POLITECNICO DI TORINO

Master Course in ICT for Smart Societies

Master Thesis

# Managing power outages in communication networks


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# Summary

For the power grids the cellular network is among the most critical power consumers, in case of faults on the power grid it is important to find solutions to guarantee to the users the communication capabilities with the best quality available for as long as possible. The aim of this thesis is the dimensioning of backup power supply of cellular networks base stations with the minimization of the total lost traffic due to outages in a year, by exploiting both solar and battery energy. The dimensioning is firstly done using the simulated power outages in the Milan Metropolitan area, then the dimensioning scenarios obtained are applied to the simulation with real outages stored by meters in the Turin Metropolitan area in order to get the best strategy to reduce the effects of outages on the communication network and on the user by involving renewable energy technologies. The simulations carried out take advantage of real traffic profiles from comparable urban areas and provide hints to which are the best choices to make in these events to meet the users' expectations in terms of service quality. Results are obtained with the consideration that Turin and Milan are cities similar in structure, weather, etc.

# Contents

# Chapter 1

# 1 Introduction

The Internet of Things (IoT) is widely applied in the deployment of smart cities, such as smart homes, smart grids, smart monitoring, smart transportation, eHealth, etc. IoT provides us a platform to improve the work efficiency and bring much convenience to our daily lives. However, with the IoT devices' expansion, the network also faces many challenges. Due to the pervasive number of IoT devices, the huge power consumption and carbon dioxide emissions pose great pressure on environmental conservation. This severe situation pushes us to consider the green IoT deployment, which is the general trend of development toward green wireless communications for the future wireless networks' design.

As we move towards the Smart Grid era, the different industries, including the Information and Communications Technology (ICT) industry, are trying to find ways of reducing their energy consumption, energy costs and carbon footprint. With the rapid development and diffusion of ICT, the energy consumption of ICT equipment and services is surging. For instance, the ratio of electricity consumption of ICT equipment and services (e.g., communication networks, computers, and data centers) to global electricity consumption has risen from 3.9% in 2007 to 4.6% in 2012 [1]. In the 2018, ICTs account for between 5% and 9% of total electricity consumption, and their development suggests a deep transformation of energy systems, from smart networks to customer management or decentralised energy exchanges [2]. Introduction of alternative energy sources, such as solar panels, wind farms and hydroelectricity through the Smart Grid are some of the solutions towards reducing the carbon footprint and the total energy consumption.

Our electric grid infrastructure is aging, and it is being pushed to do more than it was originally designed to do. Modernizing the grid to make it "smarter" and more resilient through the use of cutting-edge technologies, equipment, and controls that communicate and work together to deliver electricity more reliably and efficiently can greatly reduce the frequency and duration of power outages, reduce storm impacts, and restore service faster when outages occur. Modernization is also necessary to enable efficient management of distributed (renewable) energy production. Consumers can better manage their own energy consumption and costs because they have easier access to their own data. Utilities also benefit from a modernized grid, including improved security, reduced peak loads, increased integration of renewables, and lower operational costs.

"Smart grid" technologies are made possible by two-way communication technologies, control systems, and computer processing. These advanced technologies include advanced sensors known as Phasor Measurement Units (PMUs) that allow operators to assess grid stability, advanced digital meters that give consumers better information and automatically report outages, relays that sense and recover from faults in the substation automatically, automated feeder switches that re-route power around problems, and batteries that store excess energy and make it available later to the grid to meet customer demand.

The overall architecture of a Smart Grid, as shown in Fig.1, is composed of two layers:

- *Power system layer*
- *Communication layer*

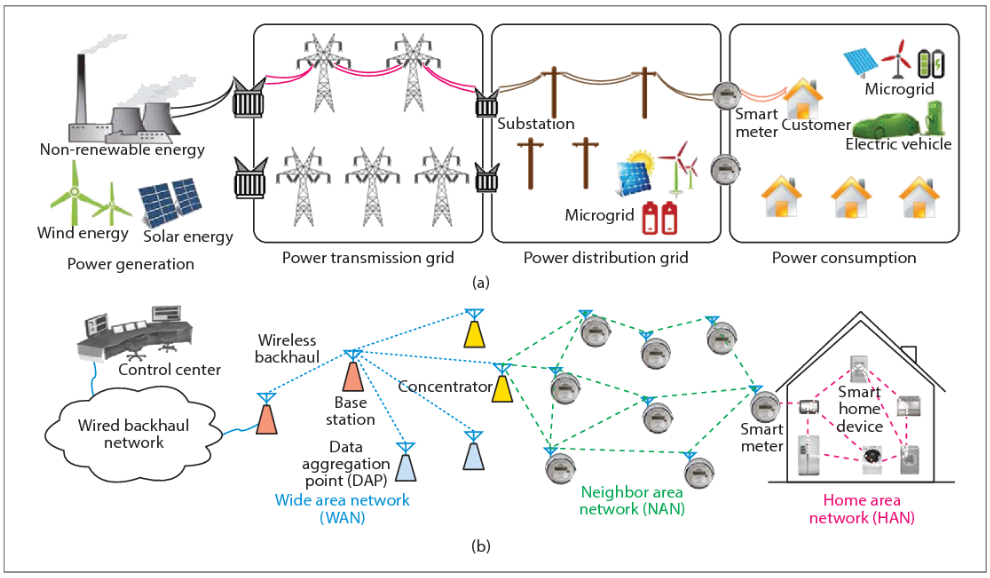


Figure 1: Smart grid architecture

Source: [3]

The grid is evolving continuously towards the Smart Grid because of the significant growth expected in electricity consumption in the coming decades and the related investment required to meet electricity and heat demand. There is an opportunity to guide this expansion using the full range of smart grid enabling technologies and practices that take advantage of the transition to less centralized electricity production while creating a more economic, efficient, and reliable electricity production and consumption system. Global energy demand is projected to more than double by 2050 owing to the growth in population and economies. More than 80% of current primary energy consumption is obtained from fossil fuels. The reserve of fossil fuels will be depleted in the next century. Finding sufficient supplies of alternative energy for the future is, therefore, one of society's most daunting challenges. Fortunately, sunlight provides the most abundant carbon-neutral energy source, which far exceeds human needs even in the most aggressive scenarios [4].

## 1.1 Introduction to power system layer

The power system layer represents the power grid (PG), which is a system based on four main operations: **generation, transport, distribution and consumption**, as shown in Fig. 1.1. Technological development over the last decade, in particular with the increased use of information and communication technologies (ICTs), has exposed the power grid to an all-new set of threats. Like any system, a PG is not fully fault-proof. A fault can occur at any point of the grid, whether due to natural causes, operational errors, cyber-attacks or physical attacks, among others causes. Whenever there is a fault at any part of the PG, different levels of consequences will be generated for the grid as a whole. Faults affecting only a small part of the PG, and with easy and fast resolution, do not imply a redirection of the energy flow through other transmission lines. However, catastrophic events may imply the isolation or overloading of other sections of the PG, due to load redistribution, which can lead to a cascade failure. The PG is undoubtedly one of the most critical infrastructures in any country.

The rapidly growing demand for energy combined with the reduction of conventional energy sources in recent years have led to the transformation of the energy sector. Households and other energy users can now both produce and consume energy. They can also either store the surplus for future use or send it to the grid for sharing with other energy users. As a result of this transformation, the smart grid gave rise to “prosumers” who contribute to the energy supply.

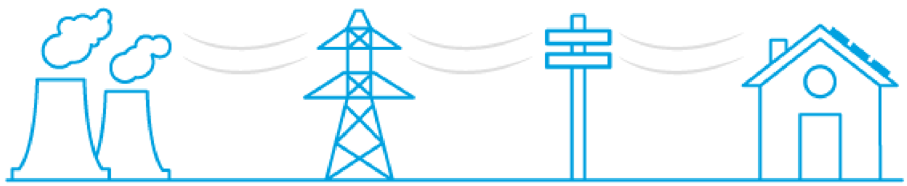


Figure 1.1: Power system layer

Source: [5]

The power grid is composed by four main actors:

- The **electricity generation** comes in traditional networks form huge power plants which work to convert mechanical energy of a turbine into electrical energy by the use of a generator. Power plants require the energy from fuels such as coal or natural gas, or primary energy flows, such as wind and sunlight in order to do this. The location of these electricity generators – and their distance from end users – varies widely. These plants generate lots of electricity and are often far away from the demand for electricity; the next system (transmission) solves this problem.

- **Transmission networks** are the set of high voltage lines in charge of delivering power across long distances. Since losses depend on the current flowing in a medium, those high voltages ranging from 220kV to 1000kV are used to reduce the current in a line even with huge power loads.

- **Distribution networks** take electricity from the transmission networks and prosumers and bring it to the final users. Voltages in this area of the network are lower since it covers a smaller area.

- **Consumption** represents the use of power by the final consumer, or prosumer, which uses the distribution network to inject excess production and to withdraw electricity when self-production is not sufficient to meet own needs.

## 1.2 Introduction to the communication layer

The **communication layer** in the Smart Grid provides the two-way flow of information within the whole grid, as shown by the blue lines in Fig. 1.2, while the traditional grid allows a one-way communication between producers and consumers.

Communication Systems are used in automation to pass data between device level (sensors, actuators, transducers etc.) and control level (PLC's, RTU's, IED's etc.), between different control level devices, or between control level and supervisory level (SCADA). These data, meaning voice, data, image, signal or video in mobile communication and the data generated by the IoT devices, are then used for operator interface, data processing and storage. Communication systems can be radio, telephone, copper cable, optical-fiber cable, satellite etc. or a combination of any of these. They are the backbone of all remote monitoring and control system as they really make telemetry and telecontrol possible.

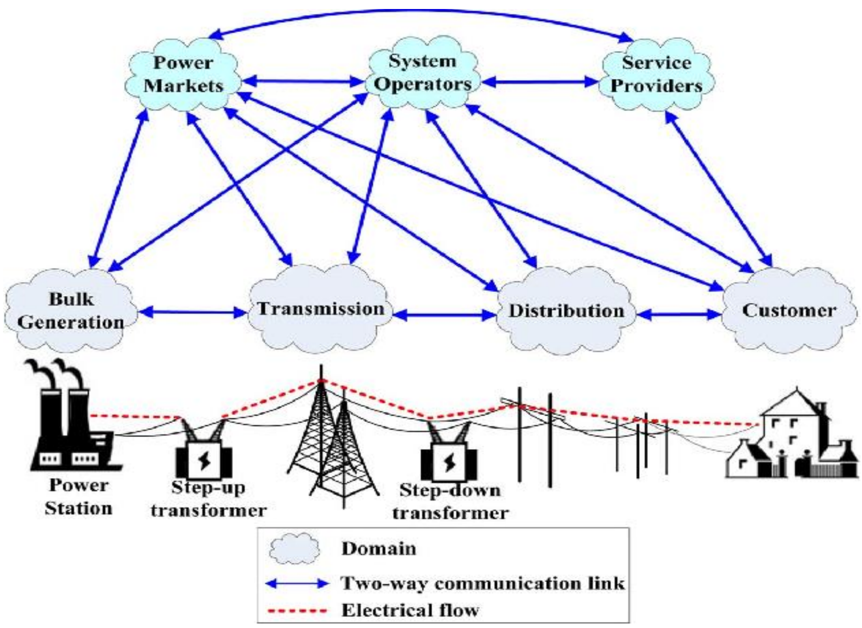


Figure 1.2: Interactions among different smart grid domains

Source: [6]

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. The increasing number of wireless devices, as mobile devices and IoT devices, that are accessing mobile networks worldwide is one of the primary contributors to global mobile traffic growth.

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 CO2 emission. In this context, carbon-low impact alternatives, like **renewable energy supply**, represent a possible solution. 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.

## 1.3 Introduction to cellular networks

A **cellular network** is a network of handheld mobile and IoT devices, in which each of these devices communicates with the cellular network by radio waves through a local antenna at a cellular base station (cell site). Nowadays those infrastructures are critical also for data transmission for people, appliances and sensors belonging to the internet of things. Internet connected devices exploit the cellular network to make intra-cell or more frequency inter-cell communication.

Cellular networks are high-speed, high-capacity voice and data communication networks with enhanced multimedia and seamless roaming capabilities for supporting cellular devices. With the increase in popularity of cellular devices, these networks are used for more than just entertainment and phone calls. Today these networks have become the lifeline of communications. A **breakdown** in a cellular network has many **adverse effects**, ranging from huge economic losses, therefore it is a high priority for cellular networks to function accurately.

For the generation technology standards before 5G, the coverage area in which service is provided is divided into a mosaic of small geographical areas called "cells", each served by a separate low power multichannel transceiver and antenna at a base station. All the cell devices within a cell communicate with the system through that cell's antenna, on separate frequency channels assigned by the base station from a common pool of frequencies used by the system. 5G instead, the fifth-generation technology for cellular networks, uses very fast, short-range signals on an unused frequency band to send and receive more total data, within a dense network of specialized small cell sites. A small cell site refers to the area within which this short-range wireless signal can be received.

A cell site, as in Fig. 1.3, or **cellular base station** is a cellular-enabled mobile device site where antennas and electronic communications equipment are placed typically on a radio mast, tower, or other raised structure to create a cell (or adjacent cells) in a cellular network.

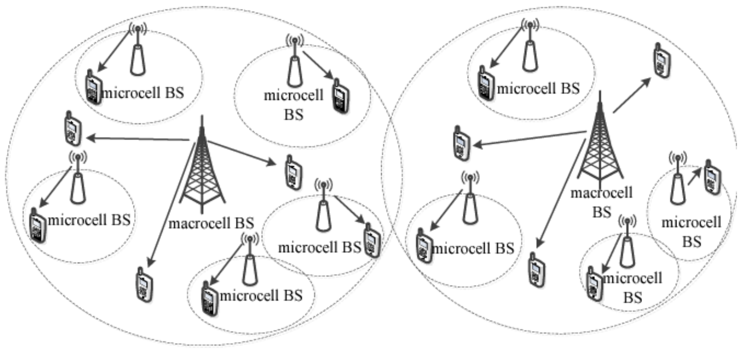


Figure 1.3: Cellular network example

Source: [7]

Over the years, the use of Information and Communication Technology (ICT) has come to dominate several areas, improving our lives, offering us convenience and reshaping our daily work circumstances in the process. Computers and other ICT infrastructure consume significant amounts of electricity, placing a heavy burden on electric grids and contributing to greenhouse gas emissions. Moreover, the large number of devices with high transmission capacity connected to the Internet is playing a major role in increasing the energy consumption by communications networks.

Powering cellular base stations with **renewable energy** are one of the long-term strategies for achieving green networks and reducing their operational costs. As an energy provider, the power grid is evolving into a smarter one, which allows more energy-efficient cellular networks and enables cooperation and interaction with the smart grid. On one hand, cellular networks can use harvested renewable energy and on-site energy storage to reduce their energy costs. On the other hand, the price of electricity depends on the energy load, which will eventually contribute to decreasing the peak consumption and global energy cost.

### 1.3.1 Cellular network components

The main components of a cellular network and their definitions are the following:

- **Mobile Station** (**MS**) - mobile device which is used from a user to access the network.

- The **Base Transceiver Station** (**BTS**) - antenna and transceiver radio equipment needed to communicate with the MSs on the field.

- **Cell** - area covered by a single BTS in which the MS can roam and still get service. Cell types adopted in this work are:

    - **Macro cells**: served by a high power cell site (tower, antenna or mast), they generally provide coverage larger than microcell. The antennas for macro cells are mounted on ground-based masts, rooftops and other existing structures, at a height that provides a clear view over the surrounding buildings and terrain. Older standards rely mainly on this type of cells.

    - **Micro cells:** have gotten more popular since the introduction of 4G and are frequently found in metropolitan areas, to improve service quality for densely populated areas such as train stations or sport venues.

- The **Base Station Controller (BSC)** is the main network element inside the BTS. It allows the communications from and to the core network.

