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Isolated Electrical Microgrids employing Renewable Energy Resources: Analysis of the electrification of remote communities in Peru

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Questa tesi di laurea è stata svolta presso l'istituto ETSEIB – *Escola* Tècnica Superior d'Enginyeria Industrial de Barcelona, Universitat *Politècnica de Catalunya* – grazie alla gentile collaborazione tra la Professoressa Alessandra Bonoli (Facoltà di Ingegneria di Bologna, Dipartimento DICMA) e il Professor Oriol Gomis (ETSEIB, Dipartimento CITCEA). Mi sento in dovere di ringraziare il Dipartimento GRECDH - *Grup de Recerca en Cooperació i Desenvolupament Humà* - dell'istituto ETSEIB per l'aiuto e il supporto ricevuto, in particolare la Professoressa Laia Ferrer e il Dottor Miguel Capò.

Questa tesi di laurea presenta brevemente una panoramica di alcuni concetti fondamentali, come Risorse Energetiche Rinnovabili e Risorse Energetiche Distribuite, e descrive l'architettura di una rete elettrica, isolata o connessa alla Linea di Media-Alta Tensione tradizionale. La tesi si focalizza su un progetto portato avanti dal gruppo di ricerca GRECDH, in collaborazione con il Dipartimento CITCEA, entrambi appartenenti all'*Universitat Politècnica de Catalunya*: tale progetto riguarda reti isolate che utilizzano risorse energetiche rinnovabili che saranno costruite in due comunità andine del Perù settentrionale. Diverse sono le soluzioni individuate per soddisfare la domanda di energia dei carichi connessi alla rete, grazie ad uno strumento software di Ottimizzazione Lineare Intera e Mista che considera diversi sistemi di generazione (eolico e fotovoltaico); inoltre vengono costruiti e analizzati dal punto di vista elettrico diversi scenari di domanda energetica, studiando i circuiti rappresentanti le reti elettriche. Vengono proposte alcune soluzioni per migliorare le prestazioni di tali reti, con particolare attenzione all'aumento dei valori di tensione di ogni carico connesso; si tengono in considerazione anche i costi aggiuntivi necessari per realizzare tali soluzioni, oltre che la loro incidenza sul budget totale originariamente preventivato. Infine, vengono commentati alcuni dati statistici riguardanti l'impatto che un progetto di elettrificazione simile a quello analizzato ha avuto sulla popolazione locale.

This project is an University Final Thesis, written in Barcelona, in ETSEIB - *Escola Tècnica Superior d'Enginyeria Industrial de Barcelona, Universitat Politècnica de Catalunya* –, thanks to the kind collaboration of Professor Alessandra Bonoli (DICMA Department – Bologna University), Professor Oriol Gomis and CICTEA Department. I really have to thank the GRECDH Department - *Grup de Recerca en Cooperació i Desenvolupament Humà* - for their help and support, in particular Professor Laia Ferrer and Mr. Miguel Capò.

This project points out a brief overview of several concepts, as Renewable Energy Resources, Distributed Energy Resources, Distributed Generation, and describes the general architecture of an electrical microgrid, isolated or connected to the Medium Voltage Network. Moreover, the project focuses on a project carried out by GRECDH Department in collaboration with CITCEA Department, both belonging to Universitat Politécnica de Catalunya: it concerns isolated microgrids employing renewable energy resources in two communities in northern Peru. Several solutions found using optimization software regarding different generation systems (wind and photovoltaic) and different energy demand scenarios are commented and analyzed from an electrical point of view. Furthermore, there are some proposals to improve microgrid performances, in particular to increase voltage values for each load connected to the microgrid. The extra costs required by the proposed solutions are calculated and their effect on the total microgrid cost are taken into account; finally there are some considerations about the impact the project has on population and on people's daily life.

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1. Introduction: an overview of main concepts

Some concepts such as Distributed Generation, Distributed Energy Resources, Renewable Energy Resources are discussed in this chapter; a general overview on the global energy demand scenario is also considered, taking into account the World Energy Outlook 2007 issued by International Energy Agency.

1.1 World Energy Outlook 2007

One of the most important reports that describes the energy world demand and energy forecasts is the World Energy Outlook [1], yearly issued by IEA (International Energy Agency); this project comments upon the main issues which the report points out, analyzing in particular the reference and the alternative scenarios, in which different political decisions and government behaviors are take into account to contrast global problems as global warming and excessive use of CO2-related energy sources.

The Reference Scenario takes account of government policies and measures enacted or adopted by mid 2007, although many of them have not yet been fully implemented. The most important of them are those implemented to limit greenhouse gas emissions, as well as various policies to enhance energy efficiency and promote renewable energy. It is known that energy subsidies have an important role to boost renewable energy use and because of that the Reference Scenario also assumes that these subsidies are gradually removed in all countries where they currently exist, as they are temporary.

The Reference Scenario describes the so-called “Business as usual”, that during the next 20 years will result in a rising global fossil fuel use, that increases energy related CO2 emissions from 29 Gt in 2007 to over 40 Gt in 2030 and contributes to the deterioration of ambient air quality, reaching a concentration of greenhouse gases of 1000 ppm (1000 part per million). The emissions growth is mainly due to increased fossil fuel use, especially in developing countries, where per-capita energy consumption still has far to go to approach that in OECD countries. Emissions in these countries are predicted to dip slightly over the period, due to a slower increase in energy demand, large improvements in energy efficiency and the increased use of nuclear and renewable energy sources.

In the considered Alternative Scenario, denominated “450 Scenario”, concentrations of all greenhouse gases in the atmosphere stabilize at 450 ppm. This level of concentration is expected to give rise to a global temperature increase of 2°C. The long term greenhouse gas concentration limit set is less than half the concentration which occurs in the Reference Scenario. The trajectory is an overshoot trajectory, where concentrations peak at 510 ppm in 2035, they stay steady for around 10 years and then decline to 450 ppm.

Here are some of the most significant highlights of the report to meet 450 Scenarios goals:

- 6% global increase in energy related CO2 emissions by 2020, relative to 2007
- Power generation CO2 intensity decreasing by 21% and average car fleet CO2 intensity decreasing by 37% by 2020 compared with 2007
- 3% increase in emissions from buildings and 9% increase in industry by 2020, relative to 2007
- Additional investment, relative to Reference Scenario, in low carbon technologies and energy efficiency close to $ 430 billion in 2020.

The figure shows how significant is Power Generation in energy related CO2 emissions outlook, representing about 44% of the total CO2 emissions in 2030 in Reference Scenario: notice that a decrease of these emissions to 32% is crucial for the commitment of 450 Scenario, which has just 65% of the CO2 emissions released in the Reference Scenario (26,14 Gt facing 39,80 Gt).

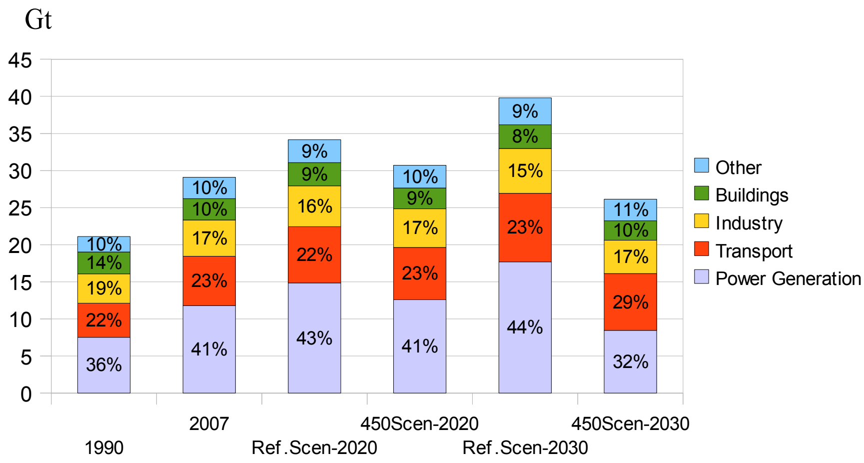


Figure 1.1: World energy related CO2 emissions (%)

World energy related CO2 emissions (values in Gt)						
	1990	**2007**	**Ref.Scen-2020**	**450Scen-2020**	**Ref.Scen-2030**	**450Scen-2030**
Other	2,09	2,88	3,11	3,07	3,62	2,90
Buildings	2,93	2,88	3,11	2,76	3,22	2,64
Industry	3,97	4,90	5,52	5,22	6,03	4,49
Transport	4,60	6,62	7,59	7,06	9,25	7,66
Power Generation	7,52	11,81	14,84	12,59	17,69	8,45

Figure 1.2: World energy related CO2 emissions (Gt)

As WEO reports, increasing Renewable Energy Sources employment is crucial to meet 450 Scenario; its growth is expected to be exponential till 2030, and the most important sources to consider are hydroelectric (more than 1600 GW) and wind power (more than 1000 GW).

In major and emerging economies, power generation plays a role even more important: in fact, to meet 450 Scenario targets by 2030, power generation related CO2 emissions have to decrease by 50%, reaching about 5 Gt; in Reference Scenario it represents more than 50% of CO2 emissions (about 9 Gt of CO2).

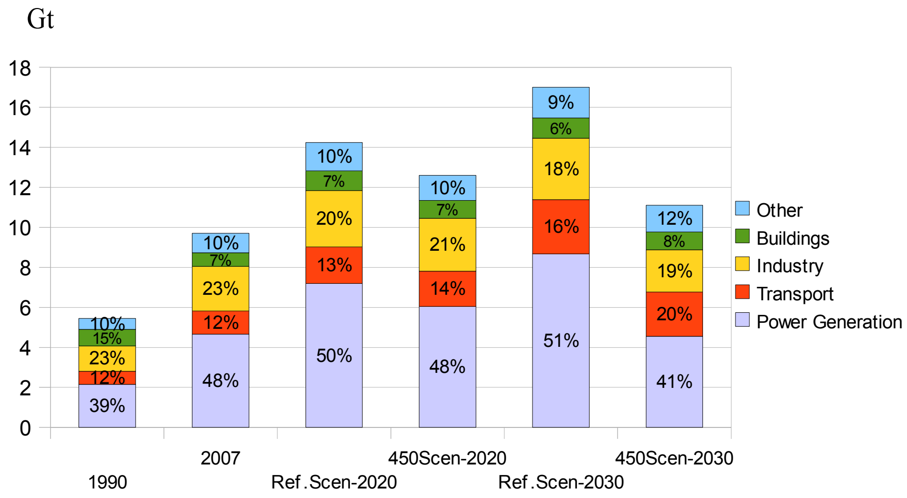


Figure 1.3: Other Major Economies energy related CO2 emissions (%)

Regarding others major economies, it is evident that hydro and wind, together with others renewable energy sources, should increase rapidly by 2030 to meet 450 Scenario targets. Installed wind power capacity would reach 330 GW, while hydro would reach 580 GW: the growth is even greater than in the OECD countries case, due to the fact in 2007 renewable energy resources are not largely employed in these countries, except for hydroelectric technology (the biggest percentage of which is in China).

1.2. Distributed Generation

As World Energy Outlook points out, it is evident that traditional energy resources are unsuitable to face global climate change and that OECD countries, together with other major economies and countries like Brazil, Russia, China and India, should largely employ renewable energy resources such as wind, hydro, photovoltaic and bio-fuels to produce energy in the future. Furthermore, large traditional power plants will not be enough to meet 450 Scenario targets, therefore during the last decade a lot of energy conversion units have been located close to the consumers of energy, and large units have been partially replaced by smaller ones. Because of that, much research and implementation have been accomplished in the area of distributed generation, in order to further develop this field of research.

Distributed Generation is commonly perceived as "Small scale electricity generation". The concept, however, involves a broad range of technologies and applications in different environments, therefore there is no consensus on a unique and precise definition. Distributed Generation definition varies according to the country: so it can be defined on the basis of voltage level [2], while other countries follow a principle that Distributed Generation is connected to circuits that feed directly to consumer loads.

Nevertheless, Distributed Generation can be described on the basis of these characteristics:

- Use of renewable energy sources
- Co-generation
- Purpose
- Location
- Power scale
- Power delivery

- Technology
- Environmental impact
- Mode of operation
- Ownership
- Penetration level

Different definitions reported by several authorities follow: “Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter. […] The definition of Distributed Generation neither defines the rating of generation source, nor the area of power delivery, penetration level, ownership, treatment within the network operation” [2].

International Council on Large Electricity Systems (CIGRE) defines Distributed Generation as “all generation units with a maximum capacity of 100 MW usually connected to the distribution network, that are neither centrally planned nor dispatched” [2].

International Energy Agency (IEA) defines it as “Units producing power on a customer’s site or within local distribution utilities, and supplying power directly to the local distribution network” [3].

Willis states that “Distributed Generation includes application of small generators, typically ranging in capacity from 15 to 10,000 kW, scattered throughout a power system, to provide the electric power needed by electrical consumers. As ordinarily applied, the term Distributed Generation includes all uses of small electric power generators, whether located on the utility system, at the site of a utility customer, or at an isolated site not connected to the power grid” [4].

Distributed Generation is also defined for specific applications in the electric system. Some of the most common applications include standby, stand alone, rural and remote applications, peak load shaving, combined heat and power and base load.

The Institute of Electrical and Electronics Engineers (IEEE) [5] defines distributed resources as “sources of electric power that are not directly connected to a bulk power transmission system. Distributed Resources include both generators and energy storage technologies.”

Professor Lambert defines a micro power system as a system that “generates electricity and, possibly, heat to serve a nearby load. Such a system may employ any combination of electrical generation and storage technologies and may be grid connected or autonomous” [6].

Moreover, generation units installed close to the load or at the customers side are also commonly identified as Distributed Generation. Pepermans also argues that generation units should at least supply active power. It is important to highlight it as the supply of reactive power and/or other ancillary services are possible but not necessary; of course it may represent an added value of the Distributed Generation.

1.2.1 Distributed Generation growth

Over the last ten years, the interest in Distributed Generation has been growing, thanks to technological innovations and a changing economic and regulatory environment. According to the World Bank, decentralization includes political, administrative, fiscal and market aspects, so distributed energy systems involve much more than the technological aspects of energy deployment.

The importance of Distributed Generation is globally evident in the energy sector and its deployment is growing rapidly worldwide. For example, the global off grid photovoltaic market is currently experiencing a growth rate of 20% per year [7]. It should be noticed that micro-generation technologies have attracted increasing attention as potential future energy technologies, as well the interest in micro-generation is also growing in government circles: the UK Department for Trade and Industry (DTI) suggests that by 2050 around 40-50% of the country's energy needs could be met by micro-generation technologies [3].

International Energy Agency [3] lists five major factors that contribute to the growth of Distributed Generation:

- Developments in Distributed Generation technologies
- Constraints on the construction of new transmission lines
- Increased customer demand for highly reliable electricity
- Electricity market liberalization
- Concerns about climate change

The great proportion of decentralized energy consists of high efficiency co-generation systems in industrial and district heating sector, fueled by coal or gas, and to a lesser extent, biomass based fuels.

As [8] points out, by locating energy sources near the load, there are many advantages for the overall system, as constraints reduced, energy efficiency increased, power quality and reliability improved. Apart from these benefits, there are also several drawbacks related to this technology. Major drawbacks concerning its utilization are:

- High cost and high initial investment required
- Need for custom engineering
- Lack of plug and play integration methods
- Few successful business models developed

As many private and public organizations report, Distributed Energy Resources penetration has not met expectations because of these disadvantages. It is expected that if relevant improvements will be developed in these fields, Distributed Energy Resources penetration should take off during next decade.

1.2.2 Distributed Energy Resources

Apart from the drawbacks mentioned above, over the last years distributed energy sources have increased their deployment and relevance, thanks to growing deregulation and governmental interest. Furthermore, Distributed Generation importance is increasing in developed countries worldwide, and its penetration is also rising due to technological improvement and more efficient deployed devices. It represents an alternative to the actual centralized electricity generation system. It is useful to have a general overview of Distributed Energy Resources (DERs): they comprise several technologies, such as diesel engines, micro turbines, fuel cells, photovoltaic, small wind turbines, batteries and flywheels, all of which use some type of power electronic interface. These distributed energy resources are connected to the distribution network to contribute to reducing losses, improving voltage quality, and increasing the capacity of the network itself. It is very important to employ fitting Distributed Energy Resources control operations together with controllable loads and storage devices, such as flywheels, energy capacitors and batteries, due to the crucial role it plays in the microgrid's stability, especially when it operates in island mode.

Here are some of the common Distributed Energy Resources used worldwide:

- Internal combustion engines
- Gas turbines
- Micro turbines
- Photovoltaic
- Fuel cells
- Wind-power

These resources have emerged over the last twenty years due to the technology development and environment protection [9]. They present several advantages, because they are low cost, low voltage and have high reliable with few emission. Considering the most developed countries in the world, it is widely believed that active distribution network management is the key to effective integration of distributed generations into traditional distribution operation and planning [10]. As [11] evidently points out, this can improve the cost-efficiency and reliability by making use of ancillary services provided by distribute generations. The challenge in the future will be increasing Distributed Energy Resources utilization and improving the network reliability and efficiency. Furthermore, the application of individual distributed generators is not simple and can cause a lot of trouble, so the best way to explore the potential of distributed generation and associated loads is to employ a subsystem called ‘‘microgrid’’. That is why in this changing scenario microgrids are crucial.

1.3. Microgrid Concept and Definition

Micro generation is expected to become an attractive means to solve the world energy situation, considering that Brazil, Russia, India, China and other South East Asian countries will expand their economies, and consequentially increase their energy demand. Distributed Energy Resources and microgrids can become a concrete alternative to fossil combustibles based power systems. Nevertheless, the possibility of exploiting local renewable energy resources, combined with the need to reduce pollutant emissions are important factors that will contribute, hopefully in a short term, to an effective penetration of micro generation in low voltage grids. Of course, recent technological developments related with the improvement of micro generation efficiency and reliability can help this process, which is why microgrids are becoming important in the context of world energy.

The scenario of an extensive penetration of local generation in low voltage grids is consequentially linked to the microgrid concept: small generation units, with power ratings less than a few tens of kilowatts, are connected generally to the main grid, but can also operate autonomously in an island mode. These small generators may increase reliability to final consumers and will bring additional benefits for global system operation and planning. European Union is investigating this concept, within the framework of a Research & Development project to study the problems challenging the integration of large amounts of different micro sources in low voltage grids [12]. Renewable power sources, such as wind and photovoltaic generators, micro turbines working on gas or bio-fuels, different types of fuel-cells are examples of micro sources technologies, and they are generally included in a microgrid structure; it is important also to include storage energy devices, such as flywheels or batteries, which can provide energy to the grid for a short time period (about 24-36 hours) when the energy produced by micro sources is not enough to supply the system demand. In addition, the energy storage is needed for instant voltage control because of the challenging dynamic properties of an isolated microgrid and slow controllability of some Distributed Generation units.

