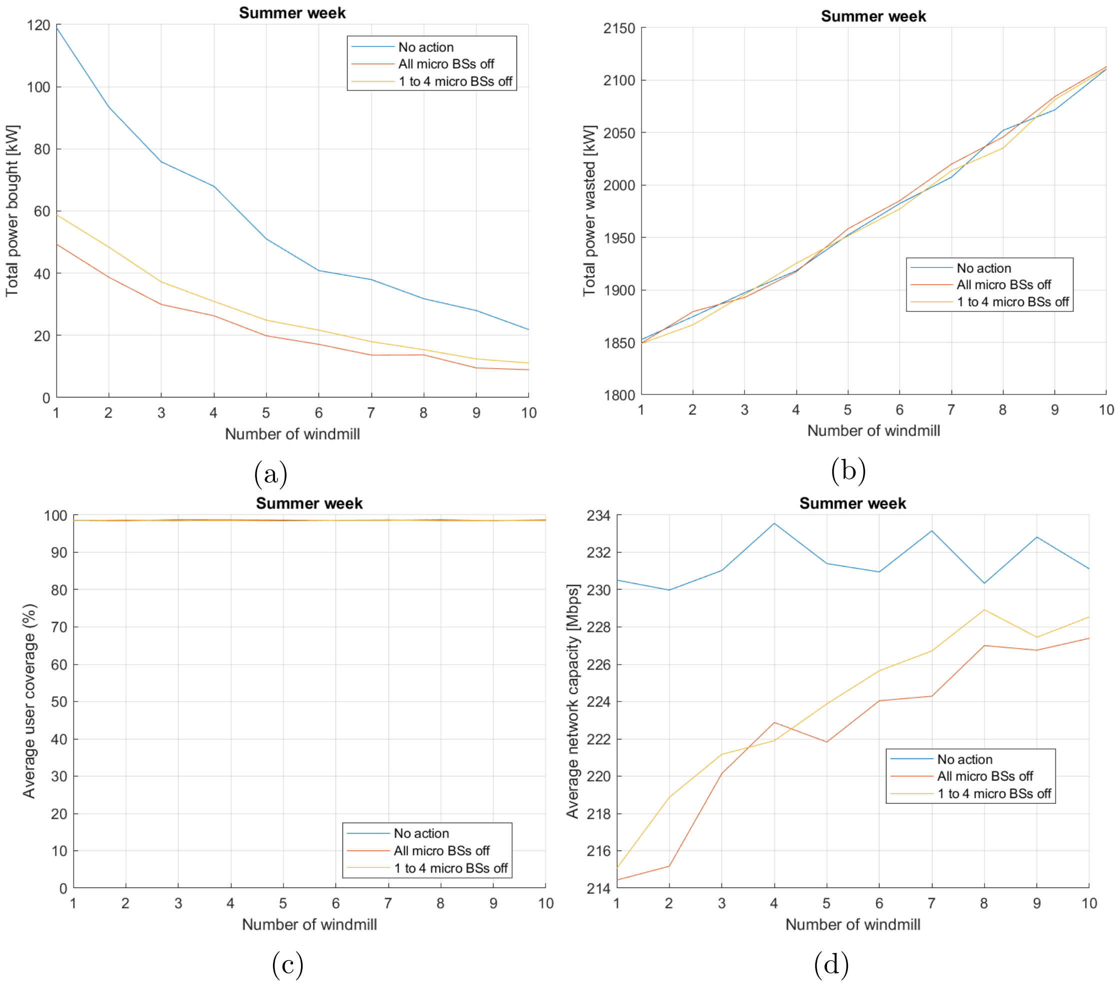
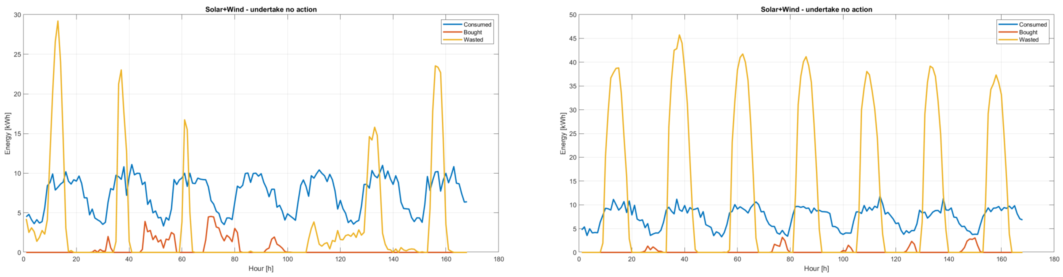


Figure 4.8: Comparison of the amount of bought power (a), the power wasted (b), the user coverage (c) and the network capacity (d) for the three different strategies in combined solar and wind energy system during summer.



(a) (b)

Figure 4.9: Evolution of the network's energy consumption, the energy bought from the traditional electricity grid, and the energy wasting during one week (168 hours) when no action is undertaken in winter (a), and summer (b).

- Nominal capacity of the whole geothermal power plant: 21 MW
- Percentage drained: varying from 5% to 20% of the total energy in steps of 5%
- Capacity of energy storage: 50 kWh, full at the start of the simulation
- Time window: 1h

The amount of bought power, the amount of wasted power, the user coverage, and the network capacity are studied below as a function of the percentage of power drained by the geothermal plant.