- **Base Station Subsystem (BSS)** – apparatus in charge of managing one or more BTSs and their BSC. Its tasks include managing the radio resources, the transmission quality and the channel allocations. Since one BSS can manage more than one BTS, a BSS can cover quite a large area.

- **Users**: cellular devices as smartphones, tablets, etc. and IoT devices as sensors, actuators, gadgets, appliances, machines, etc.

### 1.3.2 Cellular standards technologies

The different cellular standards technologies are categorized into the following generations, each improving on the predecessor in network capacity and power consumption, however the older standards are maintained for compatibility purposes.

- **2G – The first digital standard**: it has been established in 1991 and is the first digital standard. It delivered more reliable and secure communication. The 2G standard implemented the CDMA and GSM concepts. 2G networks introduced many of the fundamental mobile services we still use today, as The Short-Message-Service (SMS). With "General Packet Radio Service" (GPRS) and "Enhanced Data Rates for GSM Evolution" (EDGE) the 2G Standard was updated twice to 2.5G and 2.75G enhancing its maximum speed to 171 kbps and 384 kbps.

- **3G - Introducing mobile multimedia capabilities**: it was introduced in 2003. At its core network it used a new architecture called "Uni-versal Mobile Telecommunications System" (UMTS). Its main advancement to its predecessor 2G was a significantly higher bandwidth. This made 3G the first mobile "multi-media standard". In 2006 3G was updated to 3.5G by introducing the High-Speed Downlink Packet Access (HSDPA) communication protocol further increasing the data bandwidth of 3G up to 42 Mbps.

- **4G - High speed and ubiquitous computing**: the fourth Generation was introduced in 2012. Its main advantage is to deliver high speed communication with enhanced security to enable high-definition mobile TV, video conferencing and pervasive computing respectively ubiquitous computing with bandwidths up to 150 Mbps. [8]

- **5G – The future standard:** the fifth generation is the latest standard in cellular communication. With bandwidths of up to 1 Gbps 5G is designed to enable high speed communication with high capacities and very low latency making it the perfect communication technology for augmented reality applications, gaming, machine to machine communication and smart devices when quick reaction plays a vital role. For the time being 5G is not de-signed to replace its predecessor 4G. The parallel operation of both technologies will enable larger capacities and faster network speeds to be served in the future.

- **6G – The next horizon:** the sixth generation will be able to use higher frequencies than 5G networks and provide substantially higher capacity and much lower latency. One of the goals of the 6G Internet will be to support one micro-second latency communications, representing 1,000 times faster than one millisecond throughput.

## 1.4 Power outages and batteries

A power outage (also called a power cut, a power blackout, a power failure, a power loss, or a blackout) is the interruption of the electrical power network supply to an end user. There are many causes of **power failures** in a power grid. Examples of these causes include faults at power stations, damage to electric transmission lines, substations or other parts of the distribution system, a short circuit, cascading failure, fuse or circuit breaker operation. One of the worst blackouts happened in India in July 2012, where approximately 38% of India's power generation capacity went offline affecting 22 out of 28 states in the north and east of the country, with a $400 billion strategy recover [9].

Power failures are particularly critical at sites where the environment and public safety are at risk. Institutions such as hospitals, sewage treatment plants, and mines will usually have backup power sources such as standby generators, which will automatically start up when electrical power is lost. Other critical systems, such as **telecommunication**, are also required to have emergency power, as described in Fig. 1.4: when a blackout occurs the network capacity decreases and the network load increases, so during the time lapse between the beginning of power blackout and the mobile network overload the system needs enough backup power to avoid losing traffic.

In a **telecommunication system**, a BTS is an equipment to facilitate the wireless communication between the user equipment and the telecommunication network. In general, the BTS is supplied using the power provided by the state electricity company, using a diesel-generator set, and, in our case, using battery and photovoltaic (PV) systems. The main limit of the PV systems is the low conversion efficiency of the PV panels, which is strongly influenced by their operating temperatures. A combination of supply systems is normally adopted to provide a power backup during a failure of the main supply system. In the case of a PV system, the battery utilization must consider the duration of how long it can still support the loads without being charged.

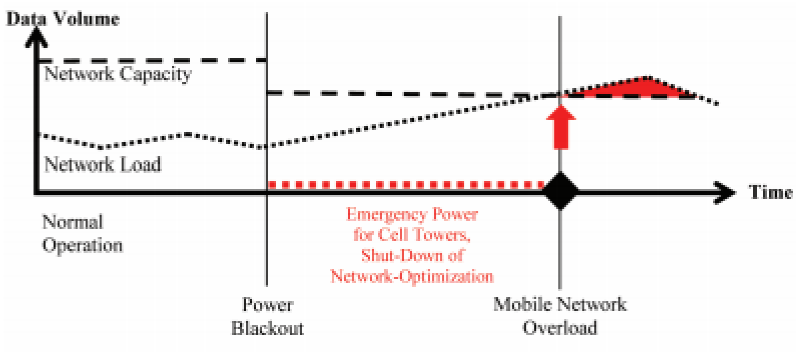


Figure 1.4: Blackout and its consequences for mobile communication

Source: [10]

**Backup power** is defined as any device that provides instantaneous, uninterruptible power. A backup power system is used to provide energy when the primary source fails. Traditional backup systems include batteries and generators, which operate on diesel, propane, or gasoline. Although these systems are well-established, the batteries and generators' drawbacks are encouraging the users to seek for alternative technologies that can provide higher reliability and durability at a rational cost. Therefore, additional renewable energy generation are considered in Smart Grid communication system. The term UPS (uninterruptible power supply) is an often-used term but can sometimes refer to systems that supply A/C power, or systems that supply power for no more than 30 to 60 minutes. Typical applications for backup power include telecommunications systems, information technology and computer systems, manufacturing processes, security systems, utility substations, and railway applications. Backup power is urgently needed during emergencies for medical services, clean water, emergency lights, communication and electrical services, among other needs, as cases where the loss of power results in a significant reduction in productivity or financial loss.

The longer the power outages and/or the higher the impact of a blackout, the more reliable the backup power needs to be and the more effort the customer will make in improving the backup powering system. These energy interruptions interfere with the normal operations of the equipment outside of the grid, compromising all the services that rely on this infrastructure, because of this their impact on the grid must be reduced.

### 1.4.1 Battery technologies

Batteries convert chemical energy directly into electrical energy. Telecommunication power systems are responsible for every-day internet, high-speed data, telephone, and other communication services. As global demand for these services continues to increase, the need for reliable battery backup equipment rises. The batteries used in this sector are mainly of two types, as shown in Fig. 1.5:

- **Lead acid battery**
  - **Pros:** The lowest self-discharge for rechargeable batteries, can provide high-discharge rates, and inexpensive, can last up to 30 years before needing to be replaced.
  - **Cons:** Cannot store batteries when they are discharged or it causes sulfation, has a limited number of full discharge cycles, and must be used for stationary or wheeled applications due to low-power density.
- **Lithium-ion battery**
  - **Pros:** Low maintenance, high-power density, and low self-discharge.
  - **Cons:** Capacity deterioration occurs quickly as the batteries need to be replaced in 2-3 years, has a moderate discharge current, and more expensive than lead acid batteries.

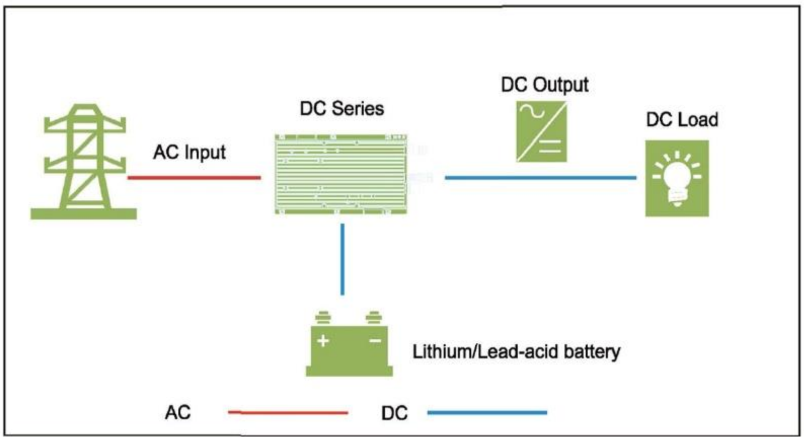


Figure 1.5: Power supply system for micro base station

Source: [11]

The majority of batteries used in the telecommunication industry are Lead-Acid type. Lead-Acid batteries are an inexpensive design compared to newer technologies such as Lithium-Ion; however, **Lead-Acid batteries** have a lower energy density, meaning that larger and heavier batteries are required to produce the same power equivalence of a smaller, Lithium-Ion battery. Lead-acid batteries are normally used as the backup power source for communication power systems, due to their low operating costs, as in the case of this work. On the other hand, **Lithium-ion batteries** have definite technical advantages in terms of power to weight to volume ratio, absence of pollutants like acid and lead.

## 1.5 Photovoltaic (PV) Panel

Solar panels, also known as photovoltaic panels or PV panels, are used to convert light from the sun, which is composed of particles of energy called "photons", into electricity that can be used to power electrical loads.

Solar panels can be used for a wide variety of applications including remote power systems for cabins, **telecommunications equipment**, remote sensing, and of course for the production of electricity by residential and commercial solar electric systems. **Solar-grid** integration is a network allowing substantial penetration of Photovoltaic (PV) power into the national utility grid. This is an important technology as the integration of standardized PV systems into grids optimizes the building energy balance, improves the economics of the system, reduces operational and electrical energy costs, and provides added value to the consumer and the utility.

When PV panels are integrated in the grid as backup power of a BTS, a hybrid system is obtained, which exploits solar energy during the day and battery power, instead, when the PV production is low or zero. Such a system, shown in Fig. 1.6, is smart, green, and cost-effective.

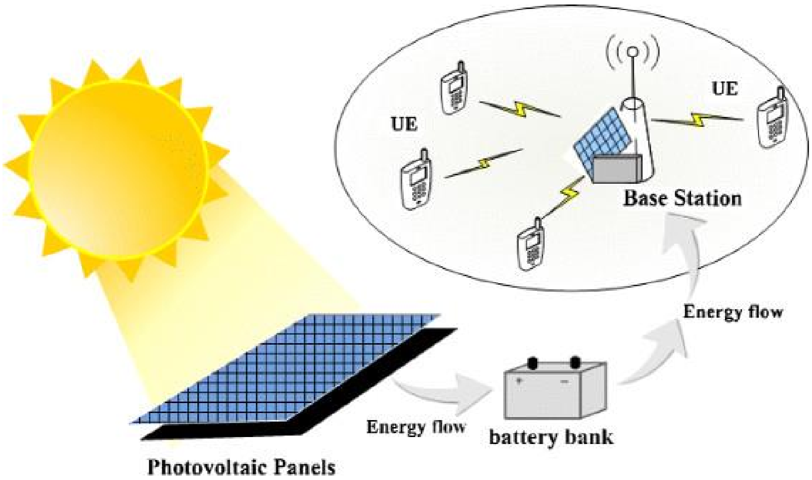


Figure 1.6: PV Panel in power grid

Source: [12]

PV production changes according to the capacity of the PV panel. Knowing that 1 kW system of solar panels can generate around 850 kWh of electricity each year [13], in our system three different capacities will be considered, as shown in Table 1, and their relative year production are calculated, multiplying the one-year production by the PV panel capacity.

| **PV Capacity** | **3 kW** | **5 kW** | **7 kW** |
|---|---|---|---|
| **Year production** | 3x850 kWh = 2550 kWh | 5x850 kWh = 4250 kWh | 7x850 kWh = 5950 kWh |

Table 1: PV Panel capacity and relative year production

## 1.6 Objective of the thesis

The goal of this thesis is to reduce effects of power outages in the **cellular networks** by introducing photovoltaic panels in the base transceiver stations (BTSs) as backup power supply when outage takes place. In particular, the aim is to reduce the total lost traffic due to blackouts and to increase the duration of the BTSs during the outage. The **renewable energy** utilization approach is sustainable and environmentally friendly. Therefore, the solar resources are deployed to procure the energy requirements. Besides limiting the usage of conventional grid energy, this choice minimizes carbon emissions and improves the performance of the systems in the context of energy consumption and cost.

## 1.7 Thesis organization

The thesis is divided in the following chapters.

**Chapter 2: Data Analysis**

This chapter is dedicated to the analysis of the data provided by IRETI company, which represent a file containing power outages occurred in Turin in a year. From its analysis useful information for this work are extracted.

**Chapter 3: Methodology**

In this chapter, the system configuration and the different scenarios of backup power supply are described. It focuses on the illustration of the strategy used to minimize the total lost traffic in a year due to outages.

**Chapter 4: Analysis of the results**

In this chapter, the results obtained are presented and analysed for each proposed scenario in Chapter 3.

**Chapter 5: Conclusions**

Conclusions and considerations based on the results reported in Chapter 4 are discussed.

# Chapter 2

# 2 Data analysis

## 2.1 Outage analysis

In Italy companies which operate in the energy transmission and distribution market have to report the information about the quality of the service provided to ARERA (*Autorità di Regolazione per Energia Reti e Ambiente*).

One of the most important metrics when measuring the quality of the electricity supply is the service continuity, which means the absence of interruptions in the supply of electricity. Interruptions can have different causes, they can be originating on the high voltage national transmission network or they can be due to force majeure reasons. Those events can be divided into two main categories:

- **"with notice"** (at least one day of forewarning)
- **"without notice"**, that can divided into "long" (longer than 3 minutes), "short" (between 1 second and 3 minutes long) and "momentary" (less than one second long).

Each year companies operating in the electricity market have to report to the Authority the continuity data about the previous year, information about the number of interruptions, their origin points, their causes and their duration.

### 2.1.1 Outage analysis on the IRETI network

In this work data provided by the Italian company IRETI are used. IRETI is a private company part of IREN group which manages electricity, methane and water distribution all over the Italian territory. Through a 7700 km long network made of high, medium and low voltage lines this company manages electricity distribution in the cities of Parma, Turin and Vercelli. In 2018 the company distributed around 4000 GWh of electricity to the end users, around 720000 customers.

Because of European transparency laws, all the utility companies are forced to provide metrics on their performance to the customers to allow choosing the best performing company in the free market regulations. IRETI because of the regulations provides an API which by inserting a POD number and the year of reference can be used to retrieve the information about all the outages relative to that pod for the year of reference.

The data of IRETI outages has been extracted and saved in a .csv file, called "*data.csv*". It is divided into the following columns:

- **POD**: alphanumeric code to insert in the API.
- **Address**: meter address.
- **Event code**: groups entries corresponding to meters affected by the same outage with the same cause.
- **Time**: timestamp of the instant in which the meter first detects the outage which extends for as long as described in the duration field.
- **Duration**: outage duration.
- **Type**: it classifies the event as *short*, *medium* or *long*.
- **Fault location**: describes the section of the grid where the fault originating the outage happened. It can be *high voltage*, *medium voltage* or *low voltage* lines, or it can be on the *interconnection network* or on the *national grid*.
- **Cause**: describes the cause of the fault.

The dataset has 3505 rows, indicating the outage cases. By analysing this data, outages information are extracted and are used for the simulated outages, that will be shown in the Methodology part.