The main concept of a microgrid is to provide uninterrupted, high-quality power to the customers by local Distributed Generation units. In addition, some of these units can also produce heat to the customers. The local production of electricity may be based on renewable energy sources (solar, wind energy or biogas), which should be exploited as much as possible. Energy storage systems should be used within the Distributed Generation units or as one larger storage in microgrid.

Before describing all the aspects concerning the microgrid and its features, it is worthwhile to give a formal definition of a microgrid. As for micro sources, distributed generations and distributed energy resources, there is no unique, technical definition; therefore there are several ways to define a microgrid.

A microgrid is defined as "A cluster of loads and micro sources that operate as a single and controllable system; this system provides both power and heat to its local area, and can supply several independent loads" [13].

Hatziargyriou and Strbac defined it in [14]: the microgrid is the interconnection of small, modular generation to low voltage distribution systems. Microgrids can be connected to the main power network or be operated autonomously, similar to power systems of physical islands.

European Commission define microgrids as "Small electrical distribution systems that connect multiple customers to multiple distributed sources of generation and storage" [15] and also points out that microgrids typically can provide power to communities up to 500 households in low voltage level.

Early definition by Lasseter [16] implied the concept of microgrid as "A cluster of loads and micro sources operating as a single controllable system that provides power to its local area."

Arulampalam describes it in [17] as "A combination of generation sources, loads and energy storage, interfaced through fast acting power electronics. This combination of units is connected to the distribution network through a single Point of Common Connection and appears to the power network as a single unit.”

The previous definitions introduce a new concept, that enables high penetration of Distributed Generations without requiring re-design of the existing distribution system. In the case of disturbances, the generation and corresponding loads can autonomously separate from the distribution system to isolate the microgrid loads from the disturbance, without harming the transmission grid’s performance. This concept can be considered when defining the operation of Distribute Generations in the traditional distribution system.

There are of course electrical and electronic devices required to efficiently produce energy and to manage the grid itself; concerning that, Lasseter [16] argued that “Power electronics would be a crucial feature regarding microgrids since most of the micro sources must be electronically controlled to gain required system characteristics. Some of the key technical issues are power flow balancing, voltage control and behavior during disconnection from the Point of Common Coupling (islanding), protection and stability aspects.” Most Distributed Energy Resources employed in a traditional microgrid are unsuitable for direct connection to the electrical network due to the characteristics of the energy produced. Therefore, some power electronic interfaces are required, such as DC/AC or AC/DC/AC inverters. It becomes evident that inverter control is thus the main and the most problematic concern in microgrid operation. These issues will be discussed in the next section.

From the grid’s point of view, a microgrid can be operated within a power system as a single aggregated load and as a small source of power; furthermore, the microgrid can provide other services supporting the network. From the customer's point of view, instead, it is a low voltage distribution service with additional features that account for significant advantages, such as increase in local reliability, improvement of voltage and power quality, reduction of emissions and decrease in cost of energy supply.

Controlling a potentially huge number of Distributed Energy Resources creates a new challenge for operating and controlling the network safely and efficiently. The designing of a fitting and suitable microgrid structure creates solutions to the problems concerning to this new network concept; in fact, microgrids permit Distributed Energy Resources to provide their full benefits. As has indeed been frequently suggested by important and significant Electric Engineering Institutions, Distributed Energy Resources are considered a basic feature of future active distribution networks and, furthermore, a microgrids crucial concept is that they can be operated either connected to the main grid or as an island mode; microgrids must maintain their stability during both these modes of operation, as [15] points out.

Generally, microgrids operate connected to the main grid, but an isolated mode can be required. In fact, when failures occur in the medium or high voltage systems, the microgrid is automatically disconnected from the system, and thus it operates in isolated mode, supplied by the micro generators distributed with it, as in the traditional physical isolated power systems. When operating independently in island mode, all loads have to be supplied and shared only by distributed energy resources. The island mode will be discussed in paragraph 1.4.

1.3.1 Microgrid advantages and drawbacks

There are several technical, economic and environmental benefits for the local area due to the presence of a microgrid, which are widely explained in references [13, 18]:

- Enhance local reliability
- Improvement of energy system reliability and resilience
- Provide uninterrupted power supply functions
- Minimization of the overall energy consumption
- Energy efficiency
- Provide increased efficiency through using waste heat combined heat and power (CHP)
- Voltage sag correction
- Reduce feeder losses
- Support local voltages
- Improved environmental impact
- Autonomous mode

Among the previous advantages, improvement of energy system reliability is certainly one of the most significant; the concept of microgrid reliability concerns the measure of the system's capability to serve the demand. There are various indexes which quantify the reliability of a distribution system, such as:

- Loss of Load Probability (LOLP) [19]
- Expected Unserved Energy (EUE)
- System Average Interruption Duration Index (SAIDI) [20]
- System Average Interruption Frequency Index (SAIFI)

- Energy Index of Reliability (EIR) [21]

Monitoring the system's reliability in a short time period and recording its quantitative measure is crucial, because reliability study of a system exposes the vulnerable areas of the system itself. This is due to the fact that consumers might have different reliability requirements, and so different strategies are needed to satisfy them. So a comprehensive planning strategy based on reliability is necessary to make the system robust and resilient. Finally, a considerable microgrid's advantage is the possibility to operate autonomously from the main grid, in some cases [22] denominated emergency mode.

Due to the fact small modular generation technologies are interconnected to distribution systems, some electronic devices are required to maintain system stability. The increased penetration of dispersed generation in traditional distribution systems may result in several technical problems in the operation of the grid:

- Steady state and transient over or under voltages at the points of connection
- Protection malfunctions
- Increase in short circuit levels
- Power quality problems [23, 24, 25]

1.3.2 Microgrid architecture

Microgrid's main goal is to feed all consumers in the area with high quality power. The concept of quality power concerns several aspects and has a significant role in microgrid general assessment. It means that a DC microgrid has a high power quality if it has stable voltage level in time.

Sources and loads should be connected with controlled telecommunication lines. The controller is another important device in a typical microgrid. Its main aim is to keep voltage level in assumed range in all loads connection points, and this becomes more difficult as the energy produced by distributed sources is not constant and vary according to the time or to weather conditions, as in the case of solar, wind or other renewable resources. In case of DC systems, this concept can be considered to be equivalent to deliver enough power to a load.

Voltage regulation in the microgrid concerns several actions, that are required when improper voltage level is observed near a load or in a connection point somewhere in the microgrid. So, if loads increase their power demand, for example between 8 am and 5 pm, controller has to manage this peak demand, by changing power production in sources located next to that point. If an energy storage system has previously stored energy, it can be discharged to supply temporarily, loads which require more energy in that moment. Nevertheless, regulating and controlling the microgrid voltage means also connecting or disconnecting controlled loads, when required.

Besides voltage level, it is necessary to keep ripples as low as it is possible. This is due to electrical devices which consume or produce current with significant ripples. On the other hand, these devices are required by the system, as bidirectional converters, because they properly connect loads or resources to the grid.

There are some potential sources of ripples, like:

- Power plants (composed of power converters [4])

- AC loads links (inverters)
- DC loads links (DC/DC converters)
- Bidirectional converters (grid links, storage systems).

All the devices that are mentioned need to meet requirements such as consumption or production of low ripple current and the possibility to control output or input voltage and/or input or output current.

Concerning DC microgrids, there are considerable advantages in comparison to AC systems, that is the possibility to easily control power flow direction. The flow direction is closely related to current and voltage direction. Hence, power control can be based only on current flow in DC systems.

Microgrid companies usually don't have to design the layout of the loads, because most of the time they are already built in the area (for example houses, industrial plants etc...), but power plant locations remains under their influence and it is a crucial decision to make in a microgrid design process. When a new power plant is designed, it is necessary to take into consideration its location and length of power lines, because voltage drop depends only on it and on actual current value.

Due to these considerations, power plants should be located as close to the heaviest loads as possible. The easiest and least problematic decisions to make are the placing of solar or wind power plants, that require just suitable surfaces and favorable weather conditions.

A traditional microgrid architecture comprises several types of devices:

- power plants
- loads (they can controlled or not by microgrid's controller)
- energy storage units
- power lines

– control system

– telecommunication lines

As presented in figure 1.4, in a basic microgrid architecture the electrical system is assumed to be radial with several feeders and a collection of loads. An important point of connection is the Point of Common Coupling (PCC), a separation device, usually a static switch, by which the radial system is connected to the distribution system. Each feeder has circuit breaker and power flow controller.

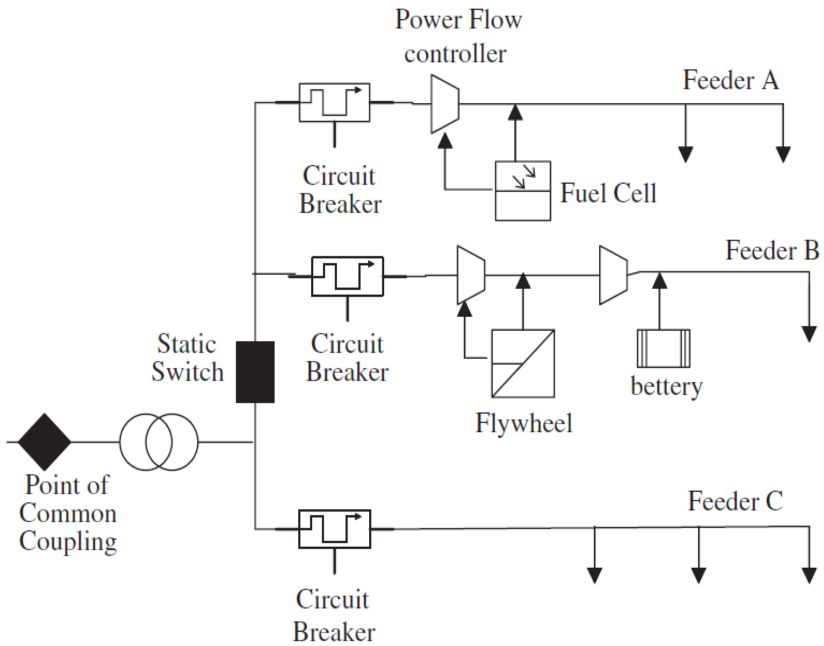


Fig. 1.4 Basic microgrid architecture.

Another traditional microgrid architecture is illustrated in figure 1.5, with the following elements:

– Low voltage network

– Loads (some of them interrupted)

– Both controllable and non-controllable micro sources

– Storage devices

– Hierarchical-type management and control scheme

– Communication infrastructure used to monitor and control micro sources and loads

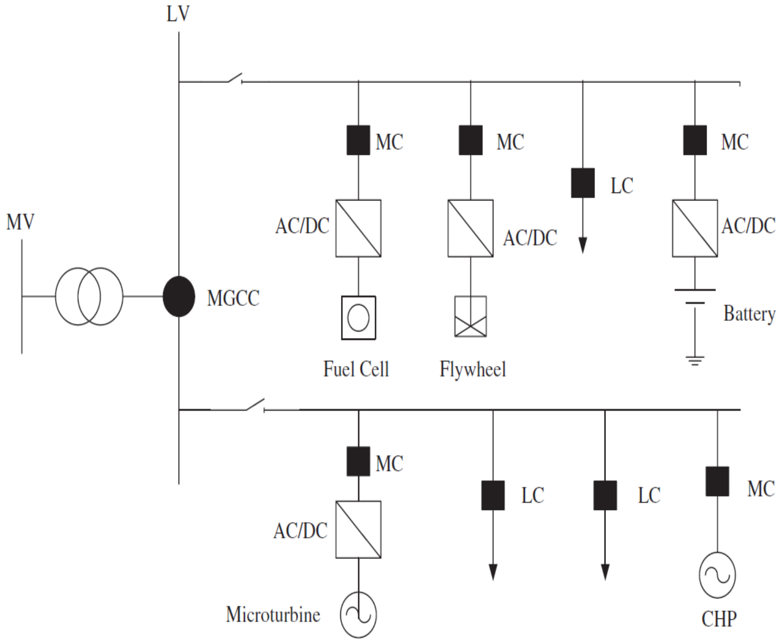


Fig. 1.5 Microgrid architecture with Microgrid Central Controller

The control of a microgrid is based on a hierarchical control architecture in order to increase system reliability [12], so it is important to accurately describe the general architecture of a microgrid control system:

- In the first hierarchical level, there is the head of the hierarchical control system, the Microgrid Central Controller (MGCC): is installed at the medium voltage/low voltage (MV/LV) substation, at the low voltage side. The Microgrid Central Controller is the head of the hierarchical control systems, and it includes economic managing functions, besides other crucial control and technical functions [22];

- At a second hierarchical control level, Load Controllers (LC) and

Micro source controller (MC) exchange information with the Microgrid Central Controller that manages microgrid operation by providing set-points to both Load Controllers and Micro source Controllers. So, each device is locally controlled, and a Load Controller (LC) controls each electrical load or group of loads.

The data exchanged between network controllers mainly includes messages containing set-points to Load Controllers and Micro source Controllers, information requests sent by the Microgrid Central Controller to Load Controllers and Micro source Controllers about active and reactive powers, and voltage levels and messages to control microgrid switches. So, in a short time period a relatively small amount of data is expected to be exchanged between such controllers.

- A suitable communication infrastructure is also required, because information exchange has to be quick and reliable. Such information exchange concerns Microgrid Central Controller and other controllers, according to the following hierarchical predefined scheme:

- a. Microgrid Central Controller promotes adequate technical and economical management policies and provides set-points to Load Controllers and Micro source Controllers
- b. Load Controller will act based on an interruptibility concept
- c. Micro source Controllers are responsible for the control of the micro source active and reactive power production levels

Generally a microgrid has a small geographical span, about a few square kilometers, so it eases the establishment of the communication infrastructure. A typical solution for this infrastructure is to use the existing Power Line Communication, which presents some interesting characteristics for this type of network, even if other type of access, such as Wireless Communication Technology, is rapidly growing.

Descriptions of the other electrical and electronic devices follow:

Storage devices

Another crucial issue in the microgrid is the operation of energy storage system, that permits the storage of energy when it is not required by the loads, and to supply it by discharging the battery or using the flywheel. Anyway, the most common storage device is an electrochemical storage, based on lead-acid battery. Its main tasks are:

- protection against voltage drops and rises
- power balancing
- starting the system

The necessary microgrid storage can come in several forms:

- Batteries or super-capacitors on the DC bus for each micro source
- Direct connection of AC storage devices (batteries, flywheels, etc...)
- Use of traditional generation with inertia with the micro source

These devices act as controllable AC voltage sources to face sudden system changes. In spite of acting as voltage sources, these devices have physical limitations and thus a finite capacity for storing energy. There are several possible solutions for a typical storage system: [26] points out that a lead–acid battery is the most suitable for microgrid applications, because it is capable of providing large currents even if only for a very short period of time.

Reference [11] points out that up to 60% of consumed energy in a microgrid can flow through the storage units; moreover, the storage unit location is also very important concerning others devices, so it has significant impact on microgrid operation and power quality.

Considering Lasseter's studies [11] about storage devices in island microgrids, the author points out that “a system with clusters of micro sources designed to operate in an island mode must provide some form of storage to insure initial energy balance.” So this power system, that can also be called Macro Grid, has storage provided through the generators inertia. In fact, if a new load comes on line, the initial energy balance is satisfied by the system’s inertia, and this results in a slight reduction in system frequency.

Of course, not all the existing micro sources have the same time response; for instance, fuel-cells and micro turbines have large time responses, in a range from 10 to 200 seconds. So, it is important to provide suitable storage devices to the system: in fact, they must be able to provide the amount of power required to balance the system following disturbances or significant load changes, that can occur in a typical microgrid that deploys Renewable Energy Sources; these cannot provide the amount of energy required due to the variable nature of the source, such as wind or solar.

Inverter controller

Most micro source technologies that can be installed in an microgrid are not suitable for direct connection to the electrical network due to the characteristics of the energy produced. That is why power electronic interfaces (DC/AC or AC/DC/AC) are required in microgrids that deploy Distributed Energy Resources.

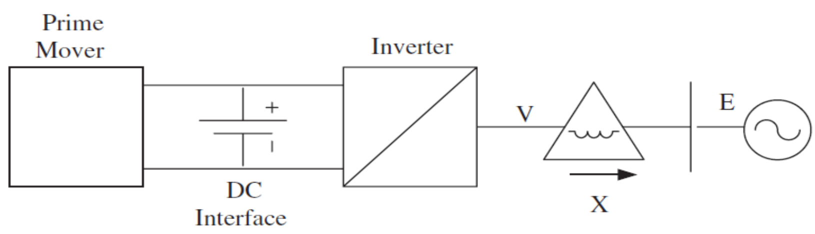


Fig. 1.6. Interface inverter system

There are two main kinds of control strategies used to operate an inverter [27]:

- PQ inverter control: the inverter is used to supply a given active and reactive power set point
- Voltage Source Inverter (VSI) control: the inverter is controlled to ‘‘feed’’ the load with predefined values for voltage and frequency

As mentioned in [28], the power electronic controls of current micro source are modified to provide a set of key functions. The critical system performance components are:

a - Voltage versus reactive power droop

b - Power versus frequency droop.

a - Voltage vs. reactive power droop

Voltage regulation is necessary for local grid's stability, in order to increase grid reliability in terms of power quality. So, generally in a system with high penetration of micro sources, a local voltage control is required because systems could experience voltage and/or reactive power oscillations if such voltage control is unsuitable. Nevertheless, small errors in voltage set points can occur: if so, the circulating current can exceed the ratings of the micro source, which is another possible problem concerning microgrid voltage regulation.

Therefore, a proper controller is required, and it is the so called voltage versus reactive power droop controller: the micro source generates reactive power, and as it becomes more capacitive, the controller reduces the local voltage set point; conversely, when reactive power becomes more inductive, the voltage set point is increased.

b - Power vs. frequency droop

Power versus frequency droop can solve problems connected to frequency generation errors that can occur in isolated microgrids. When the microgrid separates from the main grid, a reduction in local frequency appears, due to the change in voltage phase angle at each micro source. So each micro source can provide its proportional share of power.

Power Lines

Typically, microgrid's power lines can have DC or AC power lines [6]. That's why requirements for power electronic devices for such systems are important and deserve complete and accurate descriptions. The low voltage network can cover an urban area, a shopping center or even an industrial plant [12].

1.3.3. Microgrids black start

A set of rules is required to run the microgrid black start: they are identified and are embedded in Microgrid Central Controller software. Black start process involves a sequence of control actions, that are checked during the restoration stage. A crucial condition to guarantee the microgrid restoration success is the availability of some micro sources with black start capability.