1. *Bought Power*: The performance of the combined solar and geothermal energy system works well concerning the amount of bought power. In Figure 4.11a and Figure 4.10a, it is clear that during summer season the network is almost able to feed itself through its energy generation, and in winter the values remain below 500 kW in the reference scenario and 200 kW with strategy 2 and strategy 3. Therefore, shortage detection and a smaller amount of available energy make energy-saving strategies more diverse. Strategy 2 allows lower consumption than strategy 3 and this implies less energy purchased. As soon as the available energy increases, the difference fades and both strategies converge to around 25 kW.

2. *Wasted Power*: When solar energy is involved, wasting becomes an issue. In particular, during summer (Fig. 4.11b), the amount of total wasted energy is approximately 1900 kW when 5% of geothermal power is taken and grows linearly up to about 2250 kW. Even if the solar energy system is combined

with a small amount of geothermal energy, the system produces a huge surplus. However, during winter (Fig. 4.10b) the amount of wasted energy is comparable with bought energy: it goes from 220 kW to 320 kW. Enlarging the energy storage, more harvested energy could feed the network when the energy production reduces, setting to zero both bought and wasted energy. Despite the strategy choice influences other variables, it does not affect the total wasted energy: all over the simulation energy-saving modes differ from the reference scenario by few kWs.

3. *User Coverage*: Figure 4.10c and Figure 4.11c show the behavior of the user coverage with respect to the amount of power absorbed from the geothermal plant. Both in summer and winter, the network ensures the users more than 98% of the coverage. There is a perfect overlap between the three different strategies: user coverage is excellent regardless of the strategy choice. These results are due to the huge amount of energy available in the system, that allows maintaining in the system as much microcell BSs as needed to have optimal performance.

4. *Network capacity*: As already observed in previous cases, the average network capacity is influenced by the amount of energy in the system: if the available energy is high, no difference in the choice of the strategy (Fig. 4.11d). On the contrary, when the energy is not enough, the choice of energy-saving strategies reduces the network's performance (Fig. 4.11d).

Evolution of the Energy Consumption, Production, and Wasting During the Week

The case study under the analysis set to 10% the amount of energy drained by the geothermal power plant. In this section, the behavior of the system during two different seasons when strategy 1 is applied will be investigated. This choice is due to the fact that, since the amount of available energy is huge, there are no meaningful differences between strategies, while the difference between winter and summer is significant. As Figure 4.12 shows, power is mainly bought during the night: in winter (Fig. 4.12a it is more evident than summer (Fig. 4.12b. Solar energy is the main responsible for feeding the grid and in summer since the production is higher, it is necessary to buy less than 1% of the needed energy. Conversely, in winter this percentage rises to 28%.
However, the most interesting variable remains the wasted energy: the two seasons are separated by three orders of magnitude. The total of 265 kWs wasted during winter can be compared with the amount of bought power, then the system could even become independent enlarging the size of the storage. In summer, instead, the surplus is more than 2 MW and it all depends on the size of the photovoltaic

panels. Probably the best solution is to downsize the solar energy production system.

4.5 Wind and Geothermal

Influence of the Geothermal Energy Percentage on Energy and Network Performance

In Section 4.1, 5 wind turbines have been identified as reasonable wind farm size. Based on this assumption, the network will be now analyzed when the number of windmills in the energy system is fixed and the power percentage drained by the geothermal power plant varies.
In wind and geothermal energy system the following settings are assumed:

- Nominal capacity of whole geothermal power plant: 21 MW
- Percentage drained: varying from 5% to 20% of the total energy in staps of 5%
- Nominal capacity wind turbines: 2.5 MW
- Size of the wind farm: 5 wind turbines
- Capacity of energy storage: 50 kWh, full at the start of the simulation
- Time window: 1h

The influence of power percentage drained by the geothermal plant on the amount of bought power, the total wasted power, the user coverage, and the network capacity will now be investigated.

1. *Bought Power*: Wind and Geothermal power system gives quite good results both in summer (Fig. 4.14a) and in winter (Fig. 4.13a) as regards the total bought power. The power purchased by the traditional electricity grid is linearly dependent by the amount of energy grabbed by the geothermal power plant when strategy 1 is applied, while it is a bit exponential with the other two strategies. The curve of the reference scenario is deeper than the energy-saving modes curve: when strategy 2 (or 3) is applied, the total power consumption increases in parallel, then the consumed energy rises as well as the amount of available energy. For example, focusing on Figure 4.13a, bought power goes from 23% to 6% of the total energy consumption in the reference scenario, and from around 6% to 1% with energy-saving modes.