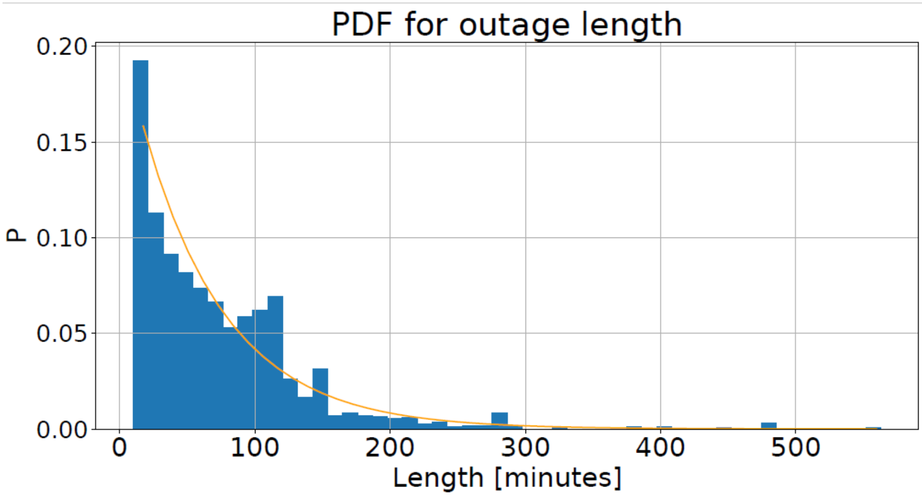


Figure 2.1: PDF of outage length

The fitted probability density function PDF superimposed over the histogram of the outage duration data is shown in Fig. 2.1. From it the following information is extracted:

- Cases of outages with length <=60 minutes represent 71.13% of total outages occurred.
- Cases of outages with length <=200 minutes represent 97.92% of total outage occurred.

Therefore, in the first part of the simulation two cases of outages length will be used as the worst cases: outage length equal to 60 minutes and outage length equal to 200 minutes.

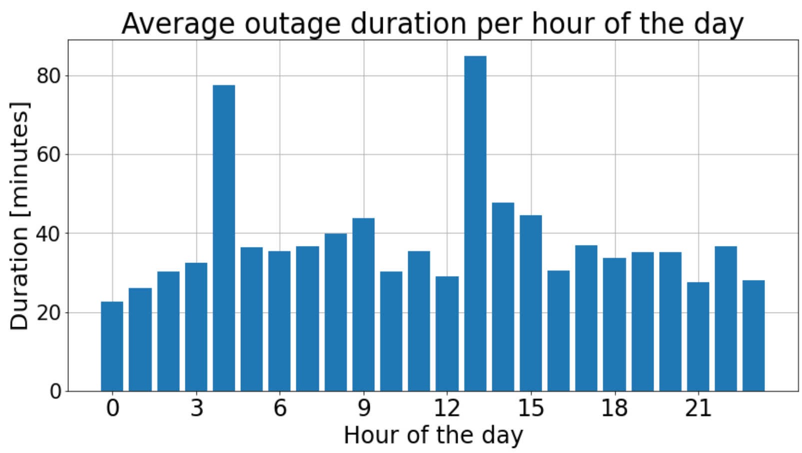


Figure 2.2: Average outage duration per hour of the day

The average outage duration per hour of the day is shown in Fig. 2.2. It is clear that the most critical hours are 4 am and 1 pm, which indicate respectively off-peak and peak of traffic demand periods. For the simulation other hours of the day in which the power outage start will be considered: the hours in which the average outage duration per hour is higher than 38 minutes (total average outage duration). Therefore, apart **1 pm** and **4 am**, also **2 pm**, **8 am**, **9 am**, **2 pm** and **3 pm** are considered as critical hours.

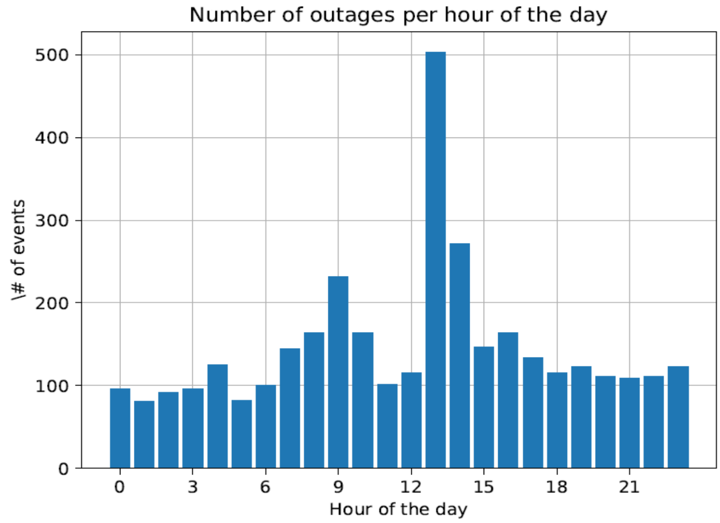


Figure 2.3: Number of outage events per hour of the day

The number of power outages (events) per hour of the day is shown in Fig. 2.3, where it is visible that the majority of outage events occur at 1 pm. The total average number of events is 145. Considering as critical the hours in which the number of outage events per hour is equal or higher than 145, then **7 am, 8 am, 9 am, 10 am, 1 pm, 2 pm, 3 pm, 4 pm** are the hours with highest number of outages, so with the highest outage frequency at that hour. Outage frequency is calculated using equation 2. Critical hours and their relative frequencies are shown in Table 2.

$$Outage\ frequency\ (probability)\ per\ hour\ i = \frac{number\ of\ events(i)}{number\ of\ total\ events} * 100 \quad (2)$$

| | 4AM | 7AM | 8AM | 9AM | 10AM | 1PM | 2PM | 3PM | 4PM |
|---|---|---|---|---|---|---|---|---|---|
| **#EVENTS** | 125 | 145 | 164 | 232 | 164 | 503 | 272 | 147 | 164 |
| **FREQUENCY (PROB. %)** | 3.57 | 4.14 | 4.68 | 6.62 | 4.68 | 14.35 | 7.76 | 4.20 | 4.68 |

Table 2: Critical hours and their outage frequency

These critical hours include the ones found by the *"Average outage duration per hour of the day"* analysis, so the final list of hours to be considered in the simulation of outages are the ones exposed in Table 2.

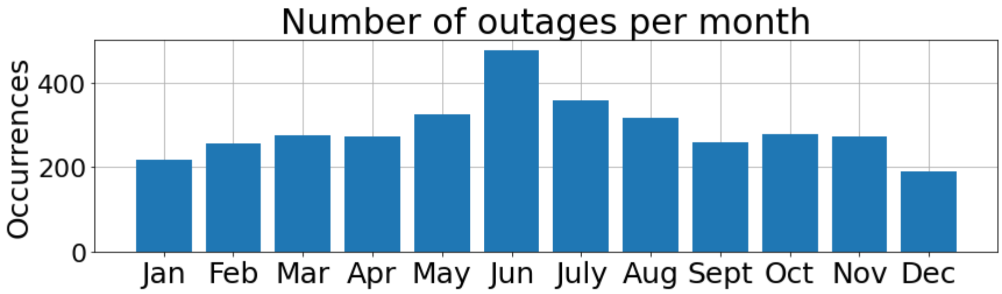


Figure 2.04: Number of outages per month

In Fig. 2.04 the number of outages per month is shown, it is visible that the months with the highest outage occurrence are May, June, July and August, since in summer there is an increased usage of air conditioners that overloads the power grid. In December and January, instead, the outage occurrences are the lowest over the year.

## 2.2 PV Panel data analysis

PV Panel production is stored in a .csv file called "*pvwatts_minute"* that contains the real data of PV production per minute from the 1st of January 2018 to the 31st of December 2018, in the city of Turin, in the north Italy. The data are provided by a "PV WATT calculator", and a file with the following 2 columns is extracted:

- Timestamp
- AC System Output (W) production

It has 525541 rows, one for each minute. The data is referred to a photovoltaic panel with capacity equal to 1kW. During the simulation, these values will be multiplied by the different PV panel capacity values in kW, i.e. 3,5,7, in order to analyse the results. Of course, higher the capacity is, higher the production per minute is.

For each PV panel capacity case the analysis done are the following:

- **Yearly PV production**, shown per month in Fig. 2.4, Fig. 2.5, Fig. 2.6.

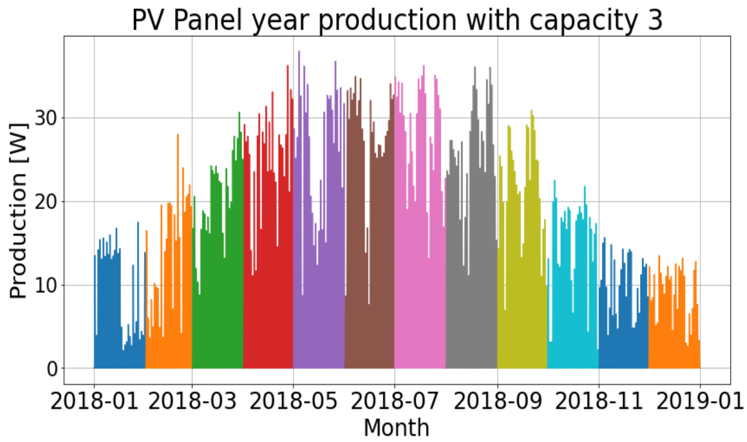


Figure 2.4: Yearly PV production with capacity 3kW

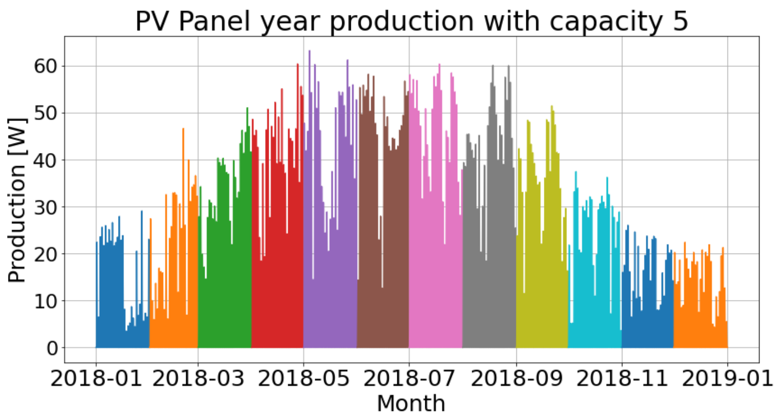


Figure 2.5: Yearly PV production with capacity 5kW

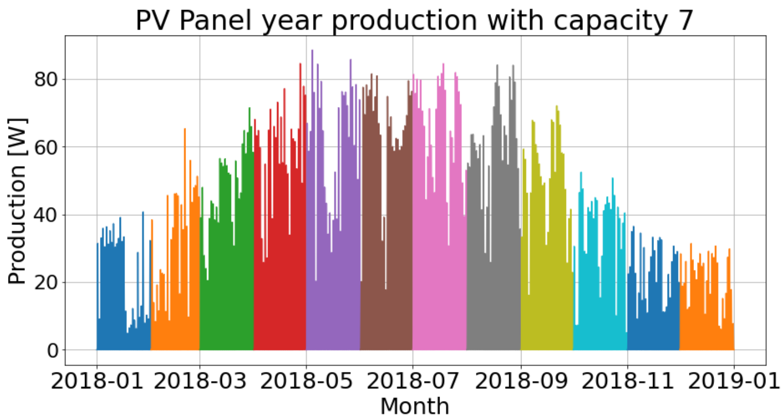


Figure 2.6: Yearly PV production with capacity 7kW

The yearly production of the PV panel has a bell shape, as the solar annual energy production, with the highest values during the months of spring and summer when the sun production is high, while the lowest production is during the cold months of autumn and winter. In particular, the maximum production is in May, while the lowest one is in December.

- **Daily PV production per capacity**, shown per hour in Fig. 2.7, in the most critical days:
    - Minimum production day – *minday*
    - Average production day - *avgday*
    - Maximum production day – *maxday*

The dotted lines represent the production if the PV capacity is equal to 3kW, the dashed lines if it is 5kW, the other lines the production with PV capacity equal to 7kW. The peak is always at 12 am, while from 8 pm to 4 am there is no PV production, it is equal to zero, since there is no solar production in those hours.

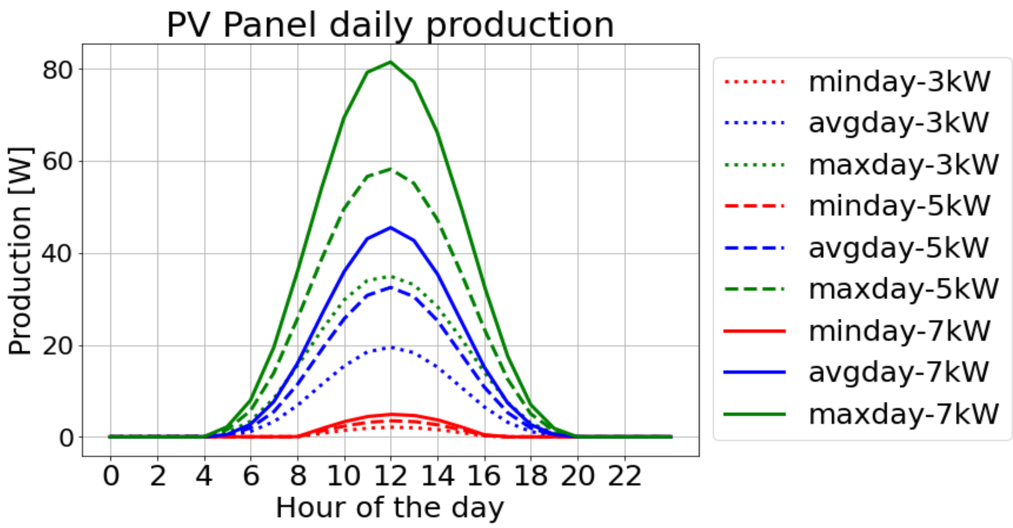


Figure 2.7: Daily PV production per capacity

The daily PV production has a bell shell too, as the solar daily energy production, it shows that for PV panel with capacity equal to 3kW the production per minute is under 35W, for PV panel with capacity equal to 5kW it is under 60W, for PV panel with capacity equal to 7kW it is under 80W.

- **Annual PV panel production** per capacity, obtained by summing all capacities per minute during the year, is shown in Table 3.

| **PV Capacity** | **3 kW** | **5 kW** | **7 kW** |
|---|---|---|---|
| **Year production** | 2877,284 kWh | 4795,473 kWh | 6713,662 kWh |

Table 3: PV panel annual production per capacity

# Chapter 3

## 3 Methodology

The aim of this project is to reduce as much as possible the effects of interruptions of the mobile communication service due to power outages of the power grid, by considering different scenarios of power backup supply for the BTSs during the outages.

The backup power supply adopted are PV panel and Lead-Acid battery. Considering that the file with Turin outages retrieved from IRETI contains the outage cases with relative timestamps (month, day, starting outage hour), a list of values called *tot_prod_pv* is created which stores the PV panel production values for each starting outage time, considering only the critical hours, described in section 2.1. It will be used during the second part of the Methodology.

The impact of the power outages on the Radio Access Network (RAN) in 3 main scenarios is analysed: a **dense**, a **medium** and a **sparse** urban zones are considered, each with its own traffic patterns and RAN topology.

Each scenario is defined through a *.json* file and a *.bts* file. Inside the first file is stored a list of ids identifying traffic traces defined in the second file. For each trace 3 fields are defined:

- **impacted**: defines whether the BTS is impacted from the outage.
- **time_start**: defines the time from the start of the trace when the outage is supposed to start and the BTS will receive no more the power from the grid.
- **time_end**: defines the time when the outage is supposed to end and the power shall be restored.

Inside the second file there are as many rows as the BTS in the selected scenario, each row composed of 4 parameters:

- **trace_file_name**: defines the file name of the file containing the raw data of the trace, it is used to import and process it.
- **cell_id**: defines the id of the cell, it is used to link these information with the first file described.
- **cell_size**: defines the size of the BTS it can assume the values of *macro* or *micro*.
- **cell_standard**: defines the standard of the cell, it can assume the values of *4G*, *3G* or *2G*.

## 3.1 Dimensioning of backup power supply

### 3.1.1 The simulator

In this work, an ad-hoc *Python* simulator is used. It allows simulating power outages in different zones of Milan. The simulator uses given traffic traces for each BTS to work. The traffic traces used are confidentially provided by a large Mobile Italian Operator. These data report the traffic demand volume of more than a thousand of BTS, located in Milan and in a wide area around it. Each trace reports two months of data for the BTS it refers to, starting at 00:00 on the 1$^{st}$ March 2015 to 30th April, with 15 minutes granularity.