So for the implementation of the Black Start the following requirements are necessary :

- An autonomous local power supply to feed local auxiliary control systems and to launch generation
- Bidirectional communication between the Microgrid Central Controller and Micro sources Controllers and Load Controllers
- Updated information, obtained before disturbance, about the status of load and generation in the microgrid and about availability of micro source to black start
- Automatic load disconnection after system collapse
- Capability to disconnection the Medium Voltage / Low Voltage distribution transformer from the Medium Voltage Network, before starting the Black Start procedure
- Capability for Low Voltage Network area separation

In the Black Start procedure developed in [29], the authors assume that micro sources with Black Start capability have batteries in the DC bus of their inverters (SSMT and SOFC), that are operated as VSI in a MMO mode, and the microgrid adopts a multi-master control approach, at least during the first stages of the sequence.

The Microgrid Central Controller has a significant role also during the microgrid restoration process, because it has to manage and store information during normal operation; the Microgrid Central Controller periodically receives such information from Load Controller and Micro source Controllers, about consumption levels and electric production; of course this information is stored in a dedicated database. Microgrid Central Controller also has information about the technical characteristics of the different micro source, for example active and reactive power limits. The basic concept of Black Start restoration process is to collect such information, that describe technical parameters of microgrid sources, create a set of rules for the restoration and embed them in the Microgrid Central Controller software: when a Black Start process is required, the Microgrid Central Controller will try to restore a scenario similar to the last one stored in the database.

Nevertheless, it is interesting to analyze the sequence of actions typically required during a Black Start procedure [29], in order to restore the Low Voltage grid after a general blackout:

a. Disconnection of all loads in order to avoid large frequency and voltage deviations when energizing the Low Voltage Network

First of all, each micro source with black start capability is an important resource during system restoration; that is why the microgrid should be also sectioned around each micro source with black start capability, in order to allow it to feed its own loads, that can be considered as protected loads. In fact, this procedure allows to run a stand-alone mode, and these actions lead to the creation of small islands inside the microgrid. They will require to be synchronized later.

b. Building the Low Voltage Network

Microgrid Central Controller has to exchange information with storage devices and the distribution transformer: the communication infrastructure is very important for that, because Microgrid Central Controller has to know when to send an order to them, in order to energize the Low Voltage cables and the distribution transformer. It is necessary to energize the Distribution Transformer as soon as possible, since the earth connection is performed at the Distribution Transformer neutral point and it is restored only after its energization. These procedures are normally carried out in order to comply with the Low Voltage Grid earthing safety procedures, as [30] points out.

c. Small islands synchronization

As mentioned above, during the disconnection of the loads from the microgrid, micro sources operating in stand alone mode should be synchronized with the Low Voltage Network. Of course, local micro sources controllers have to verify the synchronization conditions, such as phase sequence, frequency and voltage differences, in order to avoid large transient currents and power exchanges that can result during this kind of operation.

d. Connection of controllable loads to the Low Voltage network

The connection of controllable loads is performed if the micro sources running in the Low Voltage Network are not fully loaded. It is important to know the available storage capacity when connecting the amount of power, in order to avoid large frequency and voltage deviations during load connection. The smaller the deviations are, the higher grid stability results.

e. Connection of non-controllable micro sources or micro sources without Black Start capability

Connection of non-controllable micro sources was not possible at a previous stage. If "Stage D" is successfully performed, non-controllable micro sources can then be connected to the grid, because the system has micro sources and loads capable of smoothing voltage and frequency variations due to power fluctuations in such non-controllable micro sources The most significant micro sources without Black Start capability are Photovoltaic and Wind Generators and, when connected, they can be supplied by the Low Voltage grid to restart, because they cannot do it autonomously.

f. Load increase

When projecting a microgrid, the production capability should be clear from the beginning in terms of maximum amount of loads to connect to the grid itself. In order to feed as many loads as possible, depending on this issue, other loads can be connected later.

g. Microgrid synchronization with the Medium Voltage Network

Generally, two situations are possible when a microgrid is working connected to a Medium Voltage Network: the microgrid can import power or it can export power to the Medium Voltage Network. So, if the microgrid was importing power before the general blackout, it will not be possible to connect all the local loads. In this case, remaining unsupplied load can then be restored.

There are a series of electrical problems that can appear during black start restoration: for instance, when the Distribution Transformer is energized by the Low Voltage side, a large inrush current is experienced, which cannot be supported by the power electronic components of the inverters. The way to overcome this problem, consists of performing transformer energization using a ramp-wise voltage generated by the inverter of the micro source selected for this task.

The crucial operations that are required to successfully terminate a Black Start procedure are:

- Building the Low Voltage Network (including the distribution transformer energization)

- Connecting micro-generators
- Controlling both voltage and frequency
- Connecting controllable loads

1.4 Isolated microgrids

Microgrids are often employed in remote rural areas, where traditional electrification technology is unsuitable and it is not convenient for several reasons, such as high connection cost, high Maintaining & Operational costs, high investments required and so on. Many times, however, rural areas have small populations, or don't have an industrial plant, so designing a wide traditional energy plant is not economical or convenient. This is the case in this project, where in two rural areas in Peru renewable resources are employed, and they feed the loads such as a school, several houses and a medical center using electrical power lines, isolated from the traditional electrical distribution network.

As mentioned before, over the last years a large number of Distributed Generations have had a high penetration and their growth is expected to be constant and even greater in developed countries. The subsystem called microgrid can realize the emerging potential of distributed generation. So, according to this new approach, Distributed Energy Resources such as wind, solar, micro turbines and fuel cells are connected into the distribution network to increase the capacity of the network, but they also contribute to reducing losses and improving voltage quality. As just commented, controlling a potentially huge number of Distributed Energy Resources is not simple and it requires suitable electronic devices and controllers for operating and controlling the network safely and efficiently. The main challenge is controlling the microgrid when it operates independently in isolated mode: in fact, all loads have to be supplied and shared only by Distributed Energy Resources.

Microgrids usually work in a normal interconnected mode, where the microgrid is connected to a main Medium Voltage Network, either being supplied by it or injecting some amount of power into the main system. They can also operate in an island mode if necessary, it means the microgrid operates autonomously, in a similar way to physical islands, when the disconnection from the upstream Medium Voltage Network occurs. This happens generally in two cases:

- Emergency mode: for instance, in case of failure of the Medium Voltage grid
- Island required mode: possible operation in isolated mode as in physical islands

There are important management changes required by such island mode; in fact, the Microgrid Central Controller has to change the output control of generators from a dispatch power mode to a frequency mode. So two controls can be identified: a primary control, concerns Micro source Controller and Load Controller, and a secondary control, managed by Microgrid Central Controller concerning storage devices, load shedding and eventually triggers a black start function.

1.4.1. Isolated microgrid architecture

This is an electrical scheme of the microgrid employed in one of the communities belonging to the study case presented in this project. It is an isolated microgrid, without any connection cable, employing a 100 W wind generator and using a battery as storage system, that can store at maximum 1500 Wh per day. There is just a 200 W load supplied by the generator.

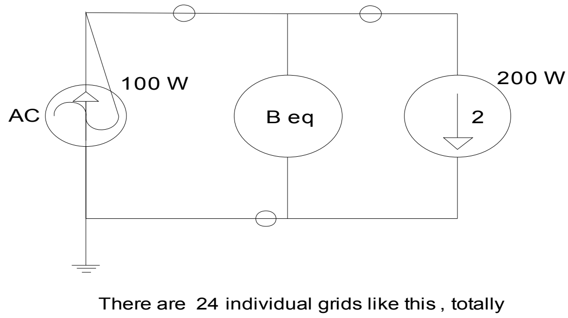


Figure 1.7 Individual Grid scheme without any cable connections - El Alumbre

In figure 1.8 another example of isolated microgrid is presented, where a single 500 W Wind Generator feeds 3 loads (400 W), one of them placed close to the generator and to the battery block (named B eq), while two loads are connected through two connection cable, which have their own equivalent impedance, measured in Ω.

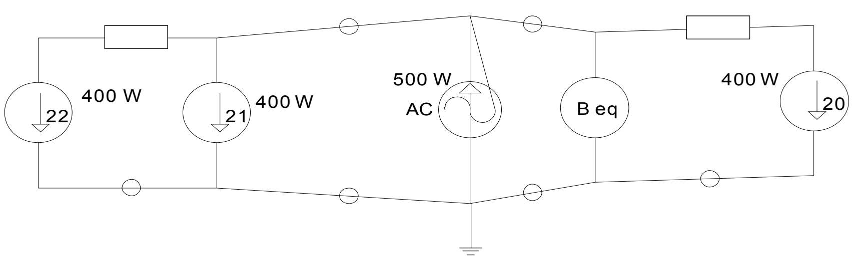


Figure 1.8 Isolated microgrid with two cable connections – El Alumbre

As mentioned before, the architecture of a system required to operate autonomously denotes some changes; the most significant aspects of an isolated microgrid follow:

Storage System

Generally, energy storages are used within the Distributed Generation units or as one larger storage in microgrid. Energy storage devices play a significant role in isolated microgrids, therefore energy storage is needed for instant voltage control because of the challenging dynamic properties of an isolated microgrid.

In reference [31], the master unit with energy storage controls the voltage of microgrid during sudden changes, as it may happen when wind or solar generators are employed. The master creates the frequency reference for other Distributed Generation units in microgrid, and active power output of master unit should never go under certain percentage, in reference [31] equal to 5% of the total load.

In case of long duration island operation of microgrid, the energy storage should be capable of being charged through some primary energy source, for instance fuel cell (as in figure 1.9); anyway this is not the case presented in this paper, where there aren't primary energy sources. In the case of large proportion of generator units based on highly varying output power (as solar or wind energy), there could also be other energy storage, in addition to the master unit, for power balancing purposes.

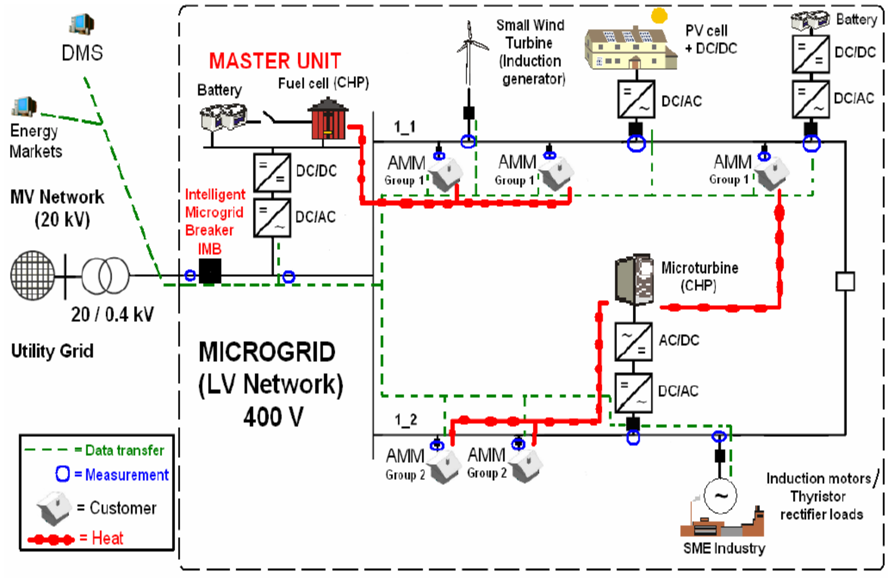


Fig. 1.9 Low Voltage Network Microgrid

<u>Intelligent Microgrid Breaker</u>

Intelligent microgrid Breaker (IMB) has to coordinate Distributed Generation units and loads during island operation, because this operation needs a communication capability device. So no additional Microgrid Central Controller is not required, as shown in figure 1.9.

Intelligent Microgrid Breaker's tasks are:

- Calculate island operation strategy
- Islanding
- Blackstart
- Fault management
- Reconnection strategy of microgrid

Intelligent Microgrid Breaker has to measure informations about status, present production or consumption levels of Distribution Generation units and loads from both sides of the connection point. Thanks to this information, it is able to evaluate islanding decision, and moreover re-synchronization after island operation is based on these measurements. In addition, there is further information about load groups stored in its database, like rated power, power factor and other technical parameters of Distributed Generation units, and state of charge of the energy storage systems.

Based on the stored information, the Intelligent Microgrid Breaker gives set-point values for units capable of active power control during island operation. This is not the only information required to act a suitable island mode operation; it is based either on the protective settings and measurements of the Intelligent Microgrid Breaker or on the information received from the Distribution Management System (DMS), as shown in figure 1.9.

Resuming, here are the basic characteristics required from Intelligent Microgrid Breaker:

- Real-time and bi-directional communication with Distribution Management System and with energy storages
- Information change with Distributed Generation units and loads
- Intelligence and adaptivity, which means built-in strategies for different possible situations

The configuration described in Peruvian study case in the next chapters doesn't have a Intelligent Microgrid Breaker, because there are only isolated microgrids, without any Medium Voltage Network connection, so no decision to isolate has to be taken. The system employs several batteries, placed next to the wind or solar generators to guarantee the microgrid energy storage requirements.

Information and Communication

In a typical isolated microgrid fast transients may occur during its operation, resulting from its global low inertia, and communication issues become very important. The transmission of information from the Load Controllers and Micro source Controllers to the Microgrid Central Controller is certainly subject to delays, as the amount of data sent by the Microgrid Central Controller; that's why a block that represents both delays is usually included in the control scheme of the microgrid. The active power set-points are given by the Microgrid Central Controller to the Micro Source Controllers every 5 seconds, in order to avoid unnecessary information in the communication line and to decrease the mean delay time.

As reference [31] points out, several options concerning the communication infrastructure are available for the microgrid designer. One of the most adopted and promising solution is Power Line Communication (PLC), while Wireless Access Technology should be one of the most interesting solution in next years.

1.4.2 Technical problems concerning isolated microgrids

As in traditional interconnected microgrids, control and protection for autonomous system presents challenging problems. Here are some of the most common issues associated to it [32]:

- Decreasing of power quality
- Stability Problems
- Safety
- Voltage profile
- Reliability
- Protection

– Imbalance/asymmetry
– Stray voltages
– Currents, electromagnetic compatibility issues
– Non-autonomous/autonomous operation

The main inconveniences for controlling an isolated microgrid concern stability problems, such as angle, frequency and voltage stability. In a traditional distribution network, there is no need to consider these issues of stability as the network is passive and remains stable under most circumstances.

In early and extremely simple Distributed Generation systems, considerations of generator transient stability are not of great significance, because a fault occurring somewhere on the distribution network would result in Distributed Generation tripping due to under-voltage; so a short period of generation would be lost, without affecting the whole system. Stability is hardly considered in most countries as a microgrid key assessment indicator. However, as Distributed Generation penetration is expected to increase, its contribution to network security is going to become greater, considering first of all angle and voltage stability.

In isolated systems, frequency stability issues become certainly of major concern: in fact, the consequence of a sudden trip of a large amount of Distributed Generation on the dynamic performance of the system have a great impact on the system itself. A network failure may cause a drop-out of a large number of Distributed Generators, which would cause a significant lack of generation and temporary drop in frequency. In the study case presented in this project, a similar failure would have a very strong impact on the isolated microgrids, as for the loads fed by such systems.

Similar problems may also occur when a large amount of wind power is integrated in the system, because of fast wind changes and very high wind speeds, that may result in the sudden loss of production causing frequency excursions and dynamically unstable situations. In the worst case scenario, this might lead to frequency instability and eventually collapse of the system, as reported in references [33] and [34].

Power quality is certainly a significant key indicator for an isolated microgrid assessment; power quality can be affected by a series of events which may occur in most isolated systems, such as voltage distortion, sags, swells, outages and imbalances, depending on a variety of events such as lightning, switching, power faults, feeder energization inrush currents, motor starts, load imbalance, harmonics, resonance, and so on. There are several investigations which study how to minimize the impact of these events on the reliability of Distributed Generations and on power quality grid, but the purpose of this paper is not to explain them accurately.

1.4.3 Isolated Microgrid Black Start

It is interesting to have an overview about Black Start Operation carried out in an isolated microgrid when an unplanned event occurs, for instance during transition to island mode; the most dangerous consequence is the microgrid's instability so, when this occurs, all Distributed Generation Units must be disconnected from the microgrid, and later re-started.

The restoration is done with the microgrid black start strategy, which controls the power balance and voltage during such operation. As reference [31] points out, “the energy storage based master unit of microgrid plays the main role in maintaining the power balance and acceptable voltage level in microgrid also during the black start”.

The duration of the black start sequence is directly connected to the load and Distributed Generation unit types. Some Distributed Generation units need longer time to reach stable operation after their connection and after sudden voltage changes: for instance, rotating machines with slow dynamic response. That is why they should be connected at the end of the black start sequence.

Reference [31] indicates some dimensioning principles for the successful black start operation based on simulation results:

- Rated capacity of the master unit with energy storage should be at least equal with largest converter based Distributed Generation units or motor drives and also 1,5 - 2 times larger than any of the rotating machines connected directly to the microgrid.

- Load groups which are connected sequentially should not be larger than the capacity of the master unit and large directly connected rotating machines must be connected separately from other loads.

2. Electrification of remote communities in Peru

Electrification systems employing renewable energy resources are suitable in rural and remote areas where traditional electrification lines cannot provide energy due to the high cost of the connection and to the reduced number of dispersed loads. So, photovoltaic and wind generators are suitable to provide energy to loads in isolated areas, using autonomous microgrids not connected to any traditional Medium or High Voltage Network. This has been carried out over the last two years in “Serra Norte”, in northern Peru, where houses are very dispersed and, because of that, individual generators were installed next to each load, without the use of any microgrid connection line. The work developed by GRECDH Team (Grup de Recerca en Cooperació i Desenvolupament Humà – Universitat Politècnica de Catalunya) over the last two years, in collaboration with CICTCEA Department (Universitat Politècnica de Catalunya), aims to build microgrids which feed loads and to use also individual generators placed next to the remainders loads. GRECDH Team started to study an optimization model using the wind map of the region, to evaluate the wind resource in each point and the position of the loads that represent the total energy demand. The team studied such optimization model, using a dedicated software, and the obtained results show the microgrids solution is cheaper than placing individual generators next to each load. The model developed by the team is a Mixed Integer Linear Programming, that aims to minimize microgrids' total cost using three technologies: wind, solar and hybrid. The solutions have to minimize the total cost, satisfy the total energy demand required by the loads, choose the connection cables to connect the loads to the generators points, considering maximum acceptable voltage drops, acceptable current values in each cable and others constraints; moreover, the model has to provide suitable electronic devices for each generator, such as inverters, batteries and regulators, that are necessary for the suitable operation of the microgrid itself.