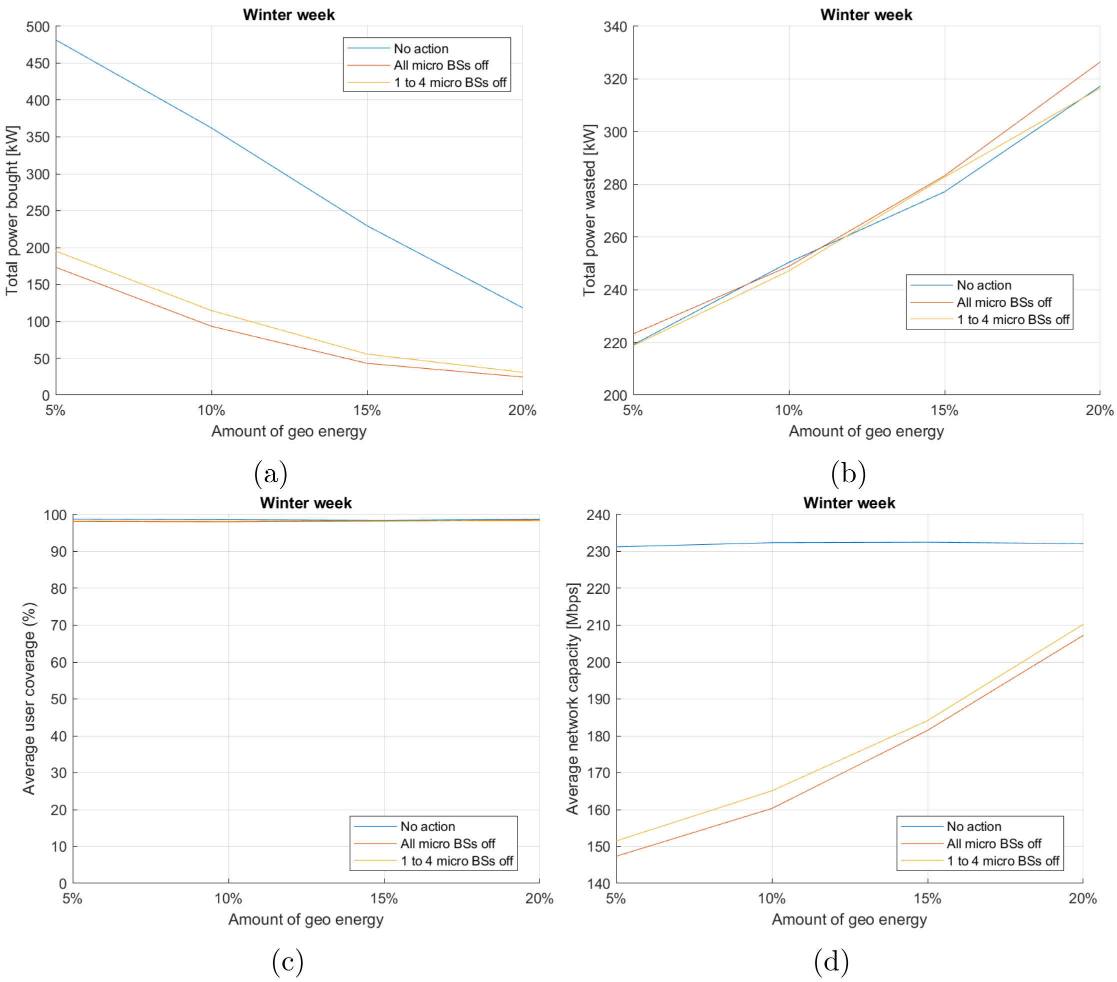


Figure 4.10: Comparison of the amount of bought power (a), the power wasted (b), the user coverage (c) and the network capacity (d) for the three different strategies in combined solar and geothermal energy system during winter.

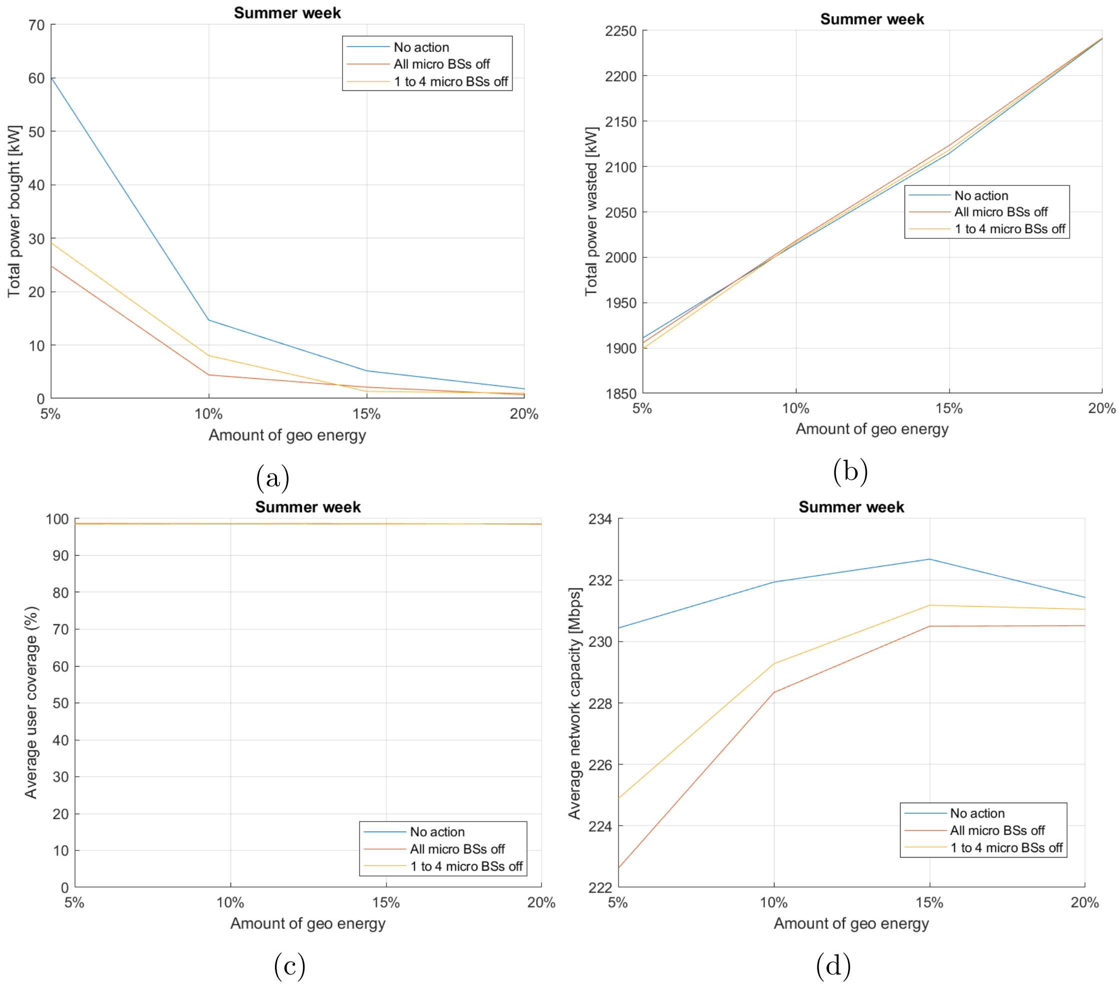
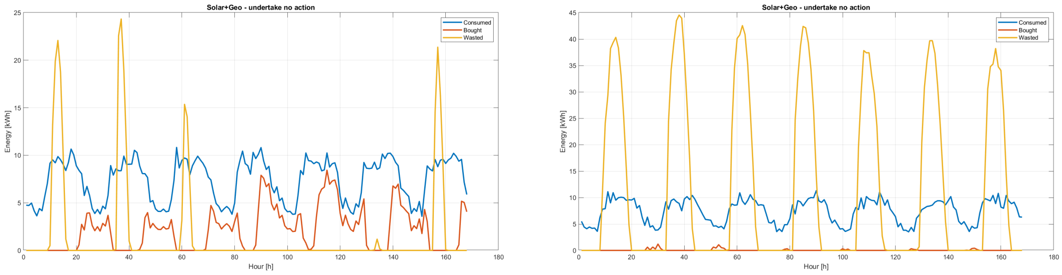