We consider 3 portions of the city, listed below. These areas were selected for being quite different in terms of their typical activities and, hence, traffic patterns. All together, the selected areas are quite representative of the various zones that coexist in an urban environment.

- *FS (Train station)* - This is characterized by intense activity levels, especially at the beginning and at the end of the working hours.
- *Residential* - The traffic in this area follows the typical behavior of people in their daily life.
- *Agricultural Park* – Represents a peripheral distribution zone.

For each zone data about macro and micro cells has been provided in separate files. The scenario is composed of macro and micro 4G cells, macro 3G and 2G cells. It is assumed that the traffic performed in the original traces from a micro cell can be performed from a macro cell, however the traffic performed from a macro cell can't be performed from a micro cell. The traffic in zones with macro and micro cells is usually handled through the micro cells, so if the traffic has been carried through a macro cell we assume that no micro cell was present in that zone. It is also assumed that 4G traffic in case of a BTS being switched off, should be first assigned to another 4G BTS - if possible - and then to 3G and 2G BTSs.

BTS configuration for the considered zones is disposed as following:

- *FS*:
  - 2 Macro BTSs (relative standard: 4G, 3G)
  - 4 micro BTSs (standard: 4G)
- *Residential*:
  - 3 Macro BTSs (relative standard: 4G, 4G, 3G)
  - 4 micro BTSs (standard: 4G)
- *Agricultural Park*:
  - 3 Macro BTSs (relative standard: 4G, 4G, 3G)
  - 3 micro BTSs (standard: 4G)

For the simulations it is assumed that all micro BTSs are impacted by the outage, while macro BTSs are never assumed impacted by it.

### 3.1.2 Outage characteristics

Outage features used in the simulation are the followings:

- *OUTAGE_START*: outage starting time.
- *OUTAGE_END*: outage ending time.
- *OUTAGE_LENGTH*: outage length in minutes.

*OUTAGE_END=OUTAGE_START+OUTAGE_LENGTH*

These values must be regulated manually. In order to choose the best ones, data outages useful information are retrieved from the IRETI file, as shown in section 2.1.1. Considering that, two worst case scenarios are examined:

- **Scenario 1**
    - Outage length equal to 60 minutes, which covers 71.13% of outage cases.
    - Outage starting time at the crucial hours of the day showed in Table 2.

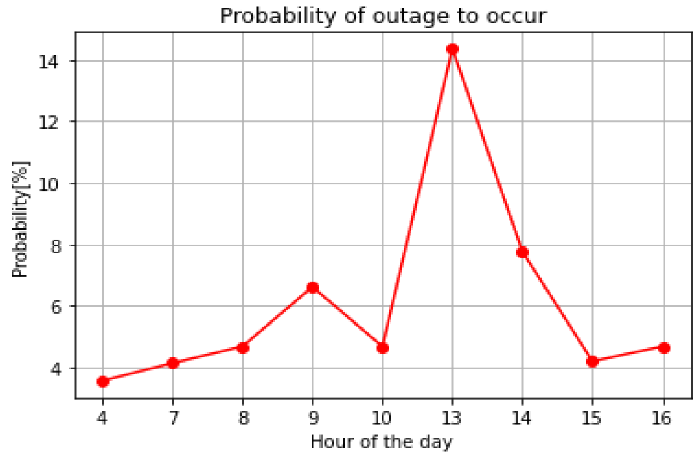


Figure 3.1: Probability of outage to happen.

In Fig. 3.1 the critical hours used in Scenario 1 and their respective probability to occur (frequency) are shown. This probability is based exclusively on the outage events present in the data retrieved by IRETI for the city of Turin.

- **Scenario 2**
    - Outage length equal to 200 minutes, which covers 97.92% of outage cases.
    - Outage starting time at 4 am and at 1 pm, the cases with highest values of outage duration longer than 1 hour.

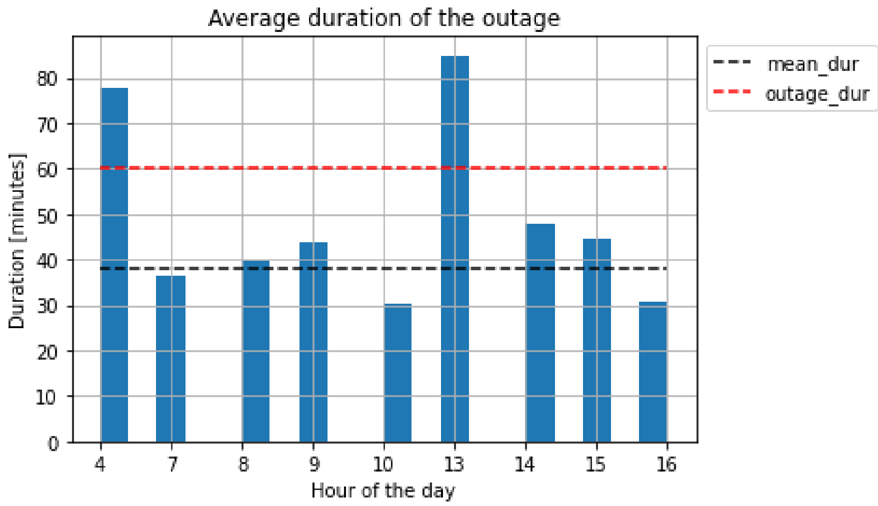


Figure 3.2: Average outage duration considerations

In Fig. 3.2 the average duration of the outage in the critical hours of the day is shown. The black dashed line represents the total average outage length (38 mins), while the red dashed line indicates the outage duration of Scenario 1 (60 mins). From this plot it is visible that the hours of the day when outages longer than 60 minutes occur the most are 4 am and 1 pm. Hence these hours will be considered as outage starting time in the Scenario 2.

### 3.1.3 Battery and PV panel capacities

In both scenarios batteries and PV panel are used as backup power supply for micro BTSs, the ones affected by the outage. Battery capacity values are set manually, while for the PV Panel production value the type of day is chosen, i.e. *maxday, avgday, minday*, representing the minimum, average, and maximum production day. These values are extracted by the PV panel production data described in section 2.2. The capacity of the PV panel is set manually.

For each zone, different scenarios of backup power supply are analysed:

- Only battery
- Only PV panel
- Both battery and PV panel

When considering the PV panel case, the analyzes are done for the three types of day mentioned above. Therefore, for each PV capacity, meaning 3kW, 5kW, 7kW, there will be three simulations, related to *minday-avgday-maxday*.

Battery capacity values adopted in scenario 1 (outages with length equal to 60 minutes) are shown in Table 4.

| BTS TYPE | CASE 1 | CASE 2 | CASE 3 | CASE 4 |
|---|---|---|---|---|
| **MACRO** | 500 VAh | 1000 VAh | 1500 VAh | 2000 VAh |
| **MICRO** | 50 VAh | 100 VAh | 150 VAh | 200 VAh |

Table 4: Capacities of battery – scenario 1

Battery capacity values adopted in scenario 2 (outages with length equal to 200 minutes) are shown in Table 5.

| BTS TYPE | CASE 1 | CASE 2 | CASE 3 | CASE 4 | CASE 5 | CASE 6 |
|---|---|---|---|---|---|---|
| **MACRO** | 1000 VAh | 2000 VAh | 3000 VAh | 4000 VAh | 5000 VAh | 6000 VAh |
| **MICRO** | 100 VAh | 200 VAh | 300 VAh | 400 VAh | 500 VAh | 600 VAh |

Table 5: Capacities of battery – scenario 2

The two cases considered for Scenario 1 (outages with length equal to 60 minutes) are shown in Table 6. In Case 1 only 4 am is considered since for the other hours of the day *maxday* and *avgday* cases have the same results, which is zero lost traffic and micro duration equal to 60 minutes.

| Case 1 | Case 2 |
|---|---|
| All battery cases (Table 4) + PV *minday* for every critical hour | All battery cases (Table 4) + PV *maxday* at 4 am |

Table 6: battery and PV panel – scenario 1

The two cases considered for Scenario 2 (outages with length equal to 200 minutes) are shown in Table 7.

| Case 1: 4am | Case 2: 1pm |
|---|---|
| All battery cases (Table 5) + PV *minday-avgday-maxday* | All battery cases (Table 5) + PV *minday-avgday-maxday* |

Table 7: battery and PV panel – scenario 2

Finally, a one-year simulation is done considering all outages occurred at the critical hours in the IRETI file. This part is done with hybrid dimensioning, so both PV panel and battery are used, considering the PV production during each outage. Battery and PV panel capacities are set manually.

## 3.2 Post-processing

By analysing the outages of Turin given by IRETI the probability of outage to occur (frequency) in the critical hours is obtained, shown in Fig. 3.1 in the section above. From dimensioning part a list of lost traffic per hour is retrieved, per each zone, per each dimensioning scenario. In order to post-process this data, the lost traffic per hour is multiplied by the probability of outage to occur, which allows to obtain the average lost traffic due to outages for one year in Milan and to understand how the different dimensioning scenarios affect lost traffic due to blackouts, using 3.1 for each zone.

*j = dimensioning scenario*
*i = critical hour when outage occurs*

$$Average\ lost\ traffic\ per\ hour = \frac{lost\ traffic(i{:}j) * outage\ probabitily(i)}{100}$$

3.1 Average lost traffic per hour per zone

*Average lost traffic per hour, lost traffic* and *outage probability (frequency)* are in percentage. The dimensioning scenarios are based on the type of PV production during the outages: the PV production at 4 am is always *minday*, while for the other hours of the day the PV production is *minday, avgday* and *maxday*.

Therefore, the analysed cases are the ones in Table 8 for Scenario 1 and the ones reported in Table 9 for Scenario 2.

| **Case 1** |
| --- |
| All battery cases (Table 4) + PV<br>*minday avgdy maxday* per critical hour |

Table 8: post-processing battery and PV panel – Scenario 1

| **Case 1: 4 am** | **Case 2: 1 pm** |
| --- | --- |
| All battery cases (Table 5) + PV<br>*minday* | All battery cases (Table 5) + PV<br>*minday-avgday-maxday* |

Table 9: post-processing battery and PV panel – Scenario 2

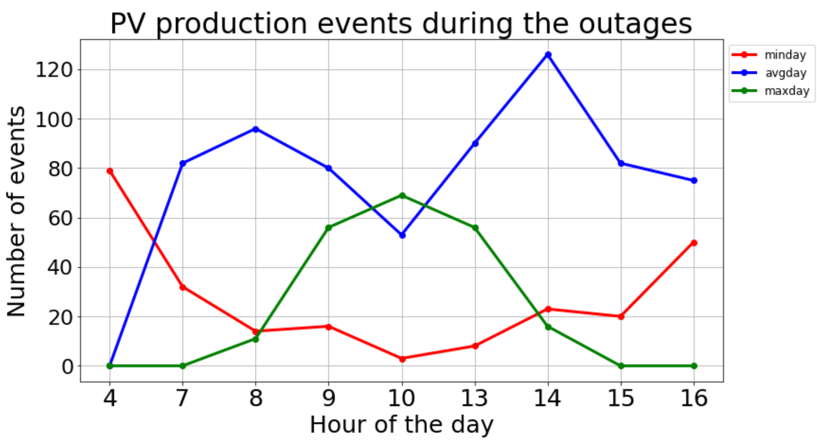


Figure 3.3: PV production events - Scenario 1

In Fig. 3.3 the PV production during the outages in Scenario 1 is shown, where the sum of events of *minday, avgday* and *maxday* per hour is plotted. The highest values of the PV production events are at 4 am for *minday*, since the sun production is low, at 2 pm for *avgday* and at 10 am for *maxday*.

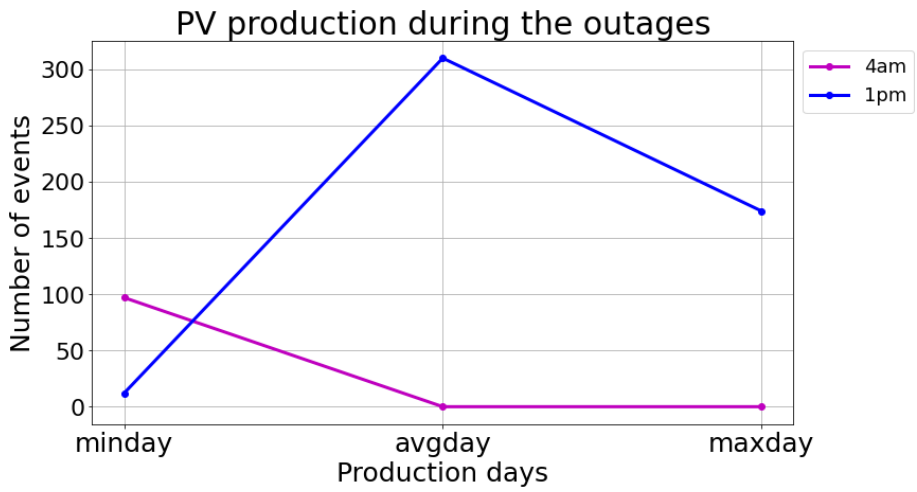


Figure 3.4: PV production events - Scenario 2

In Fig. 3.4 the PV production during the outages in Scenario 2 that occur at 4 am and at 1 pm is shown, where the sum of events of *minday, avgday* and *maxday* per hour is plotted. It is visible that at 4 am there are only *minday* events because the PV panel production is very low at that hour of the day, while at 1 pm the majority of events are during PV production *avgday.*

From the number of events of PV production "day" the probability of those events is calculated (frequency) using 3.2, and adopted to calculate a more precise lost traffic due to power outages, using 3.3 for each zone.

*"Day type" = minday, avgday, maxday*

$$Probability\ of\ PV\ \text{"day } type\text{"} = \frac{\text{"day } type\text{" } events}{total\ events}$$

3.2 Frequency of PV production day type

*j = minday/ avgday/ maxday scenarios*
*i = critical hour when outage occurs*
*frequency = probability of PV minday/ avgday/ maxday*

$$Average\ PV\ lost\ traffic\ per\ hour = \sum_{j} \frac{lost\ traffic(i;j) * frequency(i;j)}{100}$$

3.3 Lost traffic considering PV panel production during outages

## 3.3 Application of the dimensioning scenarios

The last part of the methodology consists in the integration in the simulation of outages data retrieved from IRETI for the city of Turin, described in section 2.1.1. So, for each outage case (row) of the file the following information are extracted and inserted in the simulation:

- Outage starting time
- Outage ending time
- Outage length

For each outage, the relative value of PV panel production considering the same starting hour, day, and month of the outage is extracted. These values are stored in the list *tot_prod_pv* analysed in section 2.2. The battery capacity is set manually.

The aim of this incorporation is to obtain realistic results, by using the real outages data. It is assumed that Turin and Milan are similar cities based on the fact that they are geographically close, so they have the same weather, and they have a similar natural structure. On the other hand, the dimensions of the cities and the population are different: Milan occupies an area of 181,8 $Km^2$ with 1.397.715 inhabitants, while Turin expands on 130,2 $Km^2$ of area with 848 196 inhabitants. The city of Milan is bigger, so there will be more outage cases than in the city of Turin.

Thus, assuming the worst case, the hypothesis adopted is that the same outages that occurred in Turin for one year happened also in Milan for one year, but for each of the zones considered in the simulation (*FS, Residential, Agricultural-Park*).

For each zone two scenarios are analysed, with the following features:

1. **Scenario 1**: outage cases with length less or equal to 60 minutes.

2. **Scenario 2**: outage cases with length less or equal to 200 minutes.

Outage data list and PV panel production list are sorted by month and filtered in order to consider only the cases that have starting outage hour equal to the critical chosen hours. After the simulation has finished, a list of lost traffic and duration time of the micro BTS during the outage is obtained.

## 3.4 Key Performance Indicators

The Key Performance Indicators (**KPI**) or performance indicators are a tool to measure performance in order to know if the network is providing the best possible service.

Since the aim of this work is to reduce the effects of power outages on communication networks, the KPIs adopted are the following:

- **Lost traffic** (in %): this indicator quantifies the amount of traffic which is lost during the outages of each simulation.