The optimization software evaluated several possible solutions, and found the best one for each community and for each demand scenario, taking into account both wind and hybrid generation. The optimization models were solved using a Personal Computer, Intel-Core Duo T5870 with 2Gb of RAM. These results represent the background amount of data this project analyzes: the microgrids found by the optimization software in the preliminary analysis are first analyzed, by running a simulation in Simulink-Matlab Environment, to discover the problems concerning the microgrids voltage drops; for the microgrids that do not have required electrical stability there are suitable proposal to solve such problems. In this chapter there is a general description of the communities, and the voltage drops preliminary analysis results.

2.1 Description of Peruvian communities

GRECDH Team worked in northern Peru, in the Cajamarca region. The communities are Alto Peru and El Alumbre, as next figure shows:

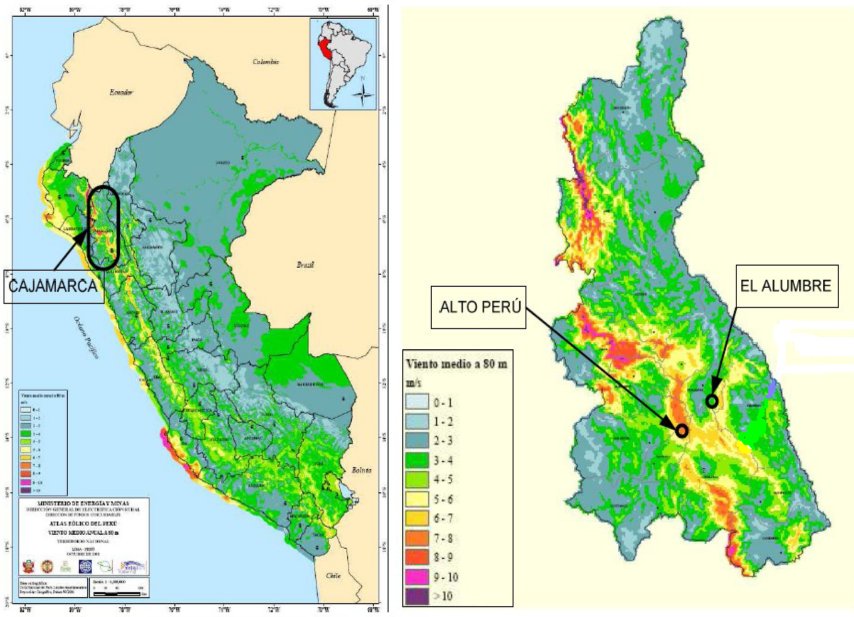


Figure 2.1: Map of Cajamarca region, Peru wind map (at 80 meters height) and localization of the two communities

The projects carried out in these places are the first electrification rural projects employing wind and photovoltaic energy in the north of Peru. Brief descriptions of the communities follow:

<u>Alto Peru:</u>

Alto Peru community is placed in the Tumbadén district, in San Pablo province, Cajamarca region. 85 families live in this community, and they are very dispersed in the area, as figure 2.2 shows:

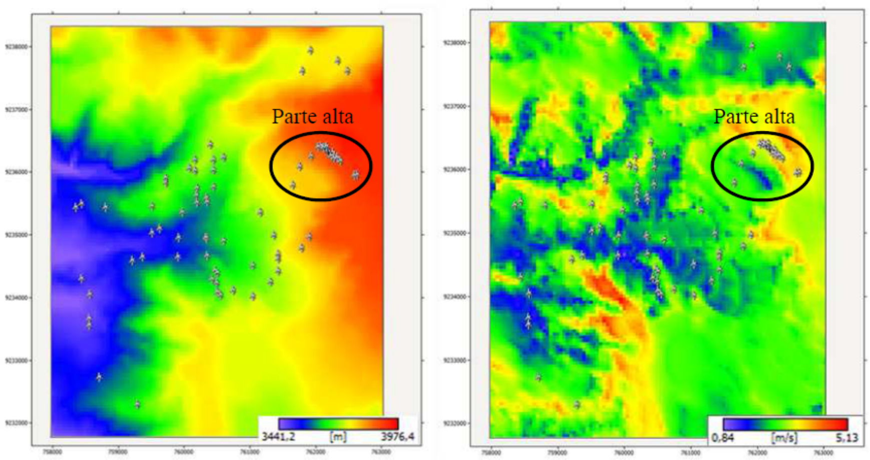


Figure 2.2 Wind map and altitude map in Alto Peru

The whole community can be divided into two zones: the "Parte Alta", or "High Part" where 26 families live, totally 99 inhabitants, and a "Parte Baja", or "low Part", where the remaining families live, 256 inhabitants in total. The most important economic activities are agriculture and animal husbandry; the agriculture products are mainly consumed by the families, and just a small part of the products are sold, while the selling of milk is a significant income for local families.

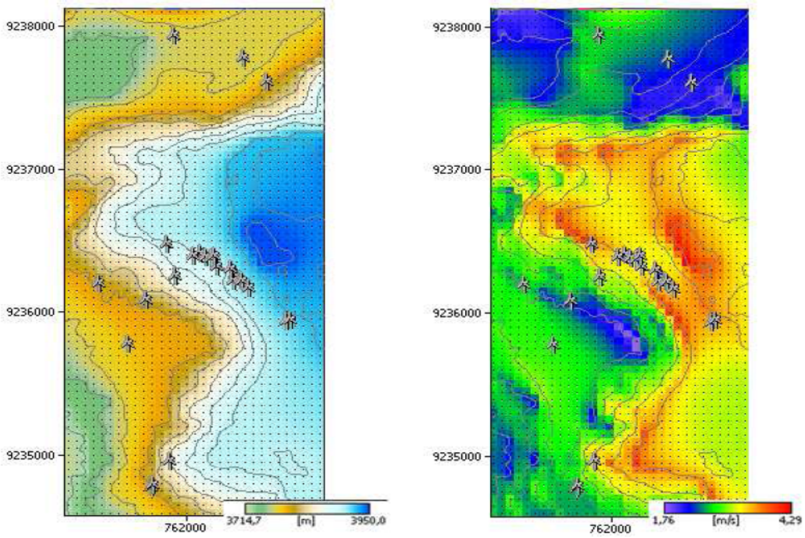


Figure 2.3: Wind map and altitude map of "High Part" of Alto Peru

Alto Peru is located in a large area (1,5 km x 4 km), altitude is between 3450 and 4000 meters, the climate is cold due to the height, and temperature normally doesn't go above 15 °C. The rainy season is from December to May, while from June to November there is a windy season with warmer temperatures.

Regarding solar resource in the community, the official governmental database [35] reports a PSH level of 4,3.

ALTO PERU	
PSH	4,3
Temperature [°C]	15
Efficiency	0,975

The "High Part" circled in figure 2.2 is the windiest area, in which the electrification project has been implemented. This area has an average altitude of 3900 meters, and it is possible to identify three sub-parts: in the central part there is a high concentration of houses, where 13 families live and the energy demand is higher, while in the other two there are just three houses for each area, pretty dispersed and without a significant wind resource to exploit.

This has been the second electrification project in this rural area that employs wind energy in North Peru; two microgrids, powered by a 500 W wind generator each, provide energy to 13 families in the central part of the High Area of the community. The project ended in July 2009, thanks to the collaboration between GRECDH UPC, Ingeniería Sin Fronteras-Cataluña, an EU organization called Green Empowerment and the Peruvian organization ITDG-Soluciones Prácticas.

Figure 2.4: Installation of 500 W wind generator in Alto Peru

<u>El Alumbre</u>

El Alumbre community is located in Bambamarca district, Hualgayoc province, in the region of Cajamarca. 35 families live in the community, 175 persons in total. In this case, the families are very dispersed, and they are quite far from one another. In the center of the community there are just 5 houses, one primary school, one health center, a community center and a church. Agriculture, animal husbandry and any kind of manpower are the most important economic activities for the most of families, but animal husbandry is certainly more important because families can sell milk.

The average temperature is about 8 °C during the day, and under 0°C during the night, the climate is cold throughout the whole year; in fact, the community is situated between 3500 and 4000 meters of altitude, and it has a surface of 3,5 x 3,5 kilometers. The houses are very dispersed in the area, although the school, the health center and several houses are close to one another in the central part.

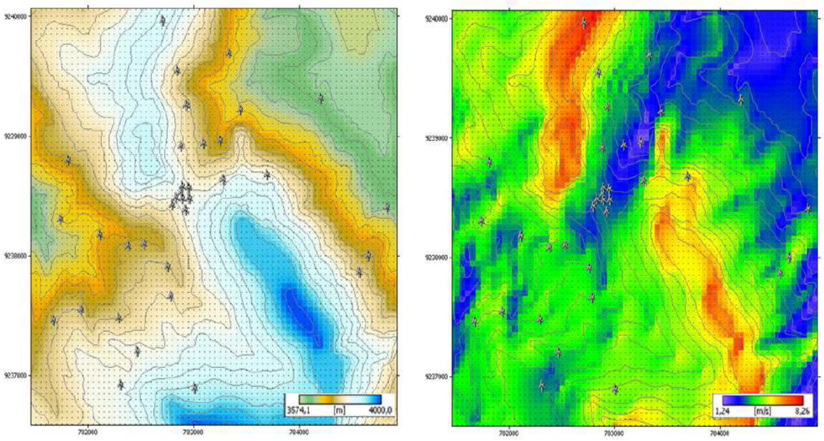


Figure 2.5: Wind Map and altitude map of El Alumbre

The windiest area is the red one in the right picture, that is also the highest area of the entire community; the lowest part has a lower wind resource.

EL ALUMBRE	
PSH	4,3
Temperature [°C]	8
Efficiency	1,00

Concerning the available solar resource, this community has a PSH equal to 4,3. El Alumbre was the first electrified community in the North Peruvian Andes, employing wind energy; the first project ended in February 2009, and it consisted of two phases:

- 100 W wind generators were installed next to each of the 21 loads, and a 500 W wind generator was placed next to the school.
- Later, 13 individual 100 W wind generators were placed next to further 13 loads, and another 500 W wind generator for the health center.

All the community loads have an individual generator, and two men were taught to do regular maintenance to the wind generators and their devices.

Figure 2.6: Installation of 100 W and 500 W wind generators in El Alumbre

2.2 Preliminary Analysis Data

The GRECDH Team worked on the optimization problem considering two demand scenarios:

- Low Demand Scenario: each house is supposed to consume 280 Wh of energy per day and have totally 200 W of electrical power, while the school and the health center consume 975 Wh of energy per day and have 600 W of electrical power. This data represents the actual scenario in the communities, considering the actual energy consumption required by the houses and the families.
- High Demand Scenario: in this scenario, the demand required by the loads is supposed to be double that of the first case, considering a future growth of energy demand; so, each house would consume 560 Wh of energy per day and have 400 W of electrical power, while the school and the health center 1950 Wh of energy per day (1200 W of electrical power)

Concerning the wind generation equipments, GRECDH Team calculated the amount of energy that each wind generator (100, 500, 1000 and 2000 W) is supposed to produce at a given point, where the wind resource is known and evaluated in wind speed (m/s).

Concerning the solar resource, the model considers that all the points of each community, can generate the same amount of energy, and so there is no optimum points to place a photovoltaic panel as done for the wind generators, where each point has its own wind resource value. It depends on the PSH index and on the panel's efficiency.

The three different photovoltaic panels can generate approximately an amount of energy between 209 and 419 Wh per day in Alto Peru; there are also three different types of solar regulators:

PHOTOVOLTAIC PANELS				SOLAR REGULATORS		
Type	Power [W]	Produced Energy [Wh / day]	Cost [$]	Type	Power [W]	Cost [$]
1	50	209,63	451	1	50	67
2	75	314,44	636	2	75	81
3	100	419,25	821	3	100	95

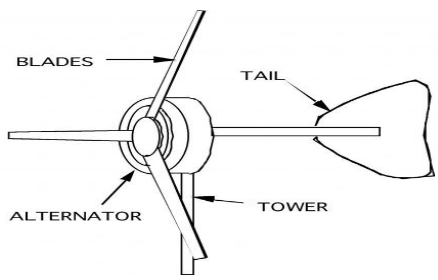
The estimated solar resource is higher in El Alumbre, so the energy the photovoltaic panels are supposed to produce is sightly higher, and type 3 can reach 434 Wh per day:

PHOTOVOLTAIC PANELS				SOLAR REGULATORS		
Type	Power [W]	Produced Energy [Wh / day]	Cost [$]	Type	Power [W]	Cost [$]
1	50	217,15	451	1	50	67
2	75	325,73	636	2	75	81
3	100	434,30	821	3	100	95

There are four different wind generators available, with electrical nominal power from 100 to 2000 W; there are also four types of wind regulators:

WIND GENERATORS				WIND REGULATORS		
Type	Nominal Power [W]	Maximum Power [W]	Cost [$]	Type	Power [W]	Cost [$]
1	100	300	974	1	420	165
2	500	1200	2737	2	1440	285
3	1000	1750	4106	3	1800	342
4	2000	3500	5132	4	3600	513

The four wind generators have horizontal axes, as shown in the figure:

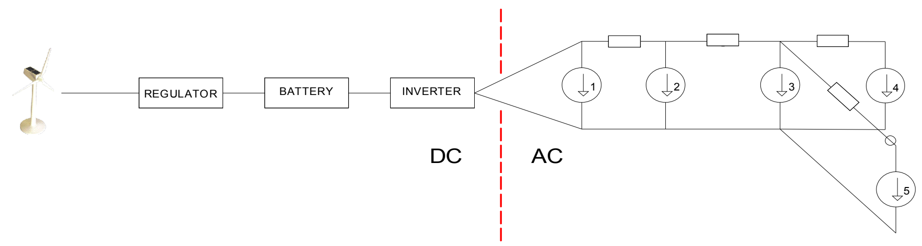


Finally, here are the four battery types: each of them can store a certain amount of energy for two days (Wh); there are also four different inverters.

BATTERIES			**INVERTERS**		
Type	Stored Energy [Wh / day]	Cost [$]	Type	Power [W]	Cost [$]
1	1500	225	1	300	377
2	1800	246	2	1200	1200
3	2400	292	3	2000	1800
4	3000	325	4	3000	2300

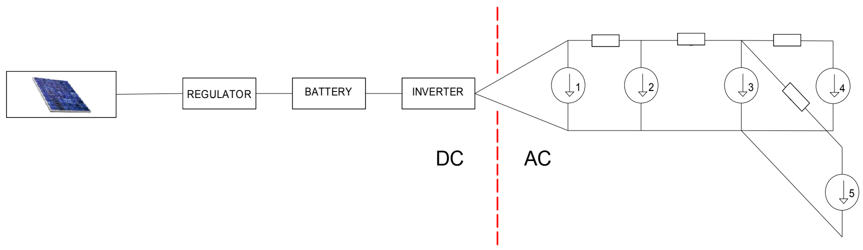
The simulation software the GRECDH Team used chose which generator was suitable to supply the loads connected to the grid, and then calculated the number and type of equipments required by the system, such as regulators, inverters and batteries.

The next scheme shows how the described devices are connected one to another: the generator (in this case a wind generator) is connected to the regulator, that is earth-connected and also connected to the battery bank; the DC / AC inverter represents the connection point to the grid: the first load can be connected to another one in series or parallel to each other as shown in the figure;

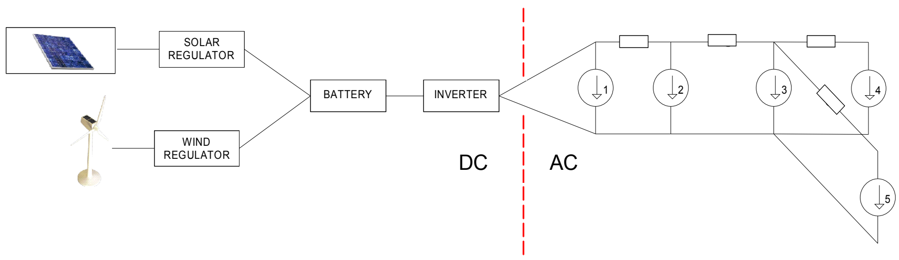


This paper aims to analyze the AC section of the grid, limited by the red line in the figure, with particular regard to the voltage drops; each cable has its own impedance, that consists of a resistive and a inductive part: of course the higher the impedance, the higher the voltage drop.

The described scheme can of course be considered when a photovoltaic panel is employed in the grids as a generator:



There are also grids supplied by hybrid generation: wind generators and photovoltaic panels are employed at the same time, they are connected to their regulators, while the battery and the inverter are placed as shown:



2.3 Description of the analysis method

This paragraph describes the electrical aspects taken into account to analyze the microgrids and the solutions given by the optimization model. The analysis method concerns three aspects:

- Cables Resistance and Inductance
- Active and Reactive Power Values
- Electrical simulation in Matlab-Simulink environment

2.3.1 Cables Resistance and Inductance

In a microgrid electrical analysis it is important to consider the cables that connect each load to another, and the cable that connects a load to the generator(s). First of all, the distances between the loads of the grid are calculated using this formula, considering the x and y coordinates:

$$\text{Distance XY (1,2)} = \sqrt{[(x1-x2)^2+(y1-y2)^2]}$$

Then the altitude difference (coordinate z) is calculated:

$$\text{Altitude Difference (1,2)} = \sqrt{[(z1-z2)^2}$$

And finally, the exact distance between two points is calculated as:

$$\text{Distance (1,2)} = \sqrt{[(\text{Distance XY,1-2})^2+(\text{Altitude Difference 1-2})^2]}$$

There is just one type of cable used in the preliminary analysis: it is an American Wire Gauge 7 Cable (AWG 7): it has a 10,50 mm² section, it is composed by aluminum and reinforced with steel, it has a Resistance per meter of 0,00271 Ω and it can support a maximum current of 89 A. This kind of cable is suitable for all the connection cables in the microgrids, since the preliminary analysis considered no reactive power in the loads, and so a power factor equal to 1.

American Wire Gauge (AWG) Cables		
AWG	**Section [mm²]**	**RESISTANCE [Ω / m]**
7	**10,50**	**0,00271**

It is easy to calculate the total resistance of each cable, that depends on its length and on cable resistance per meter. The resistance values for each cable are in the exhibit 1.

It is also important to consider the inductance of each cable, measured in Henry, that depends on cable diameter and on its length. The formula is:

CONDUCTOR INDUCTANCE = 0,2 * LN (Cable Length / r') [mH / Km]

where the cable length is measured in meters, and r' stands for:

$$r' = r * e^{-1/4} = r * 0{,}779 \ [m]$$

The induction value of each cable is calculated in mH / Km, so the next step is to calculate the induction value of each cable, that depends on cables length. In exhibit 1 there is the complete data regarding cable resistance and inductance of each microgrid.