Figure 4.11: Comparison of the amount of bought power (a), the power wasted (b), the user coverage (c) and the network capacity (d) for the three different strategies in combined solar and geothermal energy system during summer.



(a) (b)

Figure 4.12: Evolution of the network's energy consumption, the energy bought from the traditional electricity grid, and the energy wasting during one week (168 hours) when no action is undertaken in winter (a), and summer (b).

Moreover, the shortage is so strong that the choice between strategy 2 and strategy 3 does not affect the outcome: curves perfectly overlap.

2. *Wasted Power*: Wind and geothermal energy production has regular behavior during the day and it does not have a peak as well as solar energy. Correctly dimensioning the energy system, the system will never have a huge energy surplus. As shown in Figure 4.13b and Figure 4.14b, energy-wasting is constrained in winter, and almost null during summer. It reaches around 250 kW in the worst case.

3. *User Coverage*: When the network is fed by combined wind and geothermal energy system, the energy resources are higher during winter than summer: while geothermal energy is not influenced by the season, wind energy production is more efficient during winter. This is highlighted in Figure 4.13c and Figure 4.14c. The first one shows user coverage always equal to 98.5% with no link to the strategy or the geothermal power percentage, while the second one depicts that running some energy-saving mode causes poorer performance of the network. 1% less of the users are covered during summer when strategy 2 or strategy 3 are applied due to energy shortage.

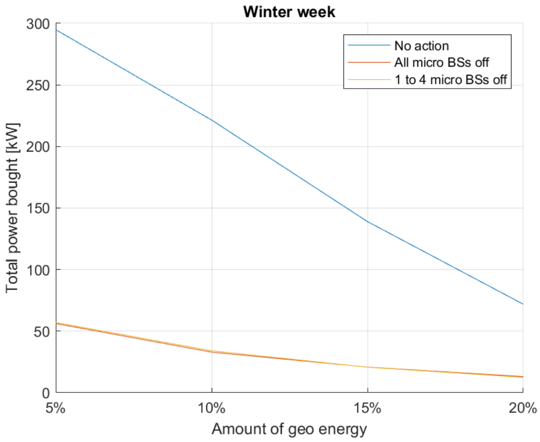
4. *Network capacity*: In Figure 4.13d and Figure 4.14d, the influence of geothermal energy on the network capacity is shown. As expected, the reference scenario has a constant value of Mbps, while energy-saving modes show a growing behavior. On average strategy 3 works better than strategy 2, but still, they have performed a quarter lower than strategy 1 in the worst case in summer.

Evolution of the Energy Consumption, Production, and Wasting During the Week

In the previous section, it has been underlined that applying energy reducing strategies significantly reduces the performance in the network, especially during summer. For this reason, the comparison between season is preferred to strategies. The network will be here fed by 5 wind turbines and 15% of the total geothermal power.
Figure 4.15 shows the evolution of the network's energy consumption, the energy bought from the traditional electricity grid, and the energy-wasting. Completely with the opposite trend with respect to systems in which solar energy is involved, in this scenario, most of the energy is requested to the traditional power plant during the day, because wind energy production is low. In summer (Fig. 4.15b), every day the network needs the supply from the main grid for 44.5% of the total energy. During winter (Fig: 4.15a), wind energy contributes more in powering the system, and bought energy goes down up to 10%, while the wasting reaches 193.5 kW all over the week. In particular, the influence of the fully charged batteries can be observed in the first 20 timestamps of the simulation, as already mentioned in some other previous cases.