- **Duration time of micro BTSs** (in minutes): this indicator quantifies how much time the battery and the PV panel are able to supply the BTSs during the outage.

### 3.4.1 Lost traffic estimation

Since the simulator is given a specific outage duration, starting time, ending time, then, after the simulation is complete, the KPI function is fed the original traffic traces - *original_traffic* - for each BTS in the scenario and the traces resulting from the simulation - *new_traffic*. Those updated traces reflect the changes that have been made to cope with the outages in order to lose as little traffic as possible. Traces are contained in a structure with $B$ rows corresponding to the number of BTS.

To find the lost traffic during the outage 3.4 is used, where the sum of original traffic traces and updated traffic traces instant per instant for each $B$ is done, during the time slot when outage occur, from *OUTAGE_START* to *OUTAGE_END*.

$$lost\ traffic = \sum_{t=OUTAGE\_START}^{OUTAGE\_END} \sum_{i=0}^{B} original\_traffic(i;t) - new\_traffic(i;t)$$

*3.4 Lost traffic estimation*

To find the lost traffic in percentage, instead, a ratio must be considered between the served traffic during the outage, called *new_traffic*, and the traffic demand during the outage, called *original_traffic*. This ratio represents the traffic that is not lost during the outage, so it's necessary to subtract it to 1 to find the lost traffic, shown in 3.5.

$$lost\ traffic\ (in\ \%) = 1 - \frac{\sum_{t=OUTAGE\_START}^{OUTAGE\_END} \sum_{i=0}^{B} new\ traffic(i;t)}{\sum_{t=OUTAGE\_START}^{OUTAGE\_END} \sum_{i=0}^{B} original\ traffic(i;t)}$$

*3.5 Lost traffic estimation in %*

### 3.4.2 Duration time of micro BTSs estimation

Since it is assumed that only micro BTSs are affected by the outage when in happens, from the updated traffic traces – *new_traffic* - are selected only the ones related to the micro BTSs, and a simple control is done on them, as shown in 3.6: the minutes in which the updated traffic is not zero during the outage are added together. Since in the zones considered during the simulation there are 3 or 4 micro BTSs, the average value between their duration times is considered as indicator for the results. It is calculated for each zone.

$$duration\ time\ = \frac{\sum_{i=OUTAGE\_START}^{OUTAGE\_END} \sum_{i\ in\ micro\ traces} (1)}{number\ of\ micro\ traces/BTSs} \qquad if\ new\ traffic(i;t) > 0$$

*3.6 Duration time of micro BTSs in minutes*

# Chapter 4

# 4 Analysis of the results

## 4.1 Dimensioning of backup power supply

In this section the dimensioning of battery and PV panel is done by simulating the outage with length 60 minutes and 200 minutes, starting at the chosen critical hours for each scenario. The dimensioning is done for each zone of Milan *-FS, Residential, Agricultural-Park-* which represent respectively high, medium and sparse density zone. Therefore, the lost traffic is higher in FS zone, where the traffic demand is elevated and low in Agricultural-Park zone, where the traffic demand is small. The best capacity values of the BTSs backup power supply are the ones that provide minimum lost traffic and maximum duration of the micro BTSs during the outage.

### 4.1.1 Scenario 1

Scenario 1 is dedicated to the case where the outage length is equal to 60 minutes, and they happen in the chosen critical hours. The simulations are done separately for battery and PV panel, but for a better understanding the results are plotted together. For each zone two cases are examined:

- All battery cases + PV panel *minday* case

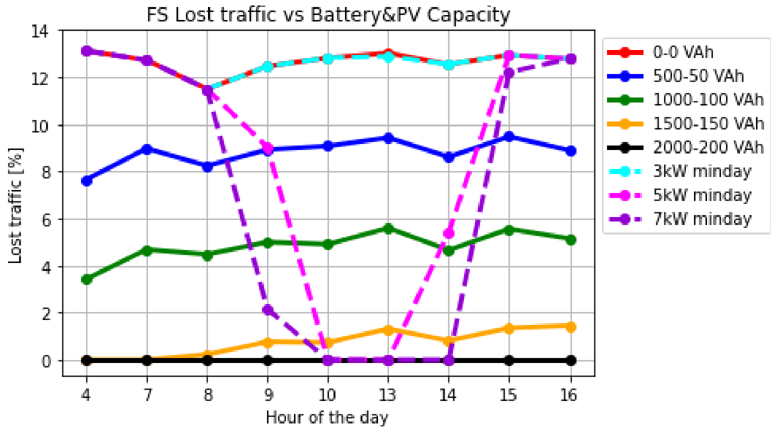


Figure 4.1: Lost traffic in FS zone per hour

In Fig. 4.1 the lost traffic per hour in the FS zone is showed for each dimensioning scenario. Considering the battery case only it is visible that by increasing the battery capacity the lost traffic decreases, arriving to zero when capacities are 2000VAh (Macro BTS) and 200VAh (Micro BTSs). Considering the PV panel *minday* case the plot shows that when capacity is equal to 5 kW the lost traffic is equal to zero at 10 am and 1 pm, while with capacity 7 kW the lost traffic is equal to zero at 10 am, 1 pm, and 2 pm.

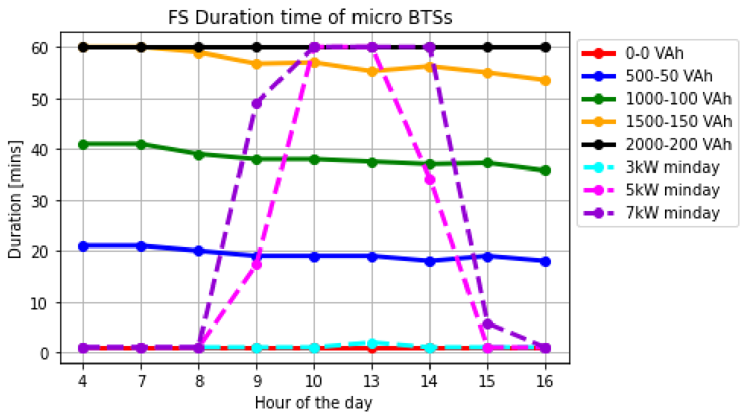


Figure 4.2: Duration of micro BTSs in FS zone

The duration of the micro BTSs during the outage in FS zone is shown in Fig. 4.2, it is visible that the duration is equal to 60 minutes, as the length of the outage, where the lost traffic was equal to zero. When the duration is lower than 60 minutes there is lost traffic because the BTSs is OFF, due to the fact that the battery or the PV panel is not capable enough to allow the BTSs to be ON during the outage.

These characteristics of lost traffic and duration time of micro BTSs are present in the results of the other zones too, moreover the lost traffic in the Residential zone is very similar to the FS one, while the Agricultural Park zones present lost traffic values lower than the others, since it is a sparse area zone.

- All battery cases + PV panel *maxday* at 4 am

PV panel *maxday* and *avgday* cases generate the same results. Only 4 am is considered as starting hour of the outage because for the other hours of the day the lost traffic is zero and the duration of micro BTSs is equal to 60 minutes, if using PV panel *maxday* and *avgday*.

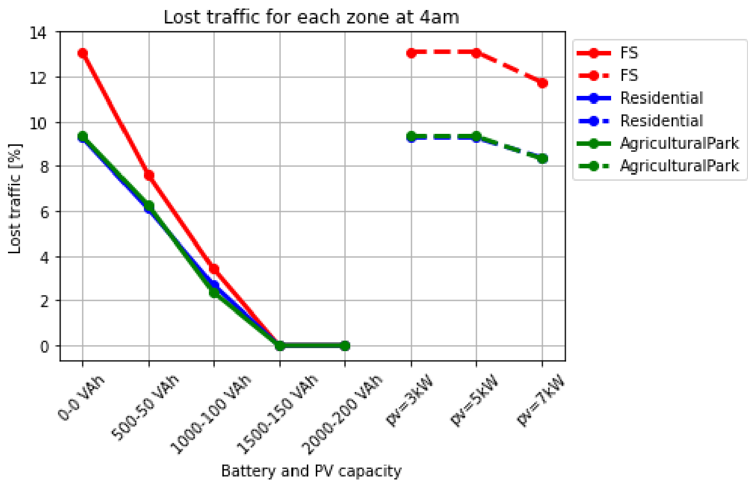


Figure 4.3: Lost traffic at 4 am

At 4 am the PV panel is not productive enough to reduce the lost traffic in a significant way, as shown in Fig. 4.3, so for the outage starting at 4 am it is better to use battery as a backup power supply for BTSs. The minimum battery capacity that ensures zero lost traffic is 1500VAh for macro BTSs and 150VAh for micro BTSs. The PV panel with capacity 7 kW reduces a little the lost traffic because the production in this case is slightly higher when the time approaches 5 am.

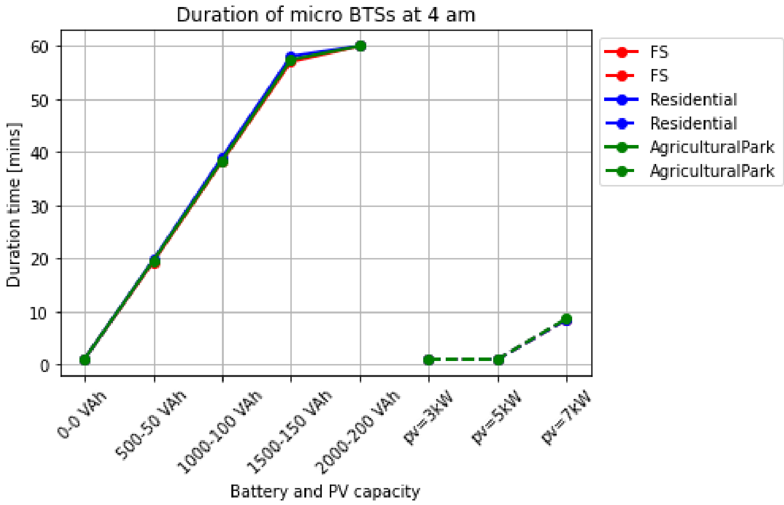


Figure 4.4: Duration of micro BTSs at 4 am

In Fig. 4.4 the duration of micro BTSs at 4 am is shown, considering that the outage is one hour long. It is visible that when using PV panel the duration goes from 1 minute up to 10 minutes, which is not enough. With the battery instead the duration is 60 minutes when capacity of macro BTSs Is 2000VAh and the one of micro BTSs is 200VAh.

### 4.1.2 Scenario 2

Scenario 2 is dedicated to the case where the outage length is equal to 200 minutes, and outages occur only at 4 am and at 1 pm since the outages with longest duration, considering the outages data of Turin given by IRETI, were reported in these two starting hours. The simulations are done separately for battery and PV panel, but for a better understanding the results are plotted together. For each zone two cases are examined:

- All battery cases + PV panel *minday maxday* at 4 am

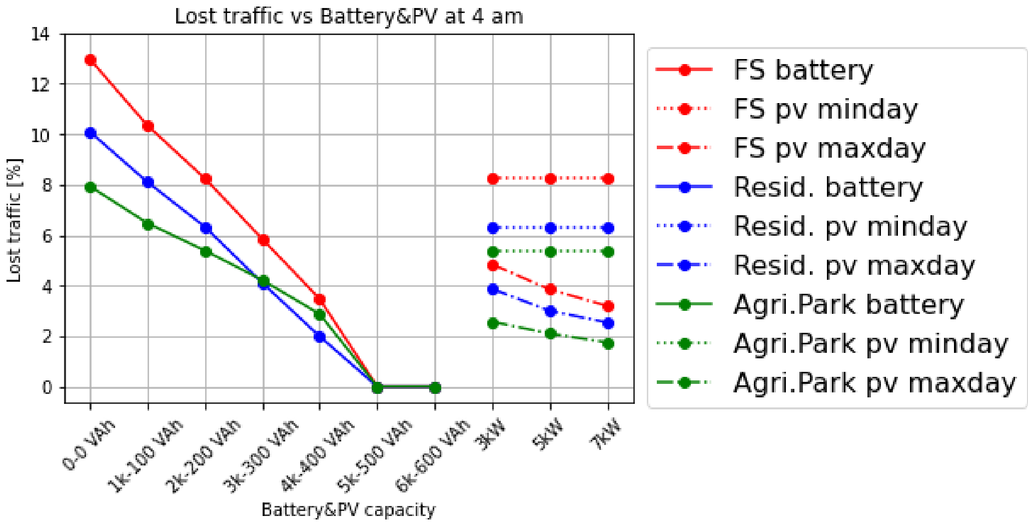


Figure 4.5: Lost traffic vs Battery & PV panel at 4 am

The lost traffic at 4 am for each zone is shown in Fig. 4.5 with the relative battery and PV panel capacity. Agricultural Park is the zone with less lost traffic, since it is a sparse zone and has lower traffic demand than FS and Residential zones. However, for all zones the *minday* production and the battery with capacity 2000VAh (Macro BTSs) and 200VAh (micro BTSs) allow to obtain almost the same lost traffic, while the lost traffic with *maxday* production is similar to the one obtained between battery capacities 3000VAh (Macro BTSs) -300VAh (micro BTSs) and 4000VAh (Macro BTSs) and 400VAh (micro BTSs). Therefore, the PV panel is productive enough to lower the lost traffic during the outages, but not to zero. Zero lost traffic is obtained only with battery capacity 5000VAh (Macro BTSs) and 500VAh (micro BTSs).

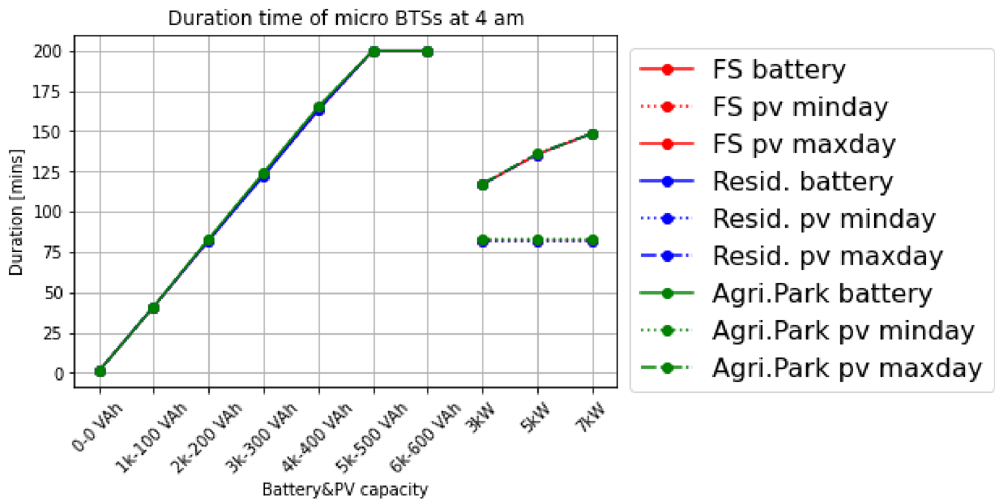


Figure 4.6: Duration time of micro BTSs at 4 am

The duration time of micro BTSs during outages at 4 am is shown in Fig. 4.6, where it is visible that the maximum duration equal to 60 minutes is given by the battery capacity 5000VAh (Macro BTSs) and 500VAh (micro BTSs). PV panel production instead is at the highest with capacity 7 kW *maxday* with duration time equal to 150 minutes, since the PV panel production increases from 5 am on, reaching its maximum production at 12 am.