2.3.2 Active and Reactive Power Values

There are important issues to consider regarding the power factor of the loads and of the generators: the power factor of an AC electric power system is defined as the ratio of the real power flowing to the load to the apparent power: real power is the capacity of the circuit for performing work in a particular time, while apparent power is the product of the current and voltage of the circuit. In an electric power system, a load with low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system, and require larger wires and other equipment.

GRECDH Team considered a power factor for all the equipment equal to 1, which is an ideal value, because power factor is always between 0 and 1. Considering an ideal power factor value, of course, simplifies the model itself, because it does not allow to consider reactive power of the equipment. The purpose of this paper is, however, to analyze the grids and simulate how they would work using a simulation software, "Simulink Matlab", that allows also to consider load and generators reactive powers. It is not possible calculate a power factor value for each load, because it depends on a series of factors as electronic devices efficiency. So, three different scenarios are considered to simulate the real features of the microgrids:

- Ideal Scenario: as in the optimization model, the loads power factor is 1
- Positive Scenario: considering a power factor of 0,90
- Negative Scenario: considering a power factor of 0,75

Reactive power can be easily calculated knowing the value of φ angle and of vectors V and I. The formulas for Reactive and Apparent Powers are:

Real Power	**P=V*I*cosφ**	**[W]**
Reactive Power	**Q=V*I*sinφ**	**[VAR]**
Apparent Power	**A=V*I**	**[VA]**

Considering the first case, in which power factor is equal to 1, there is no reactive power to consider for the loads: here are the results for the low and for the high demand cases:

LOW DEMAND CASE

COS (φ)	φ	LOAD	P [W]	A=V*I	SIN (φ)	Q [VAR]
1	0	HOUSE	200	200	0	0,00
1	0	SCHOOL	600	600	0	0,00
1	0	HEALTH CENTRE	600	600	0	0,00

Figure 2.7: Ideal Scenario: Active and Reactive Power Values in the Low Demand Scenario

HIGH DEMAND CASE

COS (φ)	φ	LOAD	P [W]	A=V*I	SIN (φ)	Q [VAR]
1	0	HOUSE	400	400	0	0,00
1	0	SCHOOL	1200	1200	0	0,00
1	0	HEALTH CENTRE	1200	1200	0	0,00

Figure 2.8: Ideal Scenario: Active and Reactive Power Values in the High Demand Scenario

Considering the Positive scenario, the power factor is 0,90; so an amount of reactive power is considered; moreover, the apparent power is 222,22 VA for 200 W loads, and 666,67 VA for 600 W loads. These can be considered as Positive results, as the difference between apparent and real power is not so high.

LOW DEMAND CASE

COS (φ)	φ	LOAD	P [W]	A=V*I	SIN (φ)	Q [VAR]
0,9	25,84	HOUSE	200	222,22	0,44	96,86
0,9	25,84	SCHOOL	600	666,67	0,44	290,59
0,9	25,84	HEALTH CENTRE	600	666,67	0,44	290,59

Figure 2.9: Positive Scenario: Active and Reactive Power Values in the Low Demand Scenario

In high demand case, the observations to do are the same:

HIGH DEMAND CASE

COS (φ)	φ	LOAD	P [W]	A=V*I	SIN (φ)	Q [VAR]
0,9	25,84	HOUSE	400	444,44	0,44	193,73
0,9	25,84	SCHOOL	1200	1333,33	0,44	581,19
0,9	25,84	HEALTH CENTRE	1200	1333,33	0,44	581,19

Figure 2.10: Positive Scenario: Active and Reactive Power Values in the High Demand Scenario

Finally, the third scenario considers a low loads efficiency, since DVD, radio and TV devices used in houses might provoke a decrease of factor power, considered equal to 0,75 in the simulation: the reactive power for the houses is 176,38 VAR, almost the double than the previous case; for the other loads it is 529,15 VAR, that's a significant value, very close to the real power, that is 600 W. Notice that the apparent power is in this case pretty high, 800 VA for 600 W loads for instance.

LOW DEMAND CASE

COS (φ)	φ	LOAD	P [W]	A=V*I	SIN (φ)	Q [VAR]
0,75	41,41	HOUSE	200	266,67	0,66	176,38
0,75	41,41	SCHOOL	600	800	0,66	529,15
0,75	41,41	HEALTH CENTRE	600	800	0,66	529,15

Figure 2.11: Negative Scenario: Active and Reactive Power Values in the Low Demand Scenario

Regarding the high demand case, the results obtained are even more significant, as reactive power reaches 352,77 and 1058,30 VAR for the loads considered. The apparent power is 1600 VA for 1200 W loads, and 533,33 VA for 400 W loads. These high values might affect the stability of the microgrids, especially for the biggest ones, in terms of voltage drops. These results will be discussed in next paragraphs.

HIGH DEMAND CASE

COS (φ)	φ	LOAD	P [W]	A=V*I	SIN (φ)	Q [VAR]
0,75	41,41	HOUSE	400	533,33	0,66	352,77
0,75	41,41	SCHOOL	1200	1600	0,66	1058,30
0,75	41,41	HEALTH CENTRE	1200	1600	0,66	1058,30

Figure 2.12: Negative Scenario: Active and Reactive Power Values in the High Demand Scenario

2.3.3 Simulation in Simulink-Matlab environment

Simulink-Matlab is a software that allows to build an electrical circuit and to simulate its behavior in a given period of time, in the commented simulation 10 seconds; it is possible to calculate several electrical measurements, as current and voltage values in each branch (considered as vectors with complex numbers), voltage drops, real and reactive power at each load. In the circuit there is just one battery, considered in most cases as an ideal current generator, standing for the battery bank required by the microgrid; by doing this, the circuit is simpler but maintains the electrical features the optimization model gave out. The electrical generator, wind or photovoltaic, is in most cases considered as an ideal voltage generator, providing 230 V at 60 Hz frequency; the hypothesis concerning the frequency is justified by the fact in Peru the electrical frequency for the national Voltage Network is 60 Hz, although the grids considered in this paper are, as commented before, isolated from the voltage network. The voltage was considered in the optimization model equal to 230, and each load must have a voltage between 210 and 230 V, considering a 8,70% maximum voltage drop.

The analysis main steps are:

- Calculate the Battery Current
- Running the 10 seconds simulation
- Gathering power and voltage drop values
- Analysis of data

<u>Calculate the Battery Current</u>

The first step of the simulation is to calculate the battery current, when it is modeled as an ideal current generator, because this is an input parameter to give in the battery block: the shown equations system is written in Matlab language, and it can be solved by using the "fsolve" function, that solves systems of nonlinear equations of several variables.

After that, the software returns the current and voltage values of each branch, and the most important value is the battery current (Ib), while the other values will be compared later to the Simulink results, as they can be considered as reference values.

```
function F=sistema_63eb(x)


vb=230;                     % Battery Voltage [V]
n27r=200;
n27i=96.86;
n27=complex(n27r,n27i);     % Load  27 Power [Watt]

n28=n27;
ng=2000;                    % Generator power [Watt]
n4=n27;
n24=n27;
n34=n27;
n1r=600;
n1i=290.59;
n1=complex(n1r,n1i);

n35=n1;
n8=n27;

n17=n27;
n30=n27;
n10=n27;

za=0.148828;                % Impedence value [Ohm]
zb=0.564422;
zc=0.4197;
zd=0.15466;
ze=0.138873;
zf=0.263999;
zg=0.171781;
zh=0.190588;
zi=0.157273;
zl=0.718473;
```

```
F=[

x(18)-x(19)-x(20)
x(19)-vb+x(39)
vb-x(21)
x(21)-x(22)
x(22)-x(23)-x(24)
x(23)-x(25)+x(26)
x(19)-x(27)-x(28)
x(27)-x(29)-x(30)
x(29)-x(31)+x(32)
x(29)-x(33)-x(34)
x(33)-x(35)+x(36)
x(29)-x(37)+x(38)

x(40)+x(2)+x(1)
x(8)+x(6)+x(7)
x(5)-x(8)-x(4)-x(3)-x(40)

x(10)+x(9)-x(13)
x(13)+x(11)+x(12)-x(14)+x(17)
x(14)+x(15)+x(16)

n27-x(18)*conj(x(1))
n28-x(19)*conj(x(2))
ng-x(21)*conj(x(4))
n4-x(22)*conj(x(5))
n24-x(23)*conj(x(6))
n34-x(25)*conj(x(7))
n1-x(27)*conj(x(10))

n35-x(29)*conj(x(11))
n8-x(31)*conj(x(12))
n17-x(33)*conj(x(15))
n30-x(35)*conj(x(16))
n10-x(37)*conj(x(17))

x(20)+za*x(1)
x(24)+zb*x(8)
x(26)+zc*x(7)
x(28)+zd*x(9)
x(30)+ze*x(13)
x(32)+zf*x(12)
x(34)+zg*x(14)
x(36)+zh*x(16)
x(38)+zi*x(17)
x(39)+zl*x(40)  ];
```

Figure 2.13: Microgrid Equations System written in Matlab environment

<u>Running the 10 seconds simulation</u>

The electrical grid can be now modeled in Simulink environment: the battery block generates a current equal to Ib, the voltage generator 230 V at 60 Hz, the loads have real and reactive power values and each branch has its own resistance and inductance as calculated before. Notice that in some cases the battery is modeled as an ideal voltage source (230 V at 60 Hz), while the generator as an ideal current source.

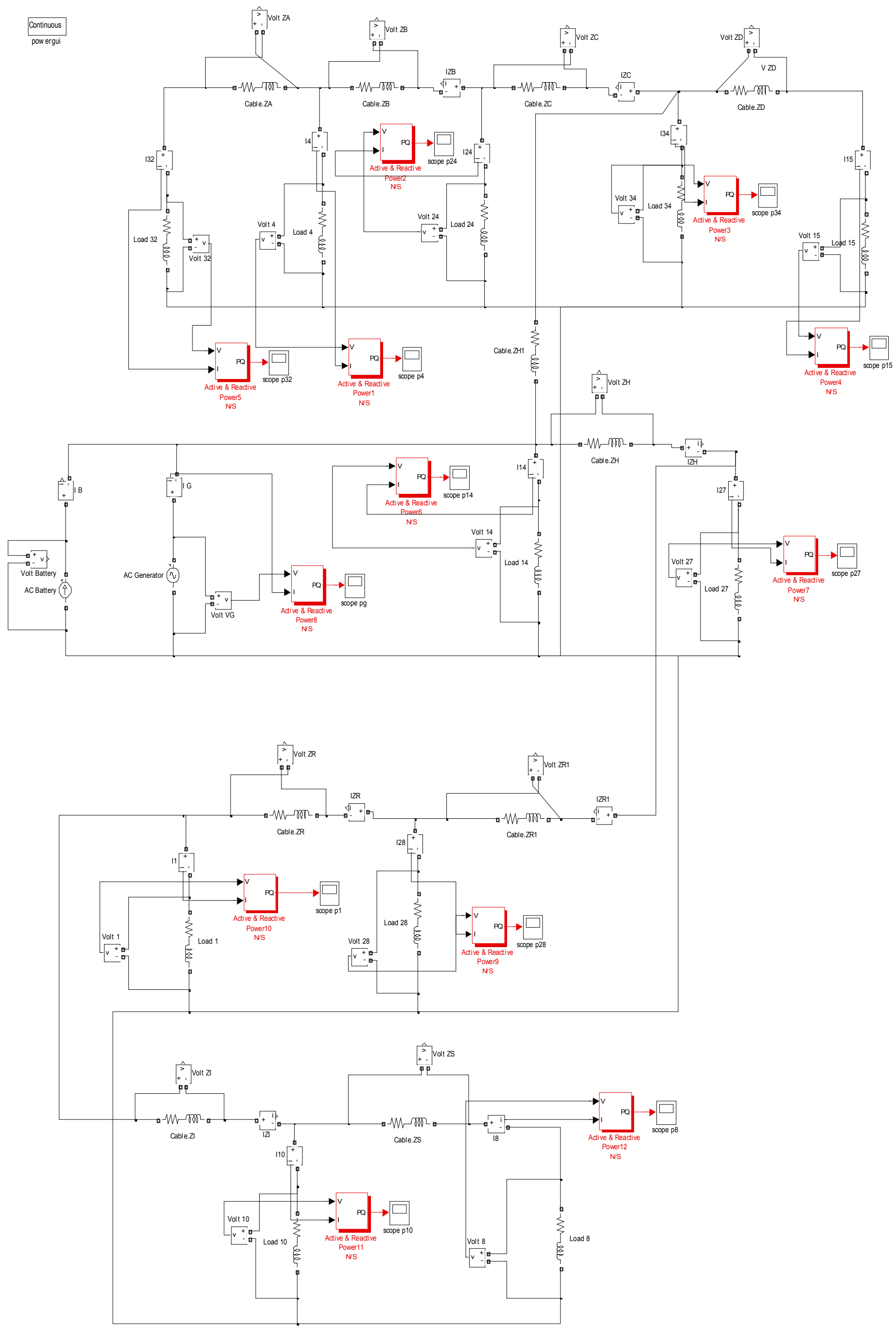


Figure 2.14: Microgrid scheme in Matlab-Simulink environment

Gathering power and voltage drop values

The 10 seconds simulation allows to study the circuit behaviour, and thanks to the ideal voltage and current measurements it is possible to know voltage and current values, and to analyze their time evolution in the scopes. In the Positive and Negative cases, so when loads have also reactive power, it is possible to also put Power Measurement Blocks, that measure the real and reactive power delivered to the loads, that do not always reach the amount of power initially put in the load blocks; notice that this is verified since Simulink allows to simulate circuit behaviours considering constant impedance (a branch voltage drop do not provoke a branch current increase), while the complex equation system Matlab can solve using “fsolve” considers an electrical circuit in which power is constant (a branch voltage drop provokes a current increase in the branch itself). In the ideal case it is not possible to use the Power Measurement Blocks because it would generate a high increase of the model complexity, and the software would have taken too much time to solve the system (up to 160 hours); for those microgrids, the power values are calculated thanks to simple Matlab equation systems, that return the real and reactive powers values expressed in complex numbers, taking into account the relation between Real Power, Voltage and Current:

$$\mathbf{P = V\ I^*}$$

Here are the currents and voltages arrays modelled in Matlab: the Power values are calculated using the previous formula.

```
Conv=57,2957795131;                          % converts grade into radiant


mi=[ 8,698 , 1,649 ,  1,649 ,1,68 ,1,638 , 1,659 , 1,664,  1,669,   1,739,  1,652, 1,651 , 4,936, 12,9 ];
fii=[-4,32, -2,00, -2, -1,32, -2,27, -1,8,  -1,66,  -1,58,0,  -1,93, -1,95, -2,07, 0];

mv=[230; 218,1 ;218,1  ;  222,1;   216,6  ;219,3 ; 220 ;220,7  ;230 ;218,5 ; 218,4;  217,6; 230];
fiv=[ 0; -2 ; -2;  -1,32; -2,27 ;  -1,80;  -1,66;  -1,58; 0; -1,93;     -1,95;     -2,07;   0];


I = mi,*exp(i*(fii/conv))
V = mv,*exp(i*(fiv/conv))
Iconj = conj(I)

for T=1:size(mv,1)

P = Iconj(T)*V(T)

end
```

Figure 2.15: Microgrid's current and voltage arrays written in Matlab environment

The voltage drops are calculated at each node, that is at each load connected to the microgrid. A voltage drop is considered acceptable if is lower than 8,70%, that means the voltage is 210 V. If voltage drop is higher than 8% is considered as "Close to limit", if it is higher than the 8,70% threshold is labeled as "Too high". An example is reported below (main grid in Hybrid Generation System, Low Demand, El Alumbre):

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	229,14	230	0,86	0,37	---
27	215,12	230	14,88	6,47	---
28	213,14	230	16,86	7,33	---
1	**211,23**	**230**	**18,77**	**8,16**	**CLOSE TO LIMIT**
35	**210,03**	**230**	**19,97**	**8,68**	**CLOSE TO LIMIT**
8	**209,71**	**230**	**20,29**	**8,82**	**TOO HIGH**
10	**209,84**	**230**	**20,16**	**8,77**	**TOO HIGH**
17	**209,62**	**230**	**20,38**	**8,86**	**TOO HIGH**
30	**209,37**	**230**	**20,63**	**8,97**	**TOO HIGH**

Figure 2.16: Voltage drops for the main grid in El Alumbre (Hybrid Generation System, Low Demand Case, Negative Scenario)

The results will be analyzed and commented in the next paragraphs for each community.

2.4 Alto Peru: microgrids preliminary analysis description

Here are the results regarding the microgrids GRECDH Team found during the Alto Peru preliminary analysis: a solution concerning just Wind Generation is described first, then the Hybrid solution concerning both wind and solar energy follows; both are considered of course in the Low Demand and in the High Demand Scenarios.

<u>Wind Energy - Low Demand Case:</u>

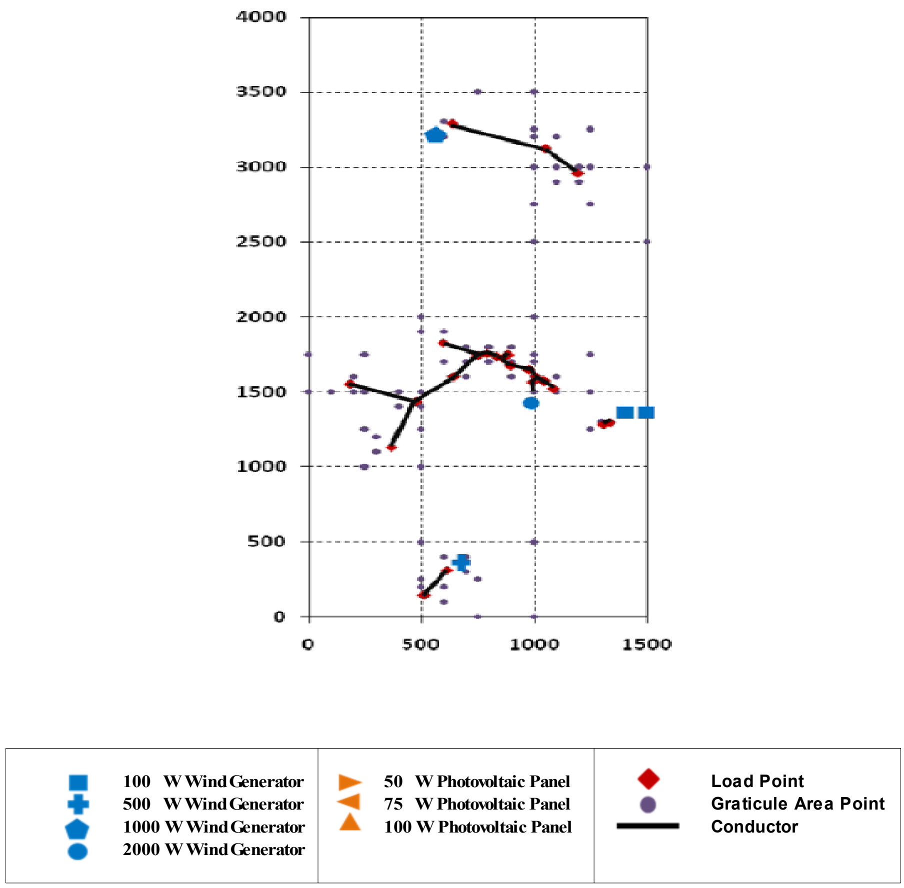


Figure 2.17: Low demand, wind generation – Alto Peru

The software suggests to build four different micro grids in the area (1,5 km x 4 km): the four microgrid schemes follow: numbers identify the loads, and they refer to Exhibit 1, in which coordinates (x;y) are expressed in meters.