4.6 Complete energy system and costs optimization

The complete framework is the energy production system provided of solar, wind and geothermal sources. All the resources collaborate in the generation of renewable energy to power the wireless access network. Every hour, based on the forecasts made on the energy consumption of the network, the optimization algorithm chooses which and how many of the renewable resources present in the system to use.
Chapter 3 in the Tables 3.3 and 3.2 quotes respectively the ranges of capacity values to choose from and the data regarding the costs of each generation power plant. As in the simulations analyzed in the sections above, the system is provided of energy storage of 50 kW wide and the batteries are assumed completely charged at the beginning of the simulation. Moreover, the time window is set equal to 1h. In this section the evolution of the power consumed by the network, the power produced by the energy system, the power wasted by the energy storage system, and the bought power from the electricity grid during one week will be investigated. The analysis will focus on summer and winter since solar and wind energy are involved and their production is deeply different all year long. Figures 4.16 and 4.18 show the evolution of the considered metrics when taking no action at all



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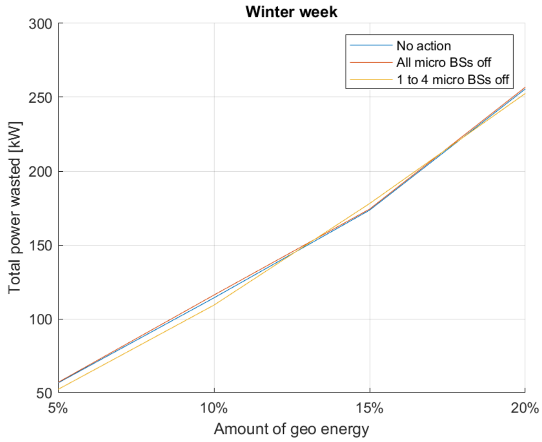

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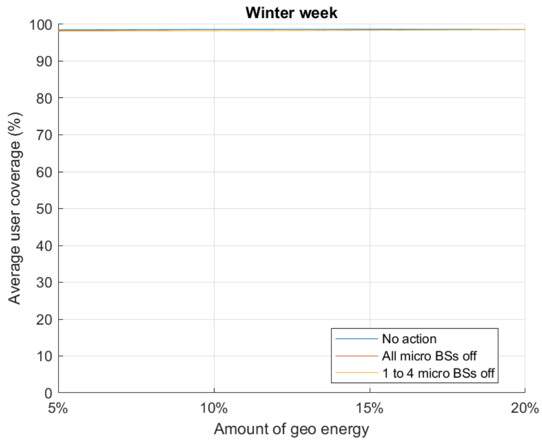

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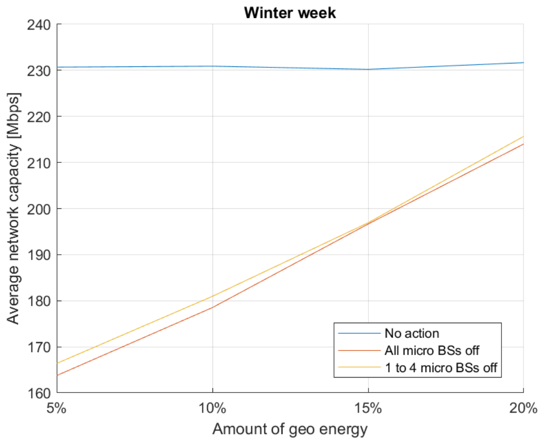


(d)

Figure 4.13: Comparison of the amount of power bought (a), the power wasted (b), the user coverage (c) and the network capacity (d) for the three different strategies in combined wind and geothermal energy system during winter.