- All battery cases + PV *minday avgday maxday* at 1 pm

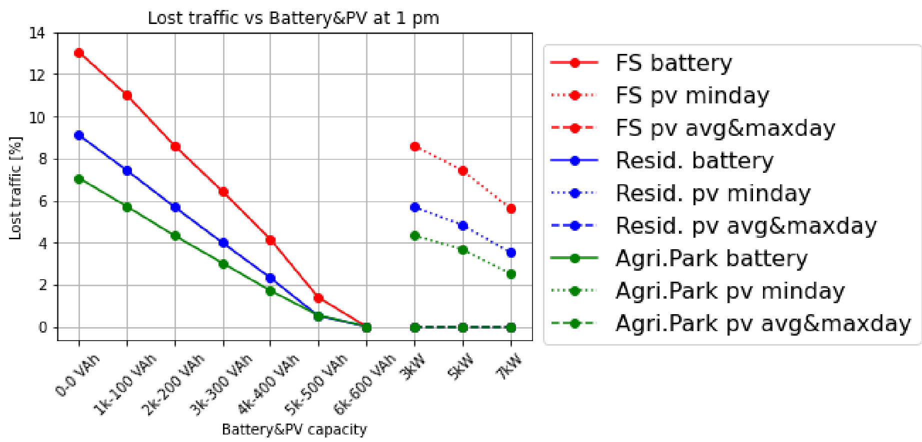


Figure 4.7: Lost traffic vs Battery & PV panel at 1 pm

In Fig. 4.7 the lost traffic at 1 pm for each zone is shown with the relative battery and PV panel scenarios. The *avgday* and *maxday* production generate the same results, so they are considered as a single case. At 1 pm the traffic demand is very high, and so is the PV panel production, therefore it is visible that *avgday and maxday* case allow zero lost traffic, while for the *minday* case with capacity 3kW the lost traffic is similar to the one obtained with battery capacity 2000VAh (Macro BTSs) and 200VAh (micro BTSs); for the *minday* case with capacity 7kW the lost traffic is similar to the one obtained between battery capacities 3000VAh (Macro BTSs)- 300VAh (micro BTSs) and 4000VAh (Macro BTSs)-300VAh (micro BTSs). There is no lost traffic with a battery capacity equal to 6000VAh (Macro BTSs) and 600VAh (micro BTSs).

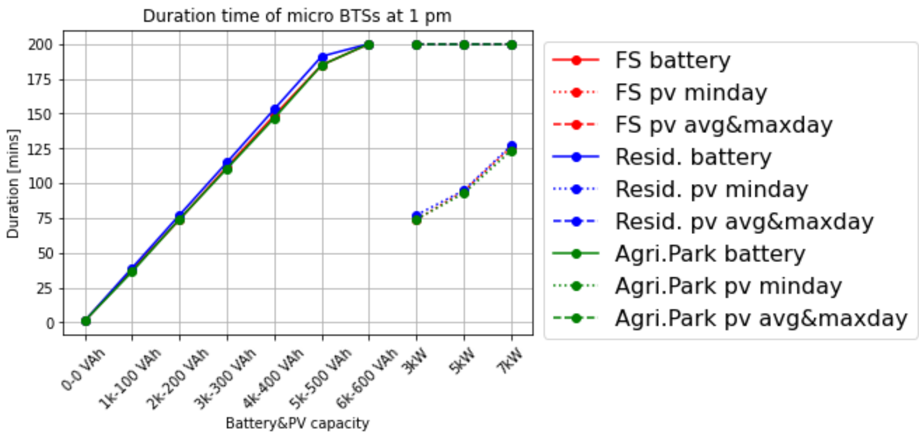


Figure 4.8: Duration time of micro BTSs at 1 pm

The duration time of micro BTSs during outages at 1 pm is visible in Fig. 4.8, where is shown that the maximum duration for all zones is obtained with battery capacity equal to 6000VAh (Macro BTSs) -600VAh (micro BTSs) and with PV panel *avgday* and *maxday* case, since they all provide zero lost traffic during the outage, while the PV panel *minday* production is not enough to cover the outage for all 200 minutes.

## 4.2 Post-processing

Post-processing represents the section that allows to understand how much traffic is lost in one year in the different zones of Milan, considering the probability of outage to occur (frequency) described in 2.1.1 and the lost traffic results obtained by the dimensioning part in the section above.

### 4.2.1 Scenario 1

Scenario 1 is dedicated to the case where the outage length is less or equal to 60 minutes, and they happen in the chosen critical hours. For each zone the following two cases are examined.

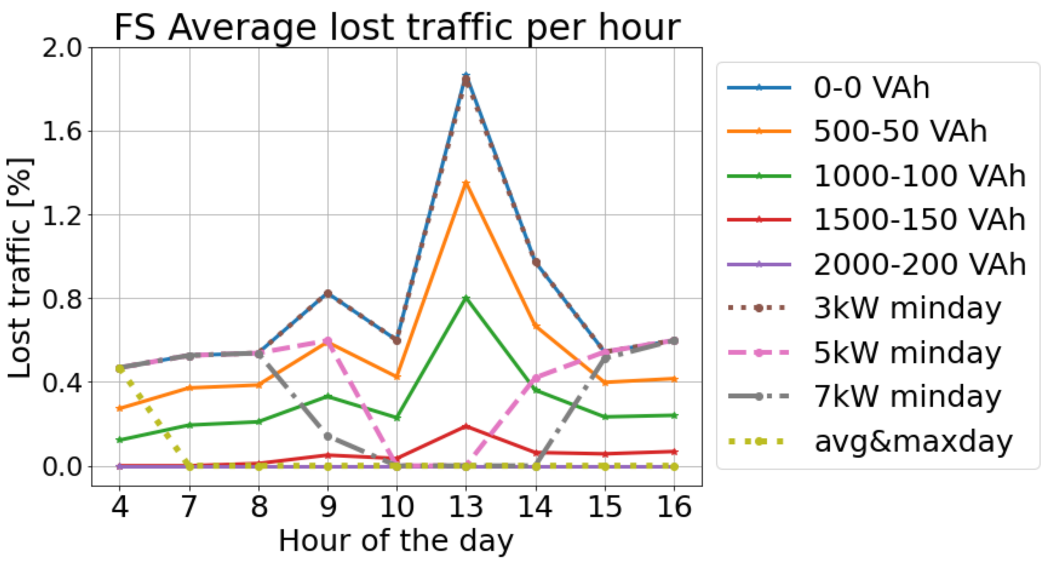


Figure 4.2.1: Average lost traffic in a year in FS zone

The average lost traffic per hour in a year for zone FS is shown in Fig. 4.2.1, with the relative battery and PV panel scenarios. The highest value of lost traffic is at 1 pm, where the traffic demand is the maximum. By increasing the battery capacity, the lost traffic decreases, arriving to zero lost traffic with capacity 2000VAh (Macro BTSs) and 200VAh (micro BTSs). *Avgday* and *maxday* production of PV panel generate the same results: lost traffic equal to zero for all hours except 4 am. *Minday* production with capacity 5 kW allows zero lost traffic at 10 am and 1 pm, while *minday* with capacity 7 kW allows zero lost traffic at 10 am, 1 pm and 2 pm, since the capacity is high and the PV production in those hours is high.

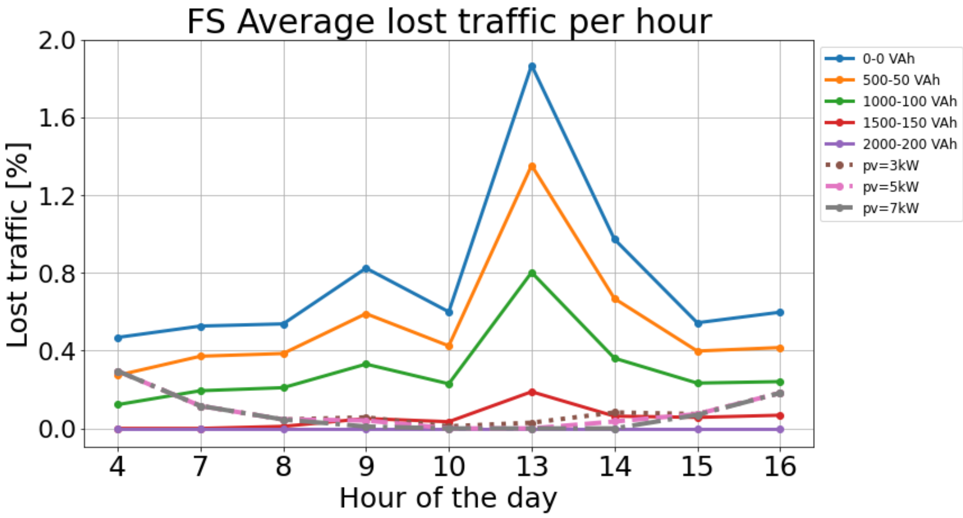


Figure 4.2.2: Average lost traffic considering PV panel production in FS zone.

In Fig. 4.2.2 the FS lost traffic per hour for one year is shown, considering PV production day type during each outage and opportunely using the relative lost traffic of that production day type. It is visible that the highest lost traffic is at 1 pm, it goes to zero when battery capacity is 2000VAh (Macro BTSs) and 200VAh (micro BTSs). PV panel production with all capacities allows to have almost zero lost traffic between 8 am and 3 pm, while for 4 am, 7 am and 4 pm the lost traffic is higher, since the PV production is low in those hours. Moreover, using PV panel as backup power supply even with capacity 3 kW and 5 kW allows to obtain an average lost traffic between 9 am and 2 pm lower than the one given by using a battery with capacity 1500VAh (Macro BTSs) and 150VAh (micro BTSs).

These considerations are very similar to the ones obtained in the Residential and Agricultural zones too, shown in Appendix A.1 Extra Figures, with the difference that the general lost traffic is lower than the FS one, because the traffic demand in a high density zone as FS is higher than the one in the other considered zones.

### 4.2.2 Scenario 2

Scenario 2 is dedicated to the case where the outage length is less or equal to 200 minutes, and outages considered occur at 4 am and 1 pm. The simulations are done separately for battery and PV panel, but for a better understanding the results are plotted together. For each zone two cases are examined:

1. All battery cases + PV panel *minday* at 4 am

It is considered *minday* case only because the production at 4 am is always minimum during the year.

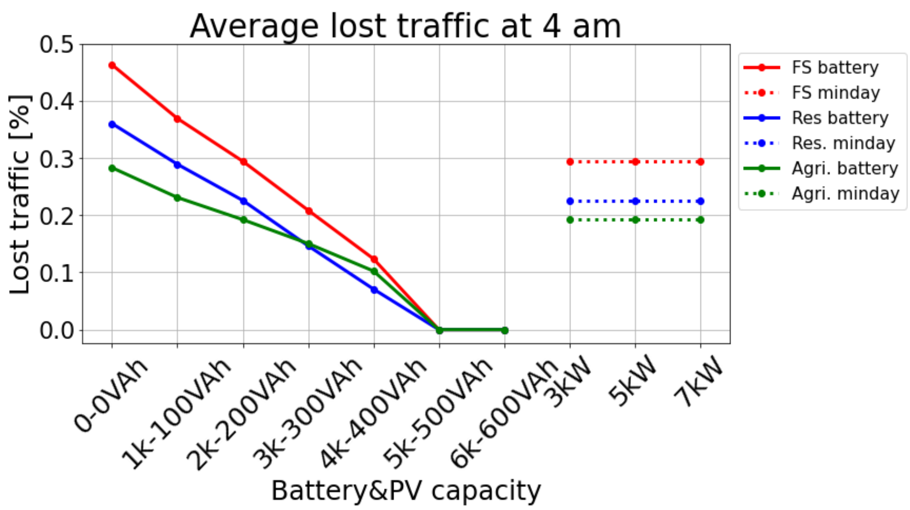


Figure 4.2.3: Average lost traffic at 4 am

The average lost traffic at 4 am for each zone is shown in Fig. 4.2.3, where it clear that the PV panel production *minday* is the same for capacity 3 kW, 5 kW and 7 kW, and the lost traffic in these scenarios for each zone is similar to the relative one obtained with battery capacity 2000VAh (Macro BTSs) and 200VAh (micro BTSs). However, the PV production is not high enough at 4 am to ensure zero lost traffic, with battery instead it is insured by using capacity 5000VAh (Macro BTSs) and 500VAh (micro BTSs).

2. All battery cases + PV panel *minday avgday maxday* at 1 pm

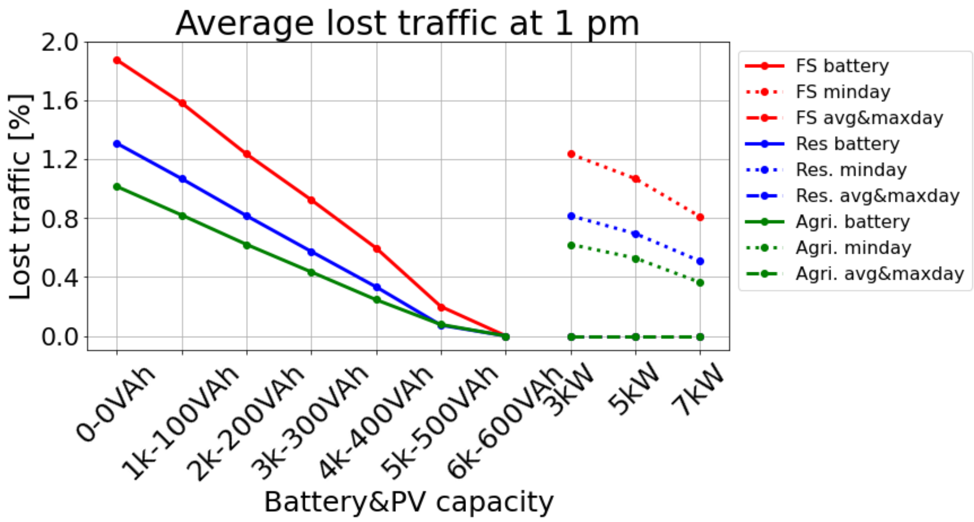


Figure 4.2.4: Average lost traffic at 1 pm

The average lost traffic at 1 pm for each zone is shown in Fig. 4.2.4, in this case the average and the maximum PV production days produce the same results, therefore they are considered as a single case, allowing zero lost traffic during the outages. The minimum PV production results instead change according to the PV capacity, as the capacity increases the lost traffic decreases, but never arriving to zero. The average lost traffic obtained with PV capacity 7 kW assumes similar values obtained by a battery with capacity between 3000VAh (Macro BTSs)-300VAh (micro BTSs) and 4000VAh (Macro BTSs)-400VAh (micro BTSs). In the battery scenario the lost traffic is equal to zero when the battery capacity is 6000VAh (Macro BTSs) and 600VAh (micro BTSs).

Lost traffic considering PV panel day type production during the outages are shown in Fig. 4.2.5 for the 4 am case and in Fig. 4.2.6 for the 1 pm case.

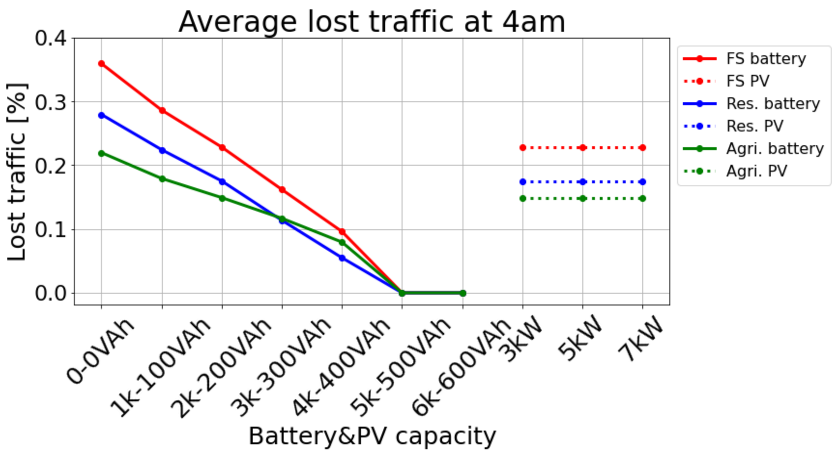


Figure 4.2.5: Average lost traffic at 4 am considering PV panel production

The 4 am case shows very similar results to the ones of Fig. 4.2.3, in both cases only *minday* is used because the PV panel production at 4 am is always minimum and it is visible also here that the average lost traffic obtained by PV panel case is almost equal to the one obtained by using a battery with capacity 2000VAh (Macro BTSs) and 200VAh (micro BTSs).