First Grid:

The first grid connects 3 loads, and has a 1000 W wind generator, two batteries (B1 and B4), two I1 inverters and a R3 regulator.

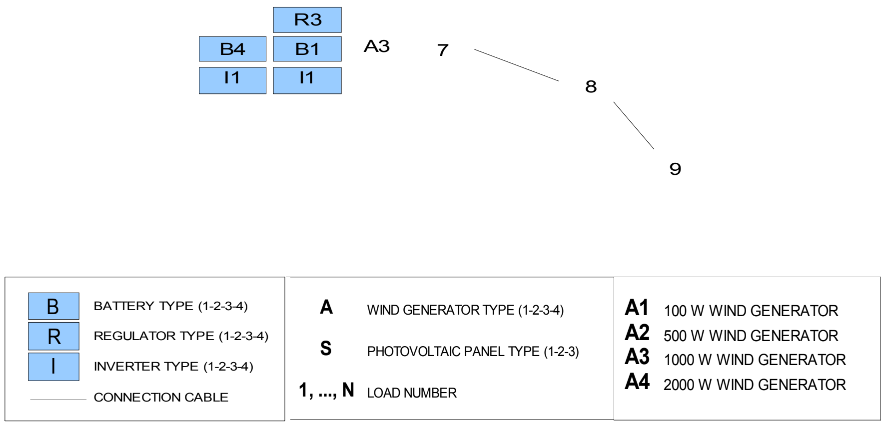


Figure 2.18: First Grid Scheme - Low demand, wind generation – Alto Peru

This is the electrical scheme of the mentioned microgrid:

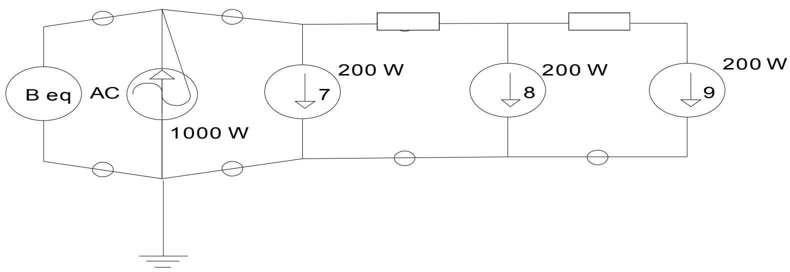


Figure 2.19: First Grid electrical scheme - Low demand, wind generation – Alto Peru

Second Grid:

The second one is the biggest, placed in the center of the area, supplying 17 house loads with a 2000 W wind Generator (indicated as A4 in the figure); 9 batteries are required to store energy (8 type B4 and 1 type B2), and a regulator (R4) and two inverters (I3) are required by the wind generator to produce energy at the given system frequency. The Generator is placed in point 73, and it is connected to the first load of the microgrid by a connection cable.

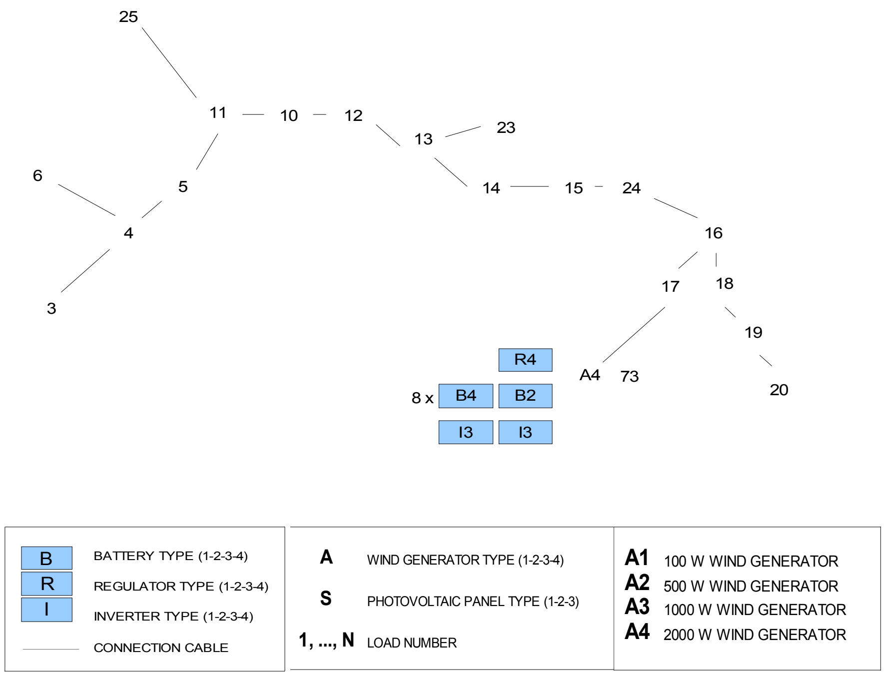


Figure 2.20: Second Grid Scheme - Low demand, wind generation – Alto Peru

Here is the electrical scheme for the considered grid (each load has 200 W of electrical power):

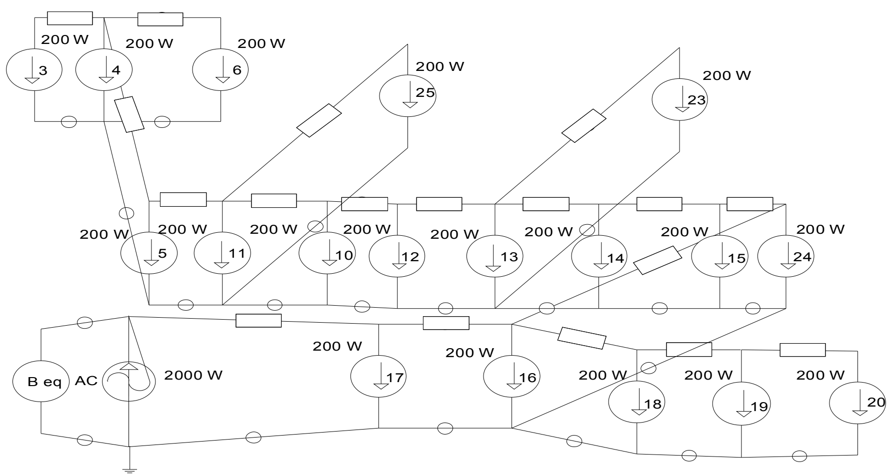


Figure 2.21: Second Grid electrical scheme - Low demand, wind generation – Alto Peru

Third grid:

The third grid connects 2 loads, that are at a distance of just 32 meters, supplied by two 100 W wind generators, and employs one battery, two inverters and one regulator.

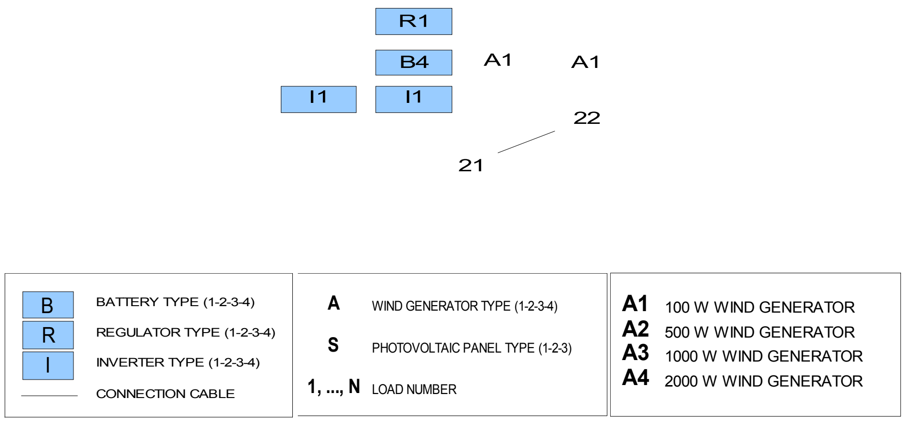


Figure 2.22: Third Grid Scheme - Low demand, wind generation – Alto Peru

Here is the electrical scheme of the mentioned microgrid:

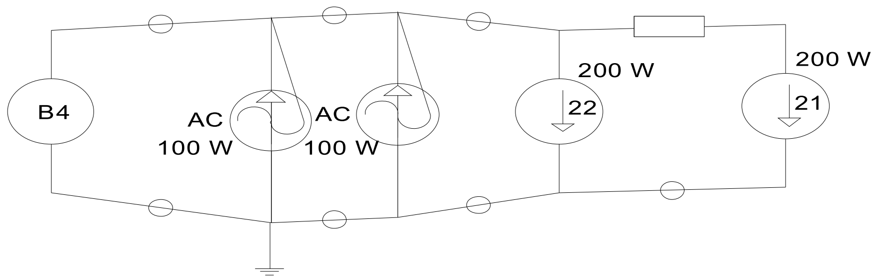


Figure 2.23: Third Grid electrical scheme - Low demand, wind generation – Alto Peru

Fourth grid:

Finally, the fourth grid connects 3 loads with a cable (about 200 meters length): a 500 W wind generator is required for supply the energy, and 2 batteries, 2 inverters and one regulator are also required.

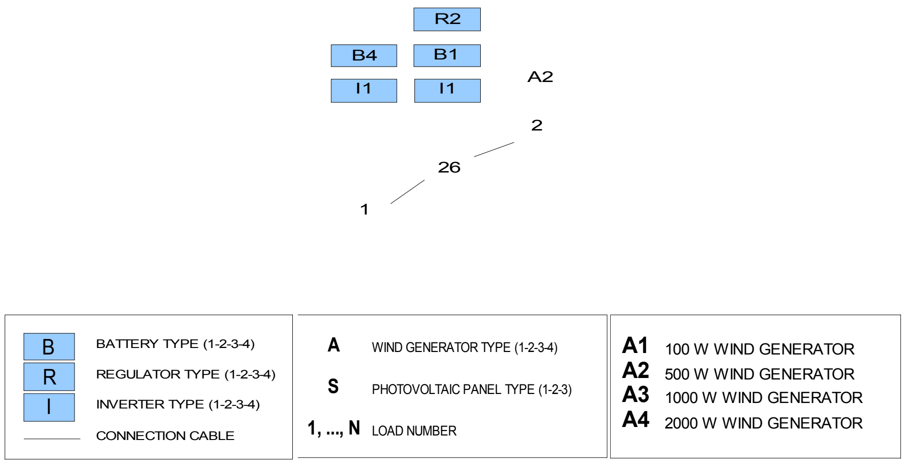


Figure 2.24: Fourth Grid Scheme - Low demand, wind generation – Alto Peru

Here is the electrical scheme for the fourth grid:

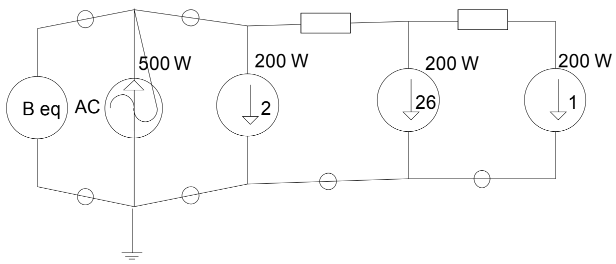


Figure 2.25: Fourth Grid electrical scheme - Low demand, wind generation – Alto Peru

Hybrid Generation System - Low Demand Case:

The second solution to supply all the loads in a low energy demand scenario in Alto Peru is a hybrid energy generation system: this solution employs both wind and photovoltaic generators, with just one grid in the central part of the area, that supplies 16 house loads using a 2000 W wind generator. Furthermore, 11 individual 100 W photovoltaic generators are required, placed next to individual loads, without any connection cables nor grid infrastructure.

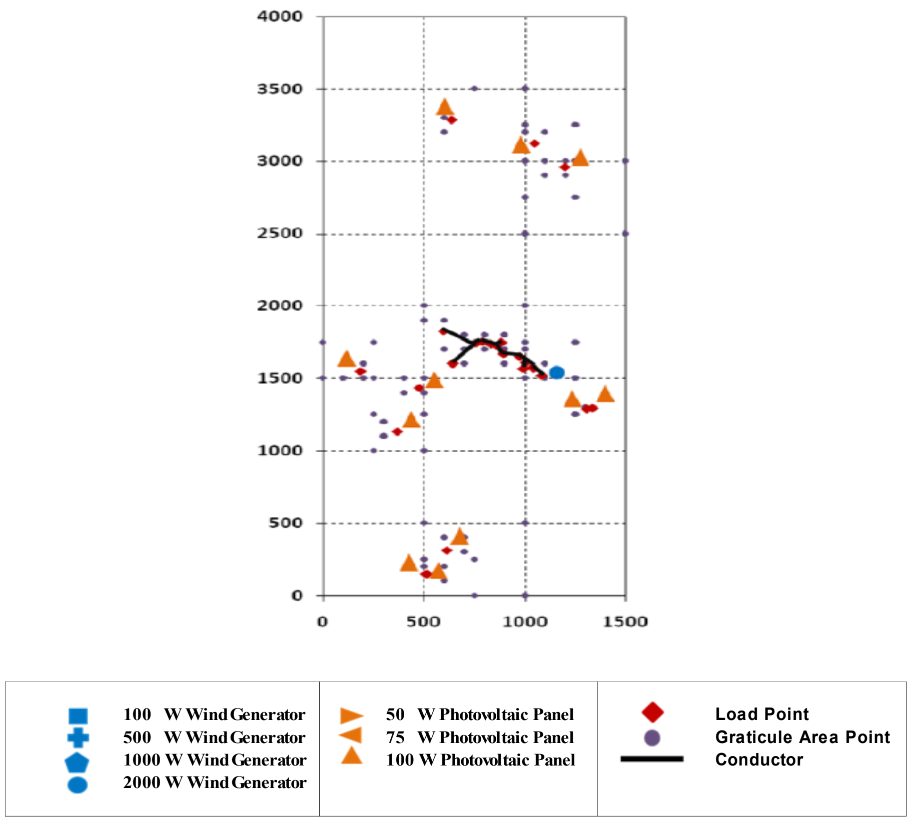


Figure 2.26: Low demand, hybrid generation – Alto Peru

Main grid:

Here is the main grid scheme, with 8 batteries next to the 2000 W generator, 1 regulator and 1 inverter:

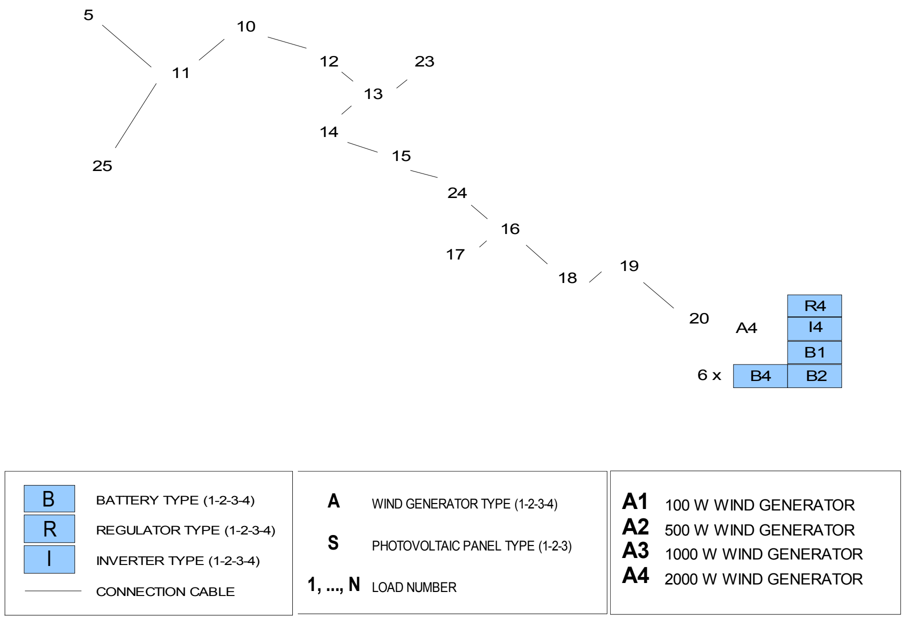


Figure 2.27: Main Grid scheme - Low demand, hybrid generation – Alto Peru

Here is the electrical scheme of the microgrid: B eq is considered as the equivalent battery of the 8 employed batteries.

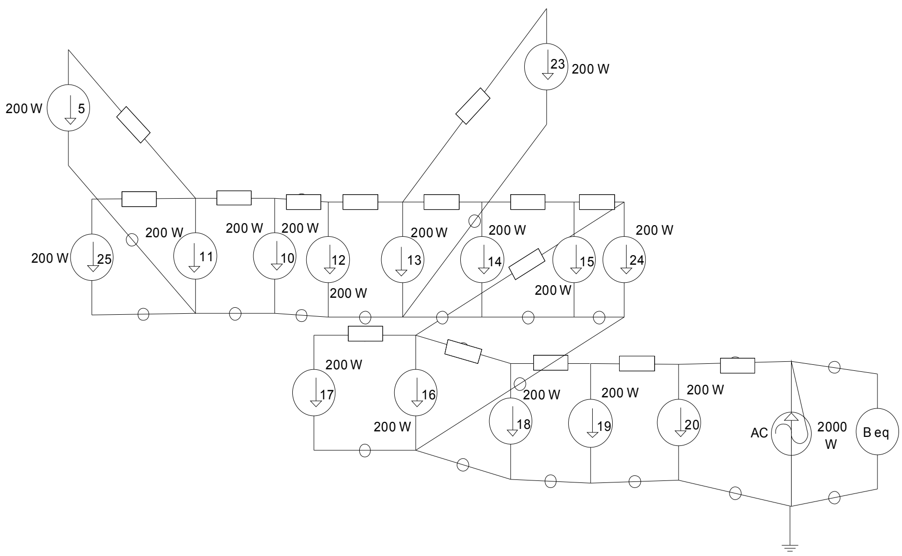


Figure 2.28: Main Grid electrical scheme - Low demand, hybrid generation – Alto Peru

Individual grid:

The eleven photovoltaic panels have a 100 W electrical power, and their architecture is very simple, since they do not need a cable.