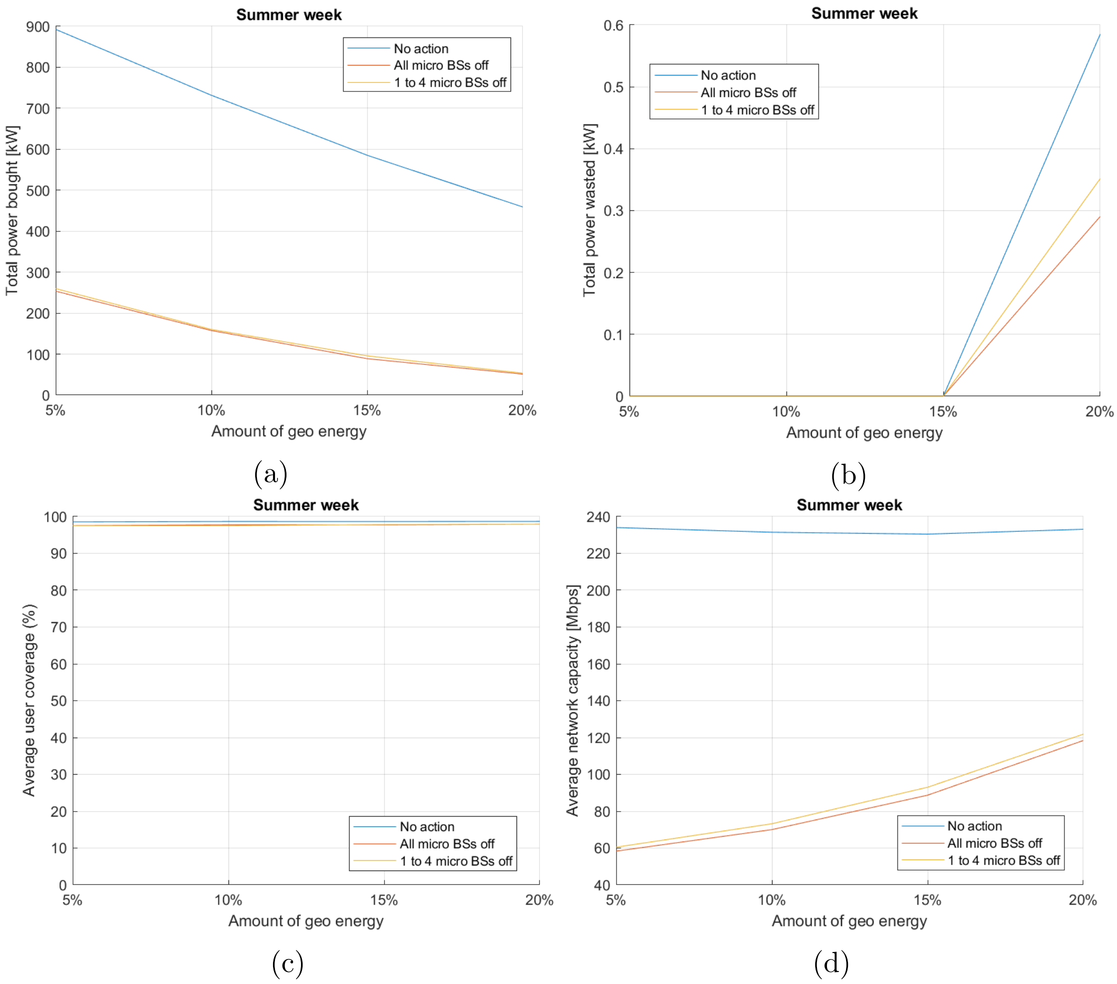
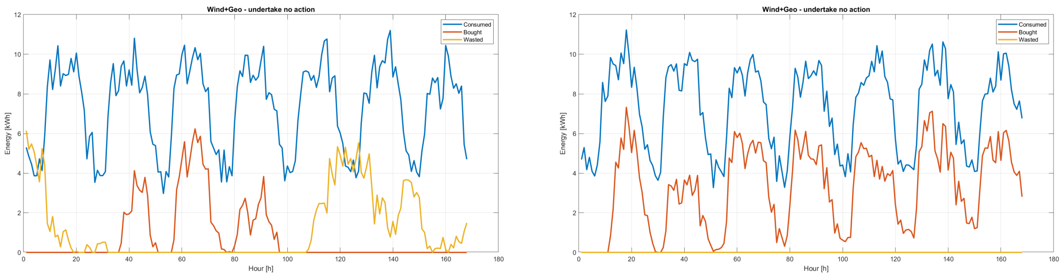
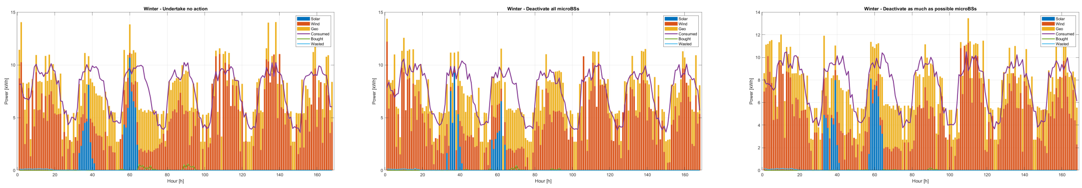


Figure 4.14: Comparison of the amount of power bought (a), the power wasted (b), the user coverage (c) and the network capacity (d) for the three different strategies in combined wind and geothermal energy system during summer.



(a) (b)

Figure 4.15: Evolution of the network's energy consumption, the energy bought from the traditional electricity grid, and the energy wasting during one week (168 hours) when no action is undertaken in winter (a), and summer (b).



(a) (b) (c)

Figure 4.16: Evolution of the network's energy consumption, the renewable energy production, the energy bought from the traditional electricity grid, and the energy wasting during one week (168 hours) for the 3 considered strategies: no action (a), all microcell Base Stations off (b), and 1 to 4 microcell Base Stations off (c).

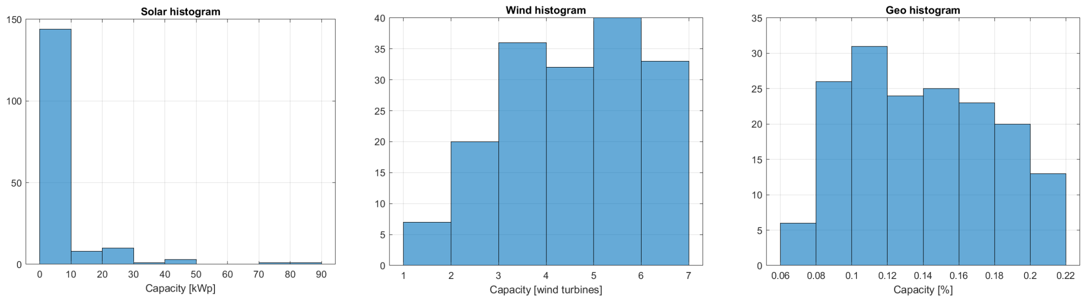
(Strategy 1), turning off all microcell Base Stations (Strategy 2), and switching off 1 to 4 microcell Base Stations (Strategy 3), respectively.