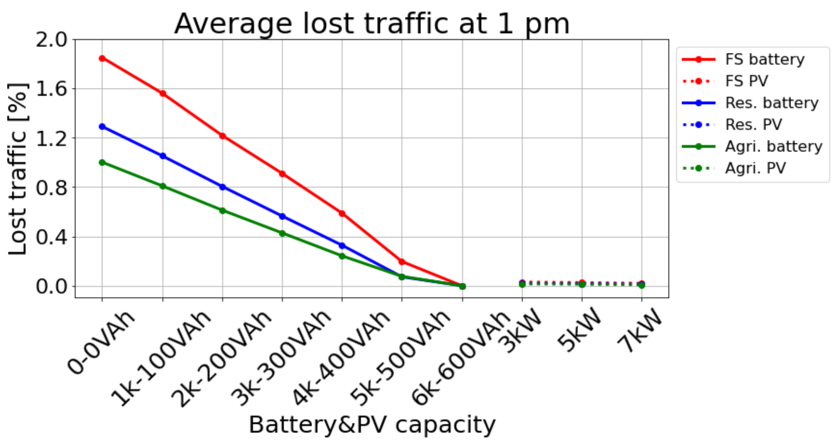


Figure 4.2.6: Average lost traffic at 1 pm considering PV panel production

The case of 1 pm considering PV panel day type production for each outage is different from the one where the PV production for each outage was not considered, shown in Fig. 4.2.2. In particular, in Fig. 4.2.6 it is clear that by considering PV panel only as backup power supply the average lost traffic at 1 pm for each zone is zero; as a matter of fact, for each PV panel capacity, the average lost traffic is lower than the one obtained using a battery with capacity 5000VAh

(Macro BTSs) and 500VAh (micro BTSs). This happens because at 1 pm the PV production is very high, and it ensures that the duration time of micro BTSs during the outage is almost 200 minutes. In the battery case instead, as in Fig. 4.2.2, the average lost traffic is equal to zero when the battery has capacity 6000VAh (Macro BTSs) and 600VAh (micro BTSs).

## 4.3 Application of the dimensioning scenarios

This section is dedicated to the application of the dimensioning scenarios obtained in section 4.2, considering the cases of battery and PV panel that minimize lost traffic and maximise the duration time of micro BTSs during the outage, in the annual simulation with the real outage characteristics, the ones saved in the data file of IRETI. The file is filtered considering only the critical hours as starting time of the outage, and it is divided in two parts:

- Scenario 1: Outages with length less or equal to 60 minutes
- Scenario 2: Outages with length less or equal to 200 minutes

Therefore, for each zone of Milan there are two scenarios of outage length and different dimensioning scenarios. This allows to visualize the average lost traffic per zone in one year, with the assumption that the power outages occurred in Turin happened for each zone of Milan too, using the traffic traces of Milan. During the simulation both battery and PV panel are considered as backup power supply, so a hybrid system is considered.

### 4.3.1 Scenario 1

From the file containing the outages happened in Turin for one year only the outages with length less or equal to 60 minutes are considered. For each zone of Milan, these outage characteristics are inserted in the simulator with the different dimensioning scenarios, considering the PV panel production during each outage. The dimensioning combinations of battery and PV panel capacity adopted in this scenario are shown in Table 10. In Case 1 and Case 4 two PV panel capacities are reported because they produce the same results.

| | |
|---|---|
| *Case 1* | PV panel capacity **3 kW & 5 kW**<br>and battery capacity 1000VAh(macro)-100VAh(micro) |
| *Case 2* | PV panel capacity **7 kW**<br>and battery capacity 1000VAh(macro)-100VAh(micro) |
| *Case 3* | PV panel capacity **3 kW**<br>and battery capacity 1500VAh(macro)-150VAh(micro) |
| *Case 4* | PV panel capacity **5 kW & 7 kW**<br>and battery capacity 1500VAh(macro)-150VAh(micro) |

Table 10. Dimensioning of scenario 1

- Average lost traffic per zone

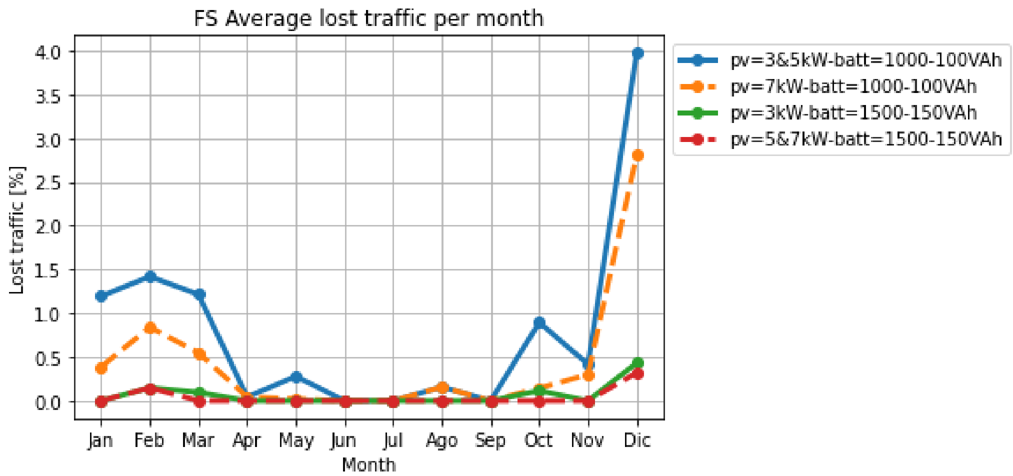


Figure 4.3.1: Average lost traffic per month in FS zone

The FS average lost traffic per month obtained from the annual simulation is shown in Fig. 4.3.1, with the relative dimensioning scenarios. When using PV panel and battery capacity 1000VAh (Macro BTSs)-100VAh (micro BTSs) it is visible that the lost traffic peak is in December, where the PV production is minimum, and that the lost traffic is high in January, February and March too, because during these months PV panel production is low and the battery cannot cover all outages. When using PV panel and battery capacity 1500VAh (Macro BTSs)-150VAh (micro BTSs) instead the average lost traffic decreases drastically going very close to zero, with small losses in the months of February and December. During the other months, even with a small capacity battery, the lost traffic is almost zero since the PV production is high enough to maintain the micro BTSs ON during the outages. The peak of lost traffic in December using

Case 1 (blue line) is 4 % circa, while using Case 4 (red dashed line) it is lower than 0.5 %.

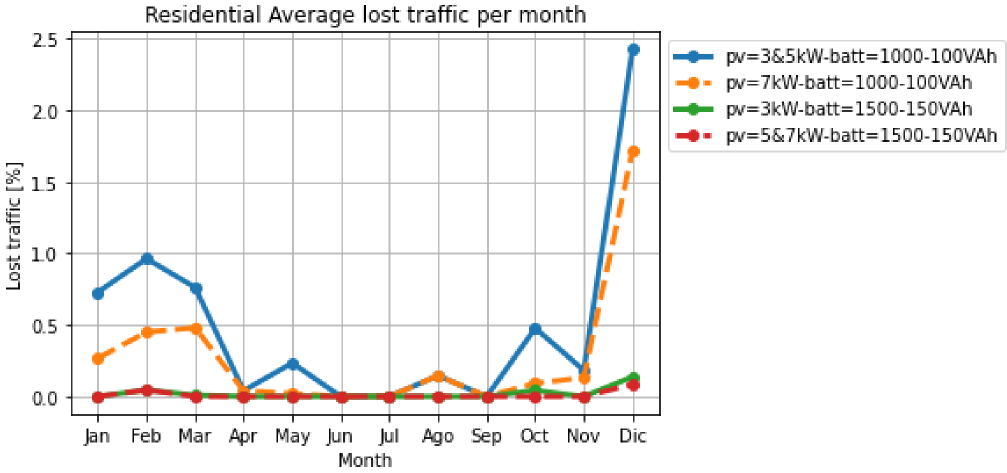


Figure 4.3.2: Average lost traffic per month in Residential zone

The Residential average lost traffic in a year shown per month in Fig. 4.3.2 assumes a similar behaviour to the FS one for each battery and PV panel dimensioning scenario, with the difference that the lost traffic is always lower than the one obtained in FS, because Residential zone represents a medium density zone, so the traffic demand is lower than the FS one, which represents instead the dense area zone. The peak of lost traffic in December using Case 1 dimensioning (blue line) is smaller than 2.5 %, while using Case 4 (red dashed line) it is lower than 0.25 %.

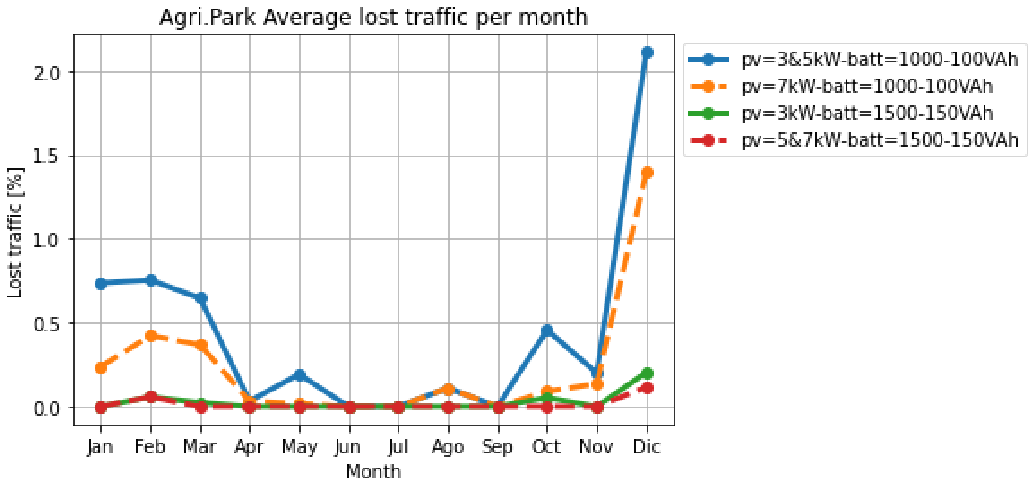


Figure 4.3.3: Average lost traffic per month in Agricultural-Park zone

The Agricultural-Park average lost traffic in a year shown per month in Fig. 4.3.3 assumes a similar behaviour to the FS and Residential one for each battery and PV panel dimensioning scenario, with the difference that the lost traffic is always lower than the one obtained in FS and Residential zones, since Agricultural-Park represents the sparse area zone, so the traffic demand in this area is the lowest with respect to the other considered zones. The peak of lost traffic in December using Case 1 (blue line) dimensioning is about 2.3 %, while using Case 4 (red dashed line) it is 0.2 % circa.

- Average duration time of micro BTSs

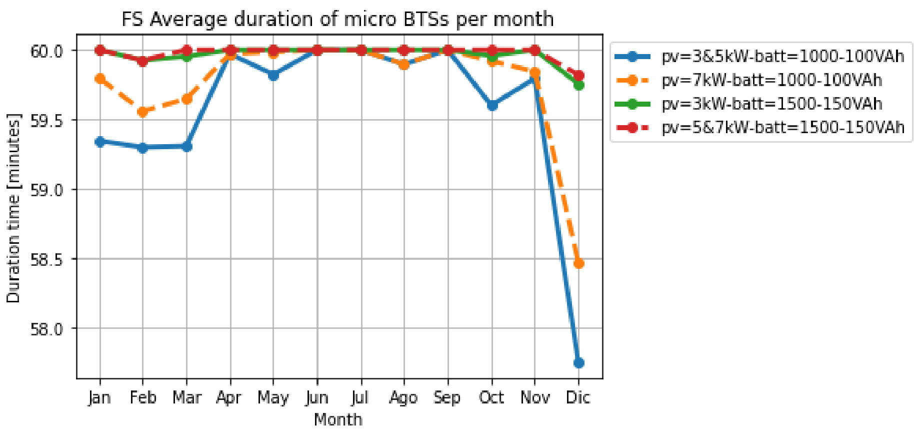


Figure 4.3.4: Average duration time of micro BTSs per month in FS zone

The FS average duration time of micro BTSs during the outages obtained from the annual simulation is shown in Fig. 4.3.4, for each battery and PV panel scenario. It is clear that, even in the worst case with PV panel capacity 3 kW/5 kW and battery capacity 1000VAh (Macro BTSs)-100VAh (Micro BTSs), the duration of the BTSs is high, assuming a value between 57 minutes and 58 minutes; considering that the outages examined in this scenario are 60 minutes long, this is a good result. When using the scenario of Case 4, PV panel capacity equal to 5 kW/7 kW and battery capacity equal to 1500VAh (Macro BTSs)-150VAh (Micro BTSs), the duration is 60 minutes for all months, except for February and December where the duration is some seconds less than 60 minutes.

These duration time considerations are obtained also for Residential and Agricultural-Park zones, visible in Appendix A.2 Extra figures.

### 4.3.2 Scenario 2

From the file containing the outages happened in Turin for one year only the outages with length less or equal to 200 minutes that start at 4 am or 1 pm are considered. For each zone of Milan, these outages characteristics are inserted in the simulator adopting different dimensioning scenarios, visible in Table 11. Since the lost traffic assumes similar behaviour to the different dimensioning scenarios in all zones, only FS results are showed.

| | |
|---|---|
| *Case 1* | PV panel capacity **5 kW/7 kW**<br>and battery capacity 1000VAh(macro)-100VAh(micro) |
| *Case 2* | PV panel capacity **3 kW**<br>and battery capacity 2000VAh(macro)-200VAh(micro) |
| *Case 3* | PV panel capacity **5 kW/7 kW**<br>and battery capacity 2000VAh(macro)-200VAh(micro) |
| *Case 4* | PV panel capacity **3 kW**<br>and battery capacity 3000VAh(macro)-300VAh(micro) |

Table 11. Dimensioning of scenario 2

- Average lost traffic

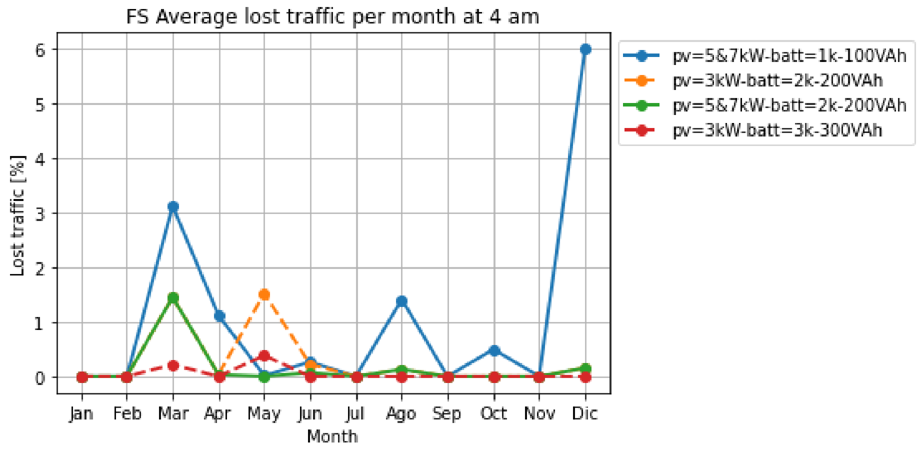


Figure 4.3.5: Average lost traffic per month at 4 am in FS zone

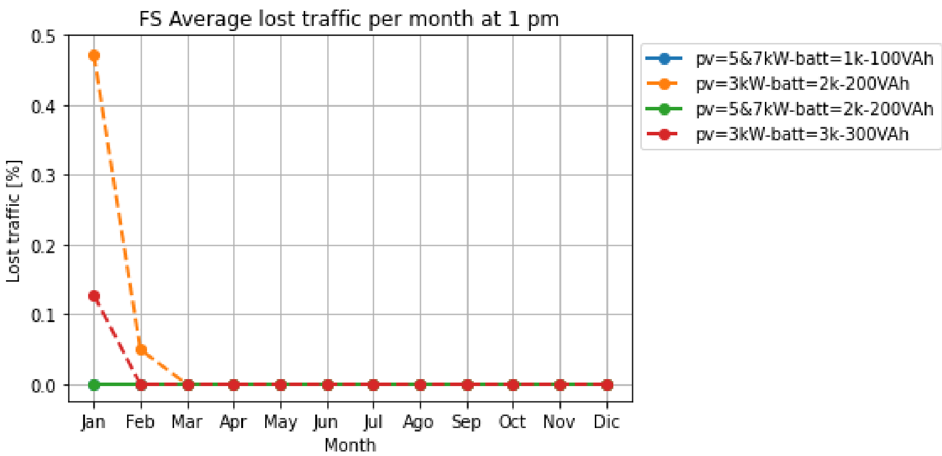


Figure 4.3.6: Average lost traffic per month at 1 pm in FS zone

In Fig. 4.3.5 the FS average lost traffic in a year is shown per month due to outages occurred at 4 am, while in Fig. 4.3.6 the one related to outages happened in 1 pm is shown. It is visible that by using the scenario of PV panel capacity equal to 5kW/7kW and battery capacity 1000Vah (macro BTSs)-100VAh (micro BTSs) the lost traffic due to outages at 4 am is zero for February, May, July, September and November. Since the PV production is low at 4 am, this means that a higher battery capacity should be used at 4 am in order to ensure zero lost traffic for all the months. In the 1 pm case instead the lost traffic is almost always zero, except for February for Case 2 (orange line) with 0.05 % lost traffic and January with lost traffic 0.15 % for Case 4 (red line) and 0.48 % for Case 2.