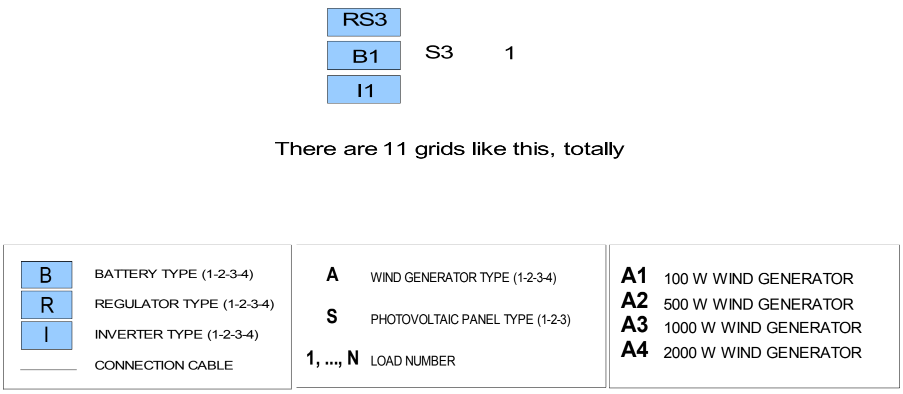


Figure 2.29: Individual Grid scheme - Low demand, hybrid generation – Alto Peru

Here is the electrical scheme for the individual grid:

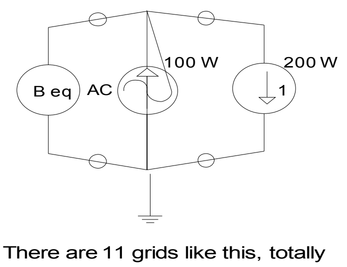


Figure 2.30: Individual Grid electrical scheme - Low demand, hybrid generation – Alto Peru

Wind Generation System - High Demand Case:

Concerning a future energy demand growth (high demand scenario), the first solution to comment upon regards the Wind Generation System, in which just wind generators are used to supply the required demand. There are four microgrids in total.

First Grid:

The first grid to be considered connects three loads, and employs a 2000 W wind generator (A4), a R4 regulator and a I2 inverter; three batteries are also employed to store energy.

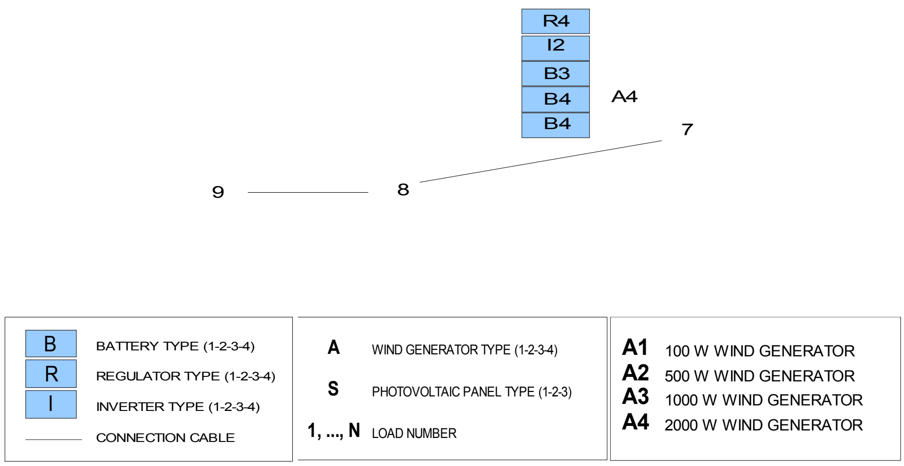


Figure 2.31: First Grid scheme - High demand, Wind generation – Alto Peru

Here is the grid scheme, in which the batteries are identified by B eq block, and the cables have their equivalent impedance.

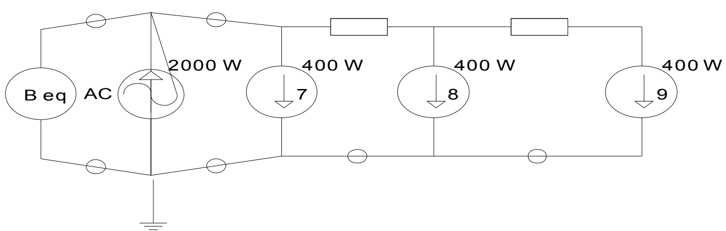


Figure 2.32: First Grid electrical scheme - High demand, Wind generation – Alto Peru

Second Grid:

The second grid is similar to the first one, as it connects three loads, but it employs a 1000 W wind generator. Three batteries are connected to store energy:

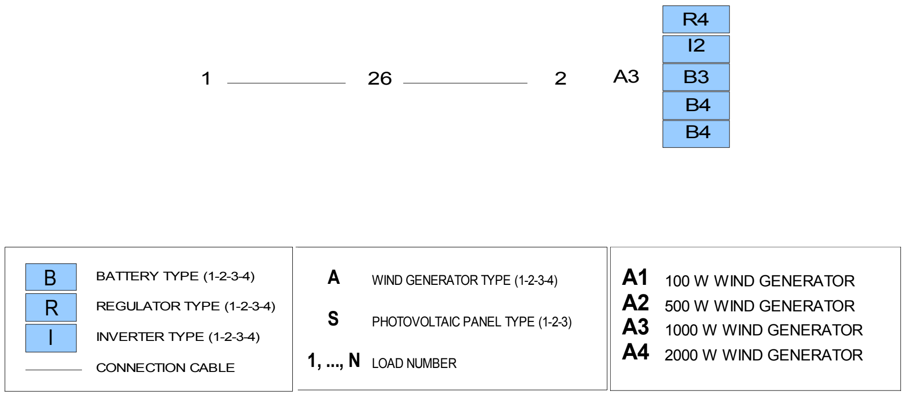


Figure 2.33: Second Grid scheme - High demand, Wind generation – Alto Peru

The electrical scheme is similar to the first one, but the generator has a lower power, 1000 W.

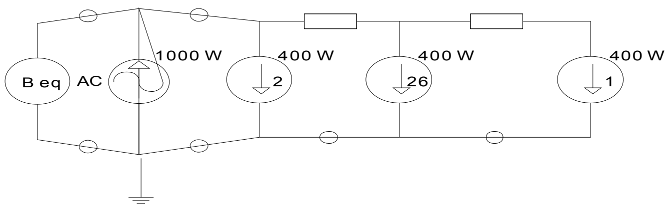


Figure 2.34: Second Grid electrical scheme - High demand, Wind generation – Alto Peru

Third Grid:

The third grid connects 15 loads, it is the largest in this grid group, and it employs two 2000 W wind generators, both placed next to load 20; the battery bank is very big, as it deploys 15 batteries. Two R4 regulators and two I4 inverters complete the grid architecture:

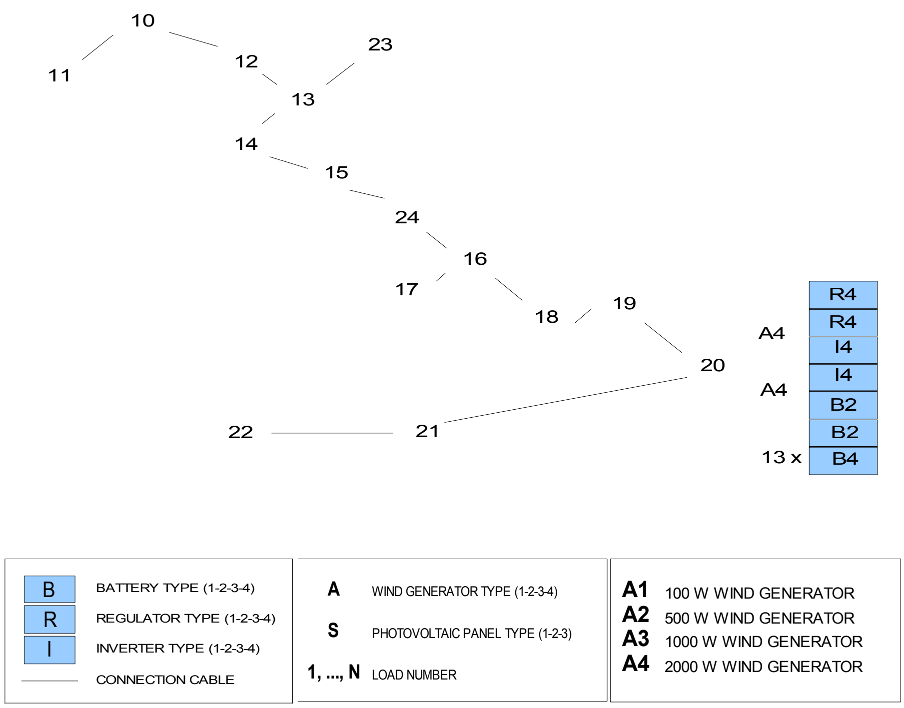


Figure 2.35: Third Grid scheme - High demand, Wind generation – Alto Peru

Here is the electrical scheme: notice that the generators are placed next to load 20, because this is the point has the highest wind resource, but they result quite far from the majority of the loads connected to the grid. The considerations about the possible improvements connected to a different generators' placing are discussed in the next chapter.

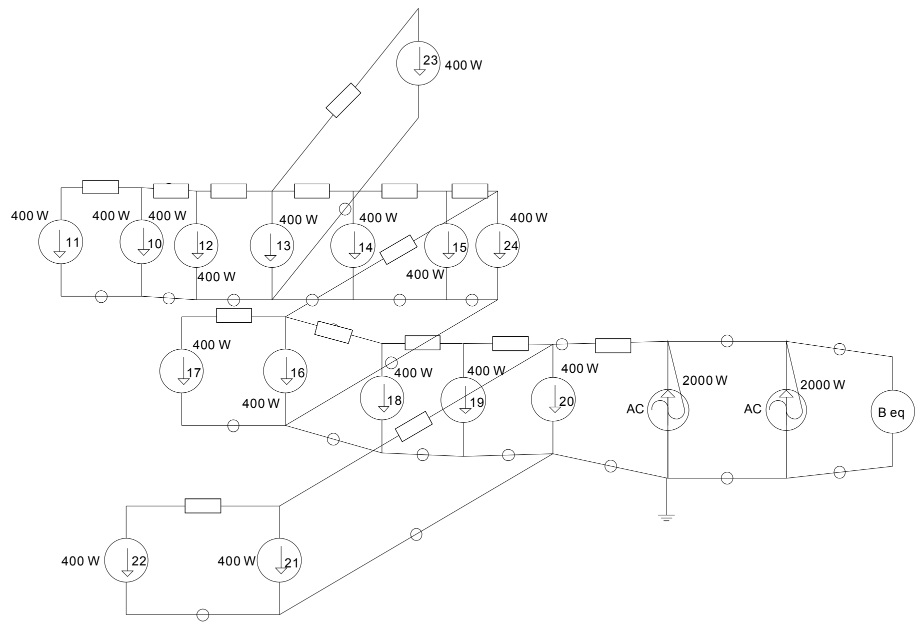


Figure 2.36: Third Grid electrical scheme - High demand, Wind generation – Alto Peru

Fourth Grid:

The last grid connects 5 loads, employs a 2000 W wind generator, one inverter, one regulator and 4 batteries to store energy.

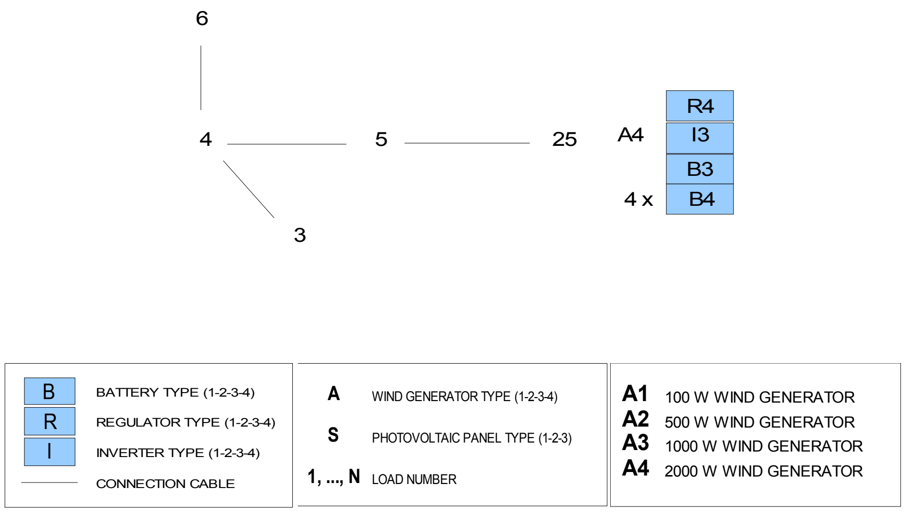


Figure 2.37: Fourth Grid scheme - High demand, Wind generation – Alto Peru

Here is the fourth grid electrical scheme:

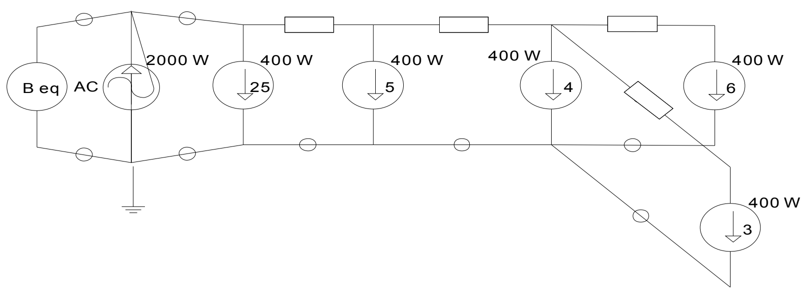


Figure 2.38: Fourth Grid electrical scheme - High demand, Wind generation – Alto Peru

Hybrid Generation System - High Demand Case:

Finally, here is the Hybrid Generation System for a High Demand Scenario (the loads have 400 W of electrical power and require 560 Wh/day). There are two micrograms, that employ two 2000 W Wind Generators and one 1000 W Wind Generator. To supply the remainder loads, the Optimization Software suggests to employ ten 100 W photovoltaic panels.

Here is the area map:

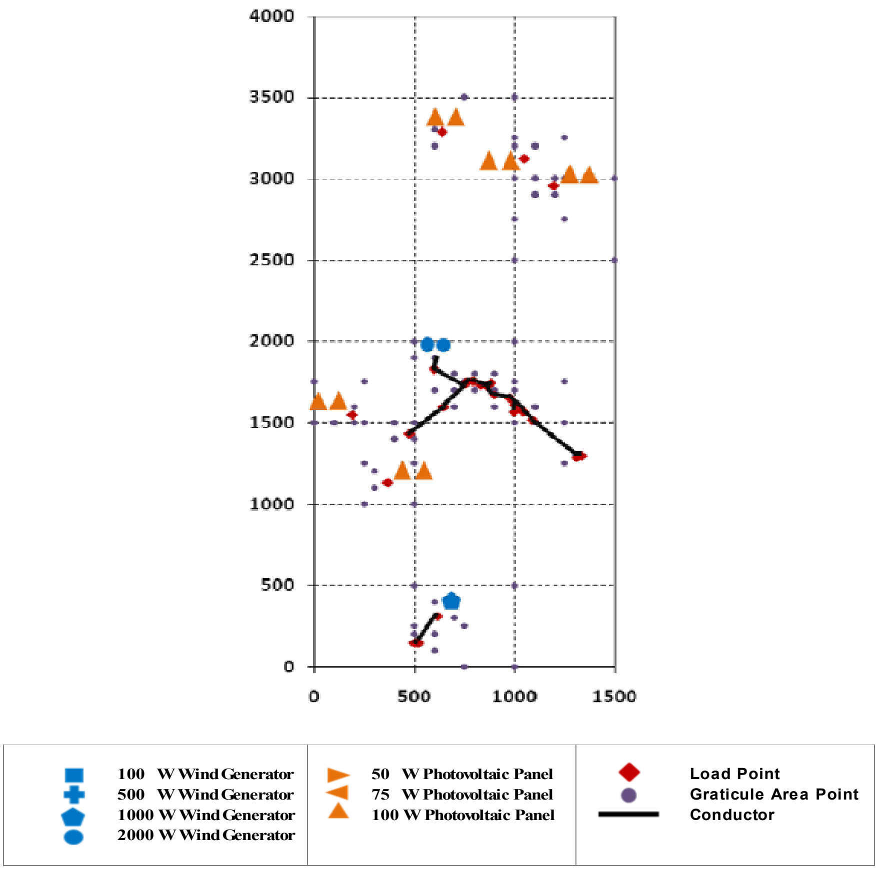


Figure 2.39: High demand, hybrid generation – Alto Peru

First Grid:

Here is the first grid scheme: two 2000 W wind generators are employed, 15 batteries are required to store energy and two inverters and two regulators complete the grid required equipment.