First of all, focus on the winter season in the reference scenario, shown in Figure 4.16a. As previously observed, the energy consumption of the network (purple line) has its higher points during daytime hours, reaching more than 10 kWh and halving in the nighttime.
The green line in the figure describes the trend of energy bought from the main electricity grid for the whole week. Only 5.63 kW, that corresponds to 0.4% of the total consumption, is needed to cover the grid's energy needs during the simulation. Compared to the previous scenarios, the result is surprising: the network is almost independent from the traditional power plant. Energy shortage is detected in particular during the night when solar energy production is voided and the combination of wind and geothermal energy is not sufficient.

Even more satisfying is the result referred to the energy surplus production. The solid blue line, which represents energy-wasting, is null almost everywhere. During the whole simulation, only 2.65 kW is squandered: a paltry rate if compared to the previous results. It is also interesting that this overproduction occurs only in the first part of the simulation. In the initial phase, the batteries are assumed to be fully charged, and this amount of energy may have influenced the simulation. These effects are smoothed during the simulation, tough.
Comparing the reference scenario with the energy-saving modes (in Figs. 4.16b and 4.16c), it is clear that they are barely applied since on average the wireless network consumes the same amount of energy among all the simulation. Energy wasting is around 2 kW both with strategy 2 and strategy 3, while the amount of energy bought from the grid goes down up to less than 0.1% of the total consumption.
Lastly, the choice of renewable resources is investigated. In Figure 4.16a, the colored bars show per each timestamp the chosen RESs. Wind energy is always picked, and most of the time geothermal energy too. Solar energy instead seems to be the least appropriate choice: in winter solar energy production is small, then larger PV modules would be needed to feed the network. For this reason, the optimization algorithm chooses it just a few times. Figure 4.17a highlights that most of the times no PV modules are included in the energy system. Most suited is geothermal: the histogram in Figure 4.17c shows almost uniform trend in the range between 0.10% and 0.2%. This means that geothermal energy can always be a solution, but with a limited percentage. While geothermal energy production is almost constant over the year, winter is the best season to produce wind energy. The optimization is done based on three components: facility cost, cost of energy bought, and cost of overproduction. As shown in Figure 4.17b, during the simulation large wind farms are preferred the most, because wind energy is cheaper than geothermal and has more constant and higher production than solar.

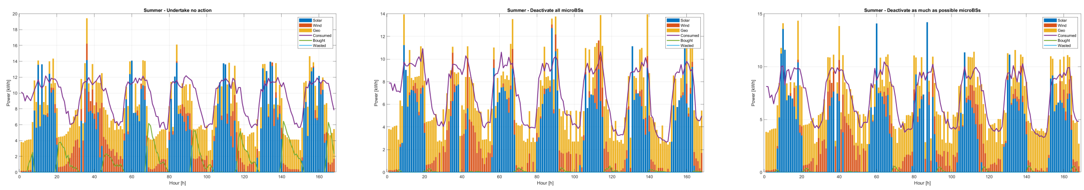
Figure 4.18a depicts how the network hourly behaves during summer. On average energy consumption reaches 10 kWh during the day and halves during the night as in the previous case. Summer turns out to be the worst-case as related to the energy bought from the traditional electricity grid: its sum amounts to 188.5 kW, which means about 11% of the total consumed energy. In return, energy-wasting is every time null.
In this case study energy-saving modes are more effective than the previous one (Figs. 4.18b and 4.18c). Despite energy consumption is almost equal to the reference scenario, the energy bought from the grid goes down up to 0.6% with strategy 2 and 0.7% with strategy 3, while the energy-wasting stays void.

With respect to the winter season (Fig. 4.16), during summer solar energy



(a) (b) (c)

Figure 4.17: Histogram of the energy system size chosen by the optimization costs algorithm for solar (a), wind (b), and geothermal (c) during winter when undertaking no action.



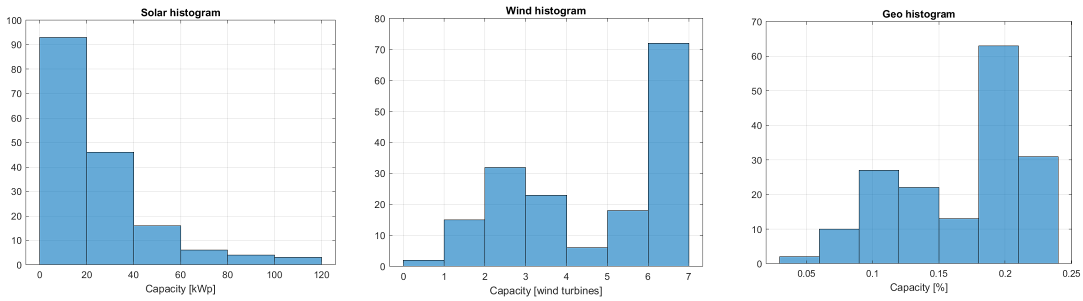
(a) (b) (c)

Figure 4.18: Evolution of the network's energy consumption, the renewable energy production, the energy bought from the traditional electricity grid, and the energy wasting during one week (168 hours) for the 3 considered strategies: no action (a), all microcell Base Stations off (b), and 1 to 4 microcell Base Stations off (c).