- Average duration of micro BTSs

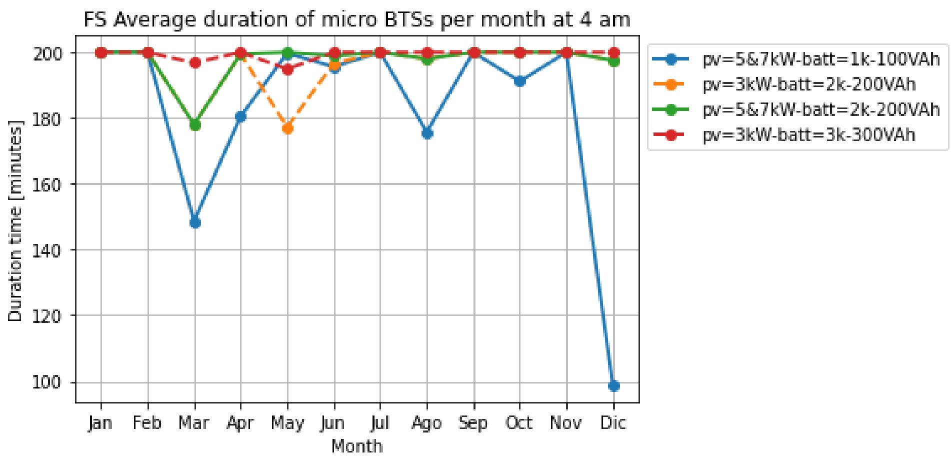


Figure 4.3.7: Average duration of micro BTSs per month at 4 am in FS zone

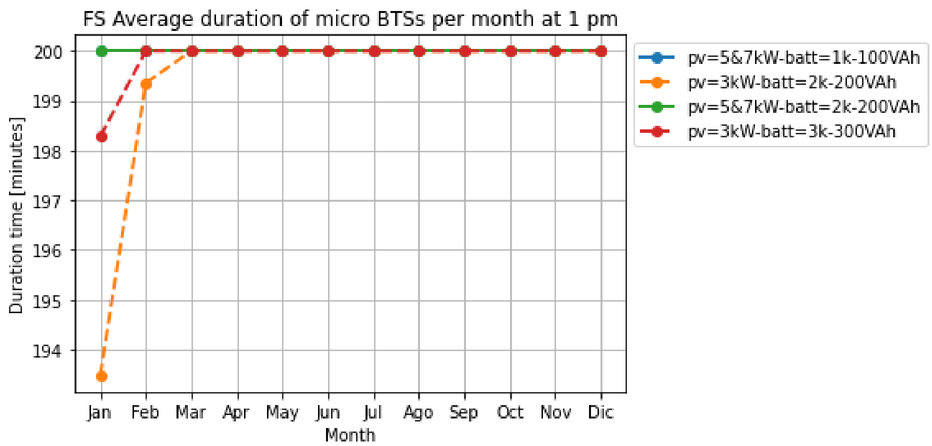


Figure 4.3.8: Average duration of micro BTSs per month at 1 pm in FS zone

The FS average duration of micro BTSs per month is shown in Fig. 4.3.7 for the 4 am case and in Fig. 4.3.8 for the 1 pm case. In the 4 am plot, the worst case can be seen in the average duration of December for Case 1 (blue line) with a duration of 100 minutes that is not a good result. Since the outage is 200 minutes and the PV production at 4 am is low, a higher battery capacity should be adopted when an outage occurs at 4 am. As a matter of fact, the duration is almost always to 200 minutes in Case 4 (red line), where the battery capacity is higher. In the 1 pm figure, instead, it is visible that the duration of micro BTSs is almost always 200 minutes, except for January by using dimensioning scenario of Case 2 (orange line), where the duration is 193 minutes.

# 5 Conclusions

The aim of this thesis was to improve the traditional grid by introducing a renewable energy as backup power supply of the BTSs affected by the power outages, in this case the micro BTSs only, in order to get more closer to the "Smart grid", meaning to reduce grid energy consumption, energy costs and carbon footprint, and to reduce traffic losses in communication networks. Since the PV panel production depends on the sun, a battery is needed when the PV production is low during the day, and always during the night. Therefore, different dimensioning scenario were tested until finding the best ones able to reduce significantly the lost traffic during the power outages. The obtained results allow to understand that a PV panel with capacity 5kW reduces the effect of blackouts in terms of lost traffic during the day, but for outages occurring at 4 am or at night a battery must be used as backup power supply of the BTSs. In particular, if outage length is lower or equal to 1 hour a battery with capacity 2000VAh for macro BTSs and 200VAh for micro BTSs ensures zero lost traffic, and if the outage duration is longer than 1 hour a battery of 5000VAh for macro BTSs-500Vah for micro BTSs is needed to obtain zero lost traffic.

# Appendix A

## Extra figures

### A.1 Post processing – Scenario 1

- Average lost traffic in a year:

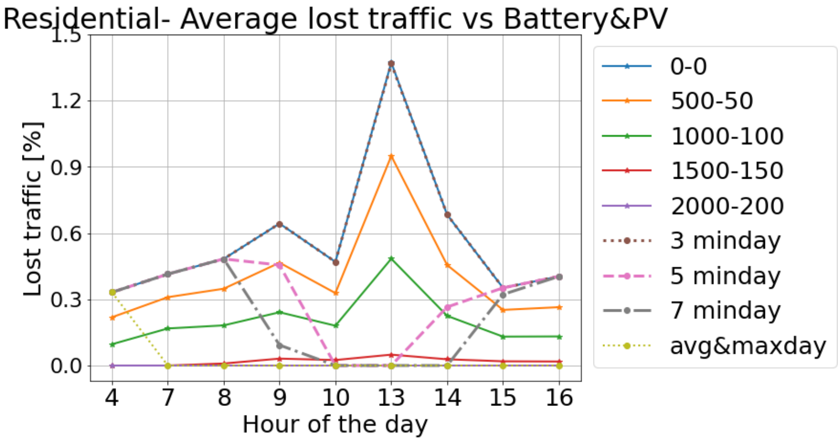


Figure A.1: Average lost traffic in a year in Residential zone

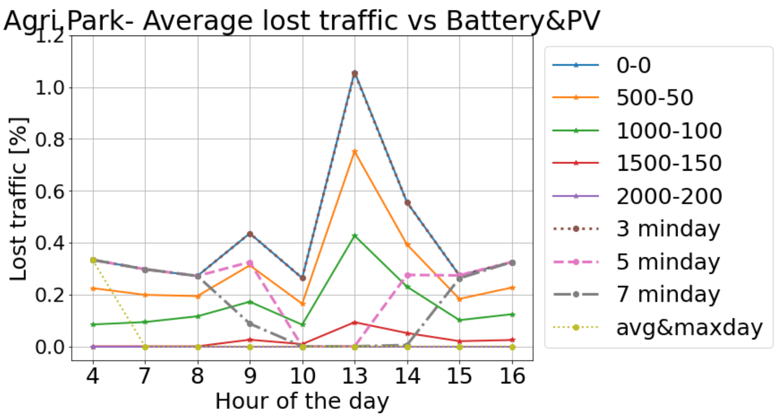


Figure A.2: Average lost traffic in a year in Agricultural Park zone

- Average lost traffic in a year considering PV panel production during outages.

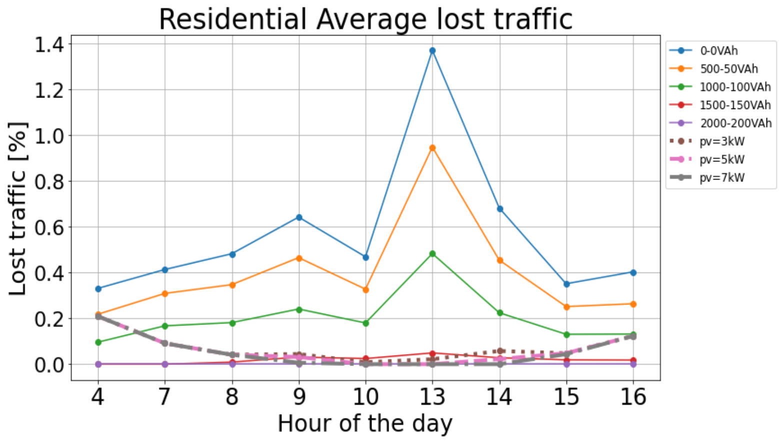


Figure A.3: Average lost traffic considering PV panel production in Residential zone.

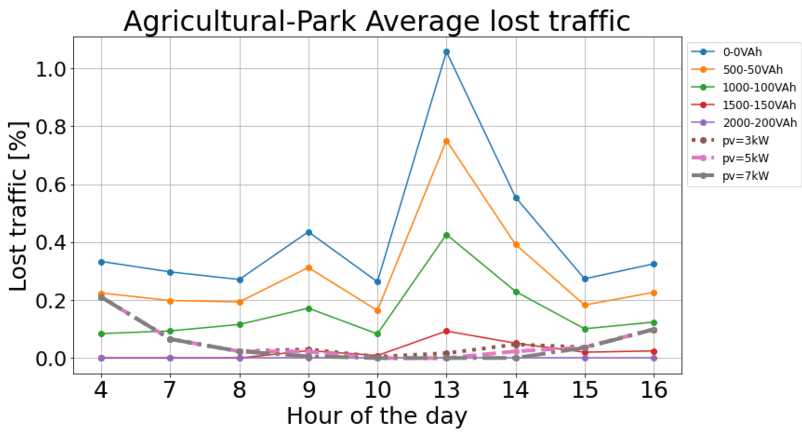


Figure A.4: Average lost traffic considering PV panel production in Agricultural Park zone.

## A.2 Application of dimensioning scenarios - Scenario 1

Duration time of micro BTSs during the outages, obtained per month from the annual simulation of the IRETI outages in the Residential and Agricultural-Park zones of Milan.

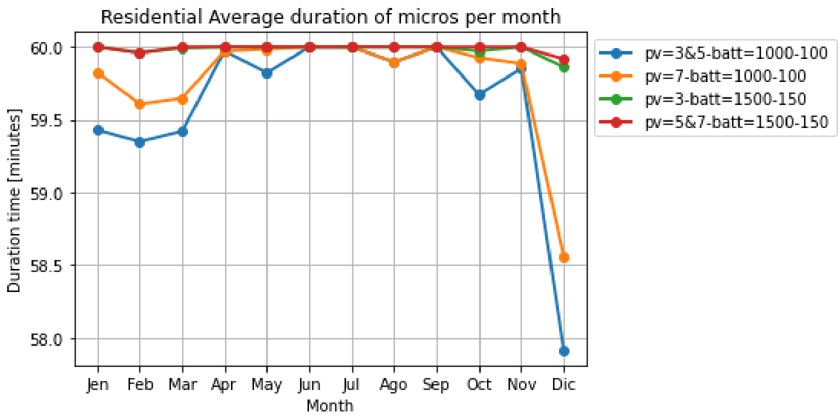


Figure A.5: Average duration time of micro BTSs per month in Residential zone

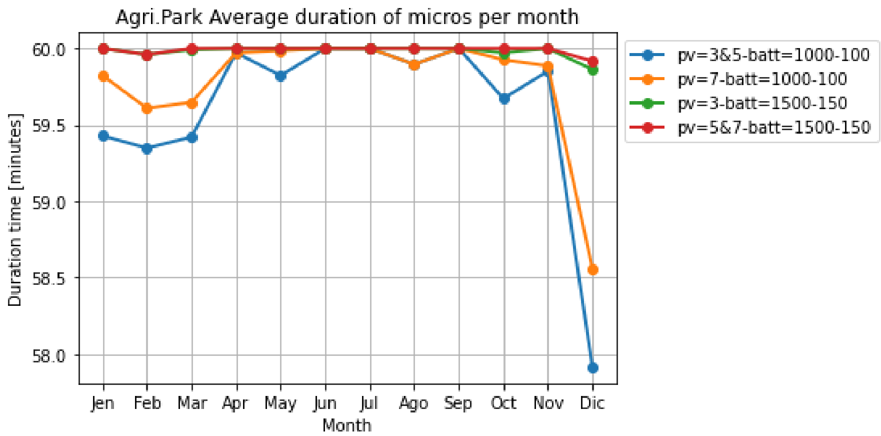


Figure A.6: Average duration time of micro BTSs per month in Agricultural Park zone

# Bibliography

[1] Salahuddin, M.; Alam, K. Information and Communication Technology, Electricity Consumption and Economic Growth in OECD Countries: A Panel Data Analysis. Int. J. Electr. Power Energy Syst. 2016, 76, 185–193. [CrossRef]

[2] https://www.enerdata.net/publications/executive-briefing/between-10-and-20-electricity-consumption-ict-sector-2030.html

[3] Garau, M., Celli, G., Ghiani, E., Pilo, F. and Corti, S. (2017) *Evaluation of Smart Grid Communication Technologies with a Co-Simulation Platform*. IEEE Wireless Communications, 24, 42-49.
https://doi.org/10.1109/MWC.2017.1600214

[4] https://www.sciencedirect.com/topics/engineering/global-energy-demand

[5] https://www.energysage.com/electricity/understanding-electrical-grid/

[6] Ruofei Ma, H. Chen, Yu-Ren Huang, W. Meng *Smart Grid Communication: Its Challenges and Opportunities* published 2013. Figure 3: Interactions among different smart grid domains.
https://ieeexplore.ieee.org/document/6451177

[7] Yang Jie, Tan Zhen-jian, H. Han, Cheng Yonghong *Energy-efficient microcell base station power control in heterogeneous cellular network* published in 2017. Figure 1: Two-tier Heterogeneous cellular networks.
https://ieeexplore.ieee.org/document/8359697

[8] https://1nce.com/en/blog/cellular-mobile-standards/

[9] https://www.theblackoutreport.co.uk/2020/12/07/11-biggest-blackouts/

[10] Christian Reuter *Communication between Power Blackout and Mobile Network Overload* published in 2014. Figure 2: Blackout and its consequences for mobile communication to illustrate the time frame.

[11] https://zruipower.com/products-item/power-supply-system-for-5g-micro-base-station/

[12] Heng Wang, Hongja Li, Chaower Tang, *Modeling, metrics, and optimal design for solar energy-powered base station system* published in 2015.

Figure 1: Schematic diagram of the solar energy-powered BS system. https://www.researchgate.net/publication/273517881_Modeling_metrics_and_optimal_design_for_solar_energy-powered_base_station_system

[13] https://www.yesenergysolutions.co.uk/advice/how-much-energy-solar-panels-produce-home