system is kept on going the most. Among all the simulations, daytime energy consumption is mainly covered by PV modules energy production. It is interesting to notice in Figure 4.19a that, although the season would allow huge quantities of solar energy, the preferred size for photovoltaic panels is always small. The production peaks caused by large modules would cause an increase in waste, for this reason, these solutions are penalized by the optimization algorithm. Wind is still the best option: in Figure 4.19b is clear that most of the times 7 wind turbines are activated during the simulation. Enlarging the wind farm size is preferable to choose another source. Finally, the geothermal histogram is shown in Figure 4.19c. The choice falls on a high percentage of energy got by the geothermal power plant, and this is mainly due to:

- Wind energy is the cheapest, but in summer its production is scarce.
- Solar energy has big peaks in day hours, but it leaves the network energetically uncovered over the night.
- Geothermal energy production is constant over time.

Final observation is about an algorithm drawback: consider timestamp 36. The tallest bar in Figure 4.18a show that the energy system is producing a surplus of energy: network consumption is 11.4 kW, while the energy production reaches 19.4 kW. All the sources available in the energy system work together, even though solar energy alone would have been enough. This means that wind and geothermal energy are kept because they are the cheapest ones, but their energy production is not sufficient to cover the network energy need. Then, even solar energy is included in the final solution and this causes overproduction. Overproduction is not necessarily an issue: at night, when solar energy is no longer available, the energy surplus stored in the batteries can be used to power the network without having to necessarily buy from the main network, since during summer the generation of wind energy is quite contained.



(a) (b) (c)

Figure 4.19: Histogram of the average energy system size chosen by the optimization costs algorithm for solar (a), wind (b), and geothermal (c) during summer when undertaking no action.

Chapter 5

Conclusion

Today, data traffic on the internet has grown hugely, resulting in energy consumption climbing. Wireless access networks are playing a more and more important role in global greenhouse emission, and contribute significantly to climate change. Therefore, besides network performance, energy efficiency is becoming one of the main goals to achieve.
The thesis aims to find out strategies and algorithms to optimally exploit the renewable energy supply system and to minimize the total expenses for the energy purchased for the power supply of the Base Stations in a wireless access network. The network under analysis is provided by 8 macrocell Base Station, each equipped by 4 microcell Base Stations, and relies on solar, wind and geothermal energy systems that are integrated with batteries. Energy reducing techniques are allowed to minimize the power consumption, deactivating all or part of the microcell Base Stations.
The study demonstrated that including renewable energy sources in the system is effective in the drop in the amount of bought energy, but the choice of the energy supply resources is fundamental to achieve the goal. The results show that in general the energy required from the electricity grid decreases linearly increasing the size of the energy system when the resources involved do not produce sufficient energy, while the relationship is exponential when the system overproduces. Another variable that is very influenced by the lack of energy is the network capacity. When no action is undertaken, the capacity is not affected by the size of the energy supply at all. If we consider strategies to reduce the consumption, on the other hand, the performance of the network drops terribly. Larger the size of the energy system, the higher the network capacity according to a monotonous function. Therefore, relying only on wind (or geothermal) energy comes out to be insufficient: the quantity of produced energy is scarce and the risk is to pauperize the network's performances when energy-saving strategies are applied. To guarantee the necessary energy support, the network should have giant wind farms

or a high percentage of geothermal energy. Being a wireless access network with quite small coverage area, this would not be the best solution since saving on the energy purchased would correspond to a larger investment in the construction of new resources.
Combining more than one renewable resource produces interesting results, especially as regards the energy bought from the traditional electricity grid. The "diversification" of the energy system improves performances: on average more than 90% of energy is supplied by RES, and user coverage and network capacity are optimal. However, there is a drawback that cannot be ignored. Energy wasting grows exponentially reaching a maximum of 2 MW, in particular when solar energy is involved. Therefore, the best option in combined energy production system is to redeploy the surplus in other frameworks or to sell these extra amounts of energy. Such idea of wireless access network will fit perfectly in the new context of Smart Grid: it would no longer be just a consumer but a *prosumer* and would contribute to the "smart" management of the electricity grid.
Furthermore, in the thesis the energy generation system is explored through a heuristic search algorithm. The idea is to dynamically build per each time stamp the energy supply structure most suited to the current energy consumption. All RESs are involved in the analysis, and it is interesting to notice that in this case, energy reduction techniques do not influence the network consumption: energy shortage is rarely detected because the combined production of such resources is enough to feed the network. In the worst case, only 11% of the total energy needed must be purchased from the main power grid. This value can drop below 0.1% if the weather conditions are favorable and energy-saving techniques are applied. The most surprising consequence is the choice that the algorithm makes among the available resources. Solar panels represent the least expensive resource in the collective imagination, the optimization function, however, penalizes solutions that produce a high surplus. For this reason, smaller photovoltaic modules are preferred which do not produce huge peaks during the light hours. On the other hand, contributing to low percentages to the construction and maintenance of geothermal plants seems to be an economically viable solution. While the most promising resource is wind: simulations show that in most cases larger wind farms are preferred to other alternative solutions.
As future work, the genetic algorithm used in the implementation of the heuristic search algorithm can be replaced with new ones, to find the most suited for this kind of problem. Moreover, the function used to choose the best candidates for reproduction could be improved by replacing the simplified formula of the LCOE with a more precise and detailed one. In this way, a more accurate choice of the solution would be guaranteed.

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