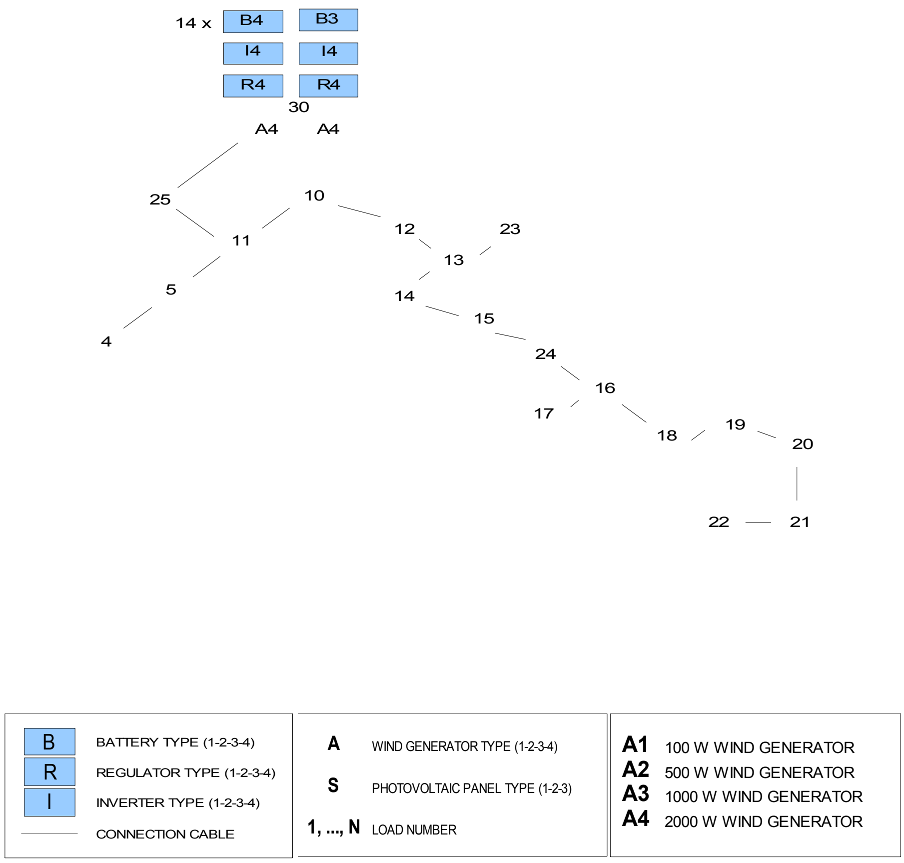


Figure 2.40: First grid scheme, high demand, hybrid generation – Alto Peru

Here is the first grid electrical scheme: B eq is considered as the equivalent battery

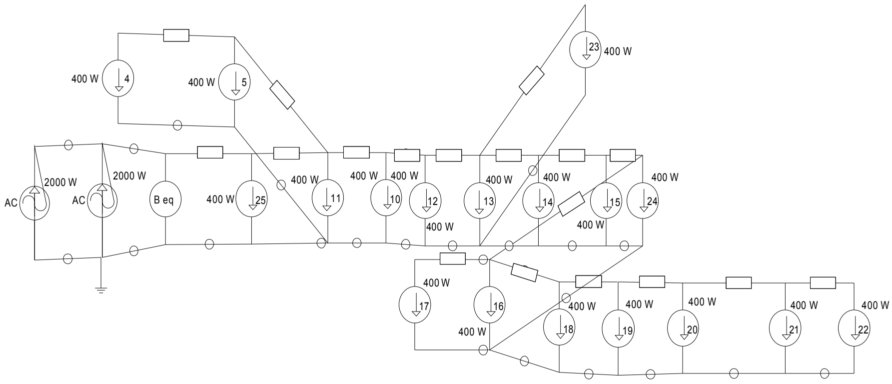


Figure 2.41: First grid electrical scheme, high demand, hybrid generation – Alto Peru

Second Grid:

This is the second grid scheme: just one 1000 W wind generator is employed to feed 3 loads: moreover, there are 9 batteries, two inverters and one regulator.

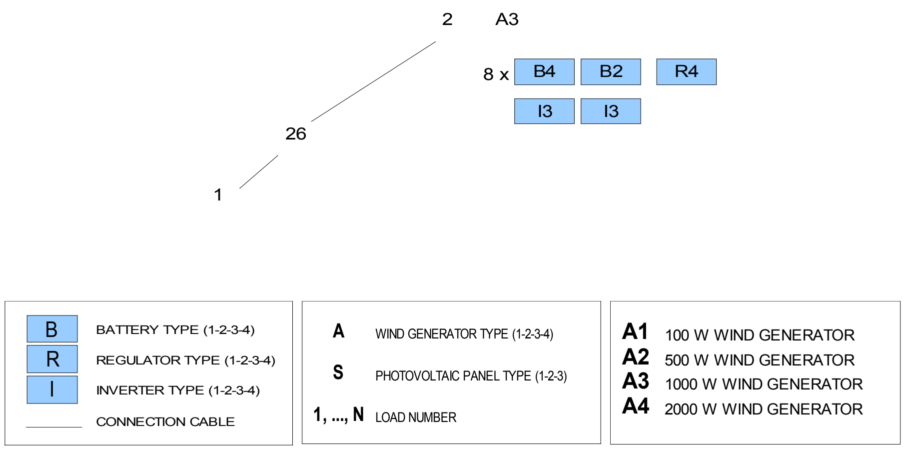


Figure 2.42: Second grid scheme, high demand, hybrid generation – Alto Peru

Here is the electrical scheme of the mentioned grid:

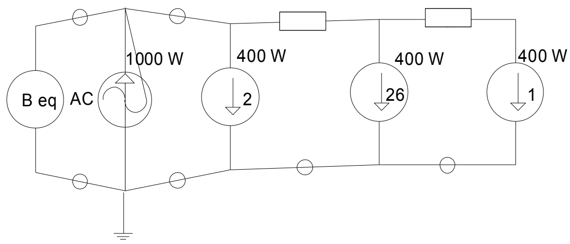


Figure 2.43: Second grid electrical scheme, high demand, hybrid generation – Alto Peru

<u>Individual Grid:</u>

As mentioned before, also ten photovoltaic panels are employed to feed 5 loads: as shown below, two 100 W panels are connected directly to the house, without any cable infrastructure. The battery bank is formed by two B4 batteries.

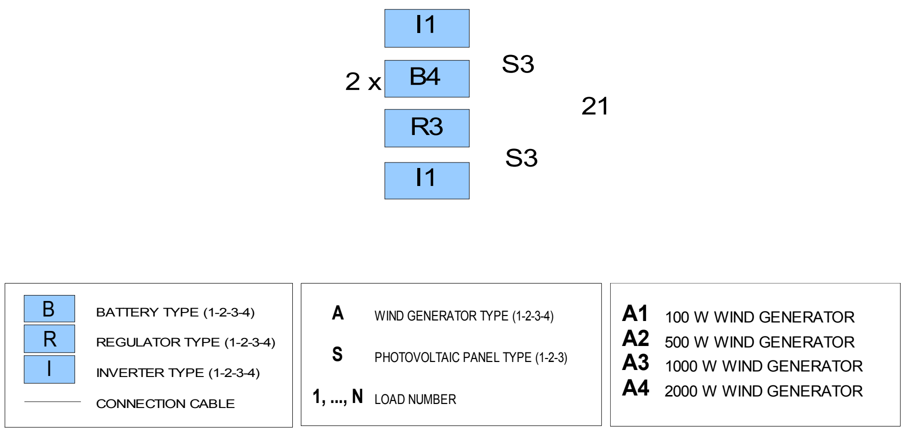


Figure 2.44: Individual grid scheme, high demand, hybrid generation – Alto Peru

This is the electrical scheme for the five described individual grids: the loads have an electrical power of 400 W.

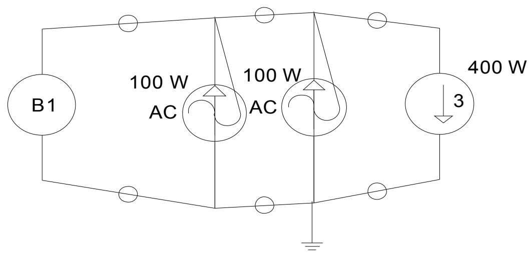


Figure 2.45: Individual grid electrical scheme, high demand, hybrid generation – Alto Peru

2.4.1 Alto Peru: Voltage Drops Analysis

In this paragraph the cable analysis for each microgrid mentioned before is described: it considers the voltage drops measured for the loads in the 10 seconds simulation run in Simulink-Matlab Environment. Expecting a voltage value between 210 and 230 V, as GRECDH Team supposed in the preliminary phase of the project, the voltage drops have to be lower than 8,70%. it is interesting notice how this restriction is always respected in the ideal scenario modeled by GRECDH - UPC Team (cos φ=1, no reactive power in the loads), while in the Positive (cos φ=0,90) and Negative (cos φ=0,75) scenarios this is not always verified. The proposed solutions to solve the problems connected to voltage drops are collected in Chapter 3.

Wind Energy System - Low Demand Case:

There are four microgrids to analyze in this case:

1 Grid:

The first grid doesn't show any problem connected to excessive voltage drops, since it is a small grid that connects just three loads. The three reactive power scenarios are described below:

1 Grid: Ideal Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
7	230,00	230	0,00	0,00	---
8	227,90	230	2,10	0,91	---
9	227,40	230	2,60	1,13	---

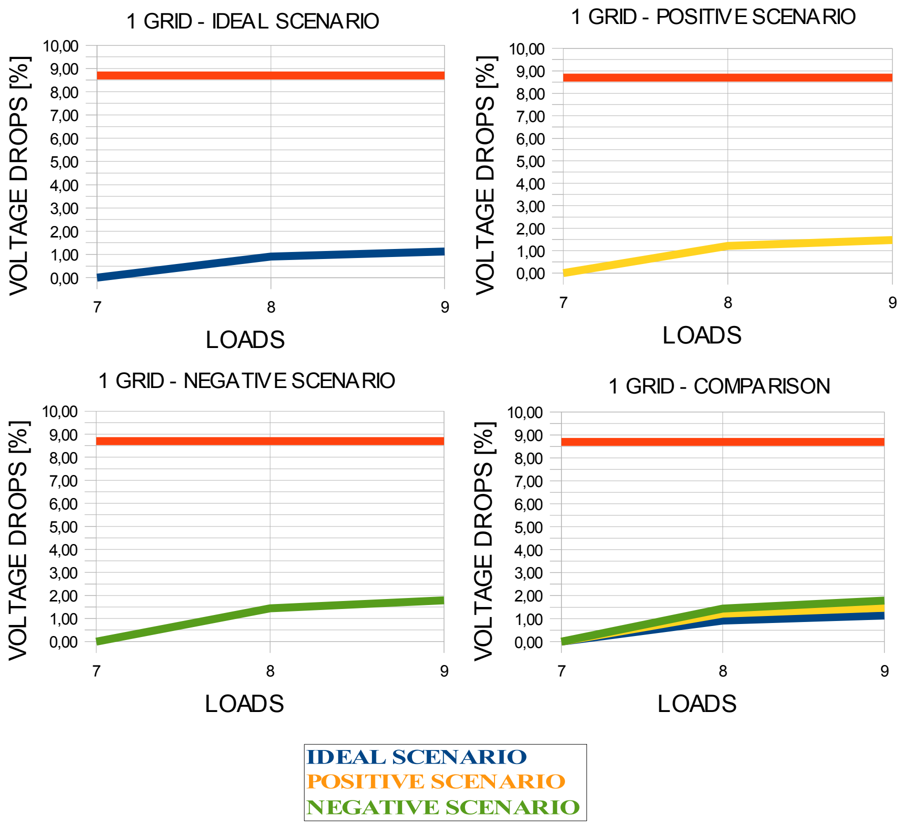
1 Grid: Positive Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
7	230,00	230	0,00	0,00	---
8	227,20	230	2,80	1,22	---
9	226,60	230	3,40	1,48	---

1 Grid: Negative Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
7	230,00	230	0,00	0,00	---
8	226,70	230	3,30	1,43	---
9	225,90	230	4,10	1,78	---

The three scenario are compared below: grid performance is satisfactory.



2 Grid:

The second grid is bigger than the previous one (it connects 18 loads), and only in the ideal scenario are the results satisfactory.

2 Grid: Ideal Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	226,96	230	3,04	1,32	—
16	225,10	230	4,90	2,13	—
18	224,79	230	5,21	2,27	—
19	224,73	230	5,27	2,29	—
20	224,58	230	5,42	2,36	—
24	223,46	230	6,54	2,84	—
15	223,33	230	6,67	2,90	—
14	220,93	230	9,07	3,94	—
13	219,21	230	10,79	4,69	—
23	219,01	230	10,99	4,78	—
12	218,67	230	11,33	4,93	—
10	217,98	230	12,02	5,23	—
11	217,43	230	12,57	5,47	—
25	217,03	230	12,97	5,64	—
5	215,82	230	14,18	6,17	—
4	214,21	230	15,79	6,87	—
6	213,54	230	16,46	7,16	—
3	213,51	230	16,49	7,17	—

2 Grid: Positive Scenario

Considering a power factor of 0,90, two loads have unacceptable voltage drop values:

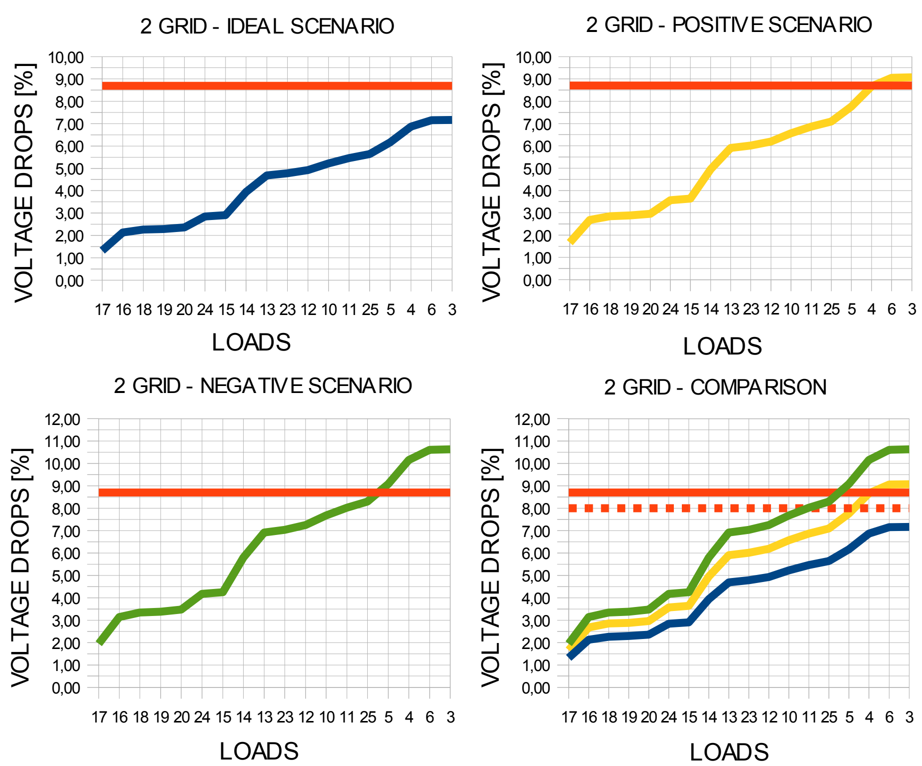
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	226,17	230	3,83	1,67	—
16	223,84	230	6,16	2,68	—
18	223,45	230	6,55	2,85	—
19	223,38	230	6,62	2,88	—
20	223,19	230	6,81	2,96	—
24	221,80	230	8,20	3,57	—
15	221,64	230	8,36	3,63	—
14	218,60	230	11,40	4,96	—
13	216,43	230	13,57	5,90	—
23	216,18	230	13,82	6,01	—
12	215,76	230	14,24	6,19	—
10	214,89	230	15,11	6,57	—
11	214,21	230	15,79	6,87	—
25	213,69	230	16,31	7,09	—
5	212,14	230	17,86	7,77	—
4	210,06	230	19,94	8,67	CLOSE TO LIMIT
6	209,17	230	20,83	9,06	TOO HIGH
3	209,14	230	20,86	9,07	TOO HIGH

2 Grid: Negative Scenario

When the amount of reactive power is higher, 4 loads are labeled as “Too high” and moreover two are “Close to limit”.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	225,51	230	4,49	1,95	---
16	222,78	230	7,22	3,14	---
18	222,32	230	7,68	3,34	---
19	222,24	230	7,76	3,37	---
20	222,02	230	7,98	3,47	---
24	220,39	230	9,61	4,18	---
15	220,22	230	9,78	4,25	---
14	216,66	230	13,34	5,80	---
13	214,11	230	15,89	6,91	---
23	213,82	230	16,18	7,03	---
12	213,34	230	16,66	7,24	---
10	212,33	230	17,67	7,68	---
11	211,54	230	18,46	8,03	CLOSE TO LIMIT
25	210,92	230	19,08	8,30	CLOSE TO LIMIT
5	209,10	230	20,90	9,09	TOO HIGH
4	206,64	230	23,36	10,16	TOO HIGH
6	205,59	230	24,41	10,61	TOO HIGH
3	205,56	230	24,44	10,63	TOO HIGH

Here is the comparison of the three scenarios:



IDEAL SCENARIO
POSITIVE SCENARIO
NEGATIVE SCENARIO

3 Grid:

The third grid connects two loads, and it doesn't show unacceptable voltage drop values in the considered scenarios.

3 Grid: Ideal Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
22	230,00	230	0,00	0,00	---
21	229,96	230	0,04	0,02	---

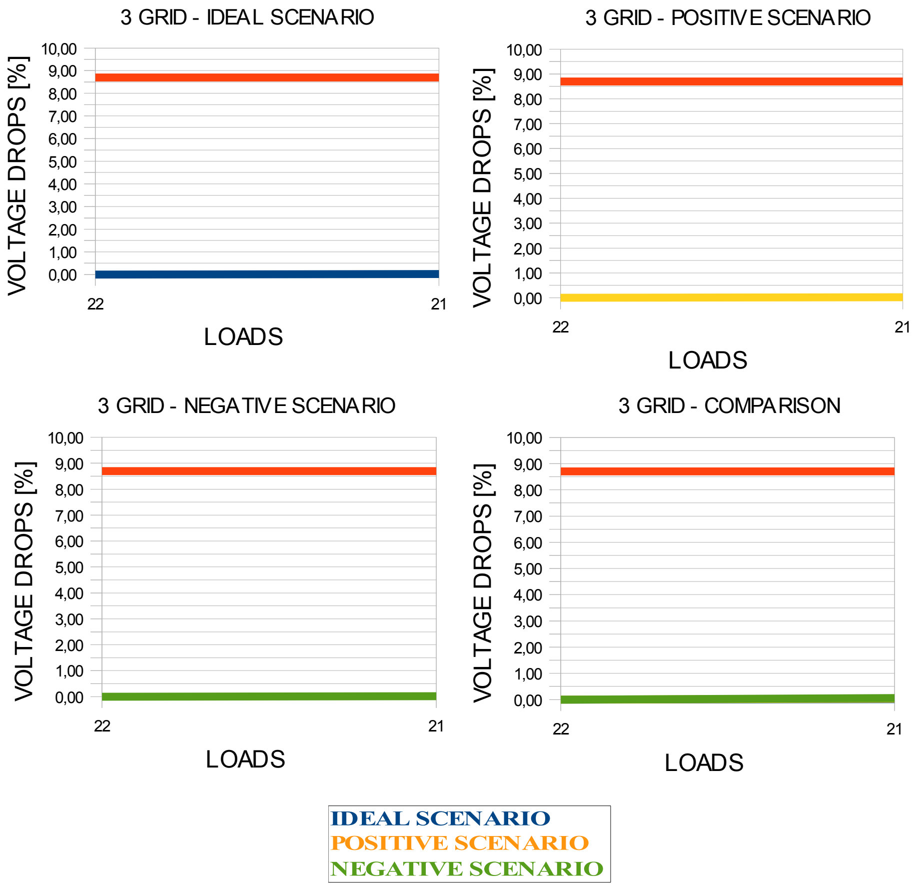
3 Grid: Positive Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
22	230,00	230	0,00	0,00	---
21	229,91	230	0,09	0,04	---

3 Grid: Negative Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
22	230,00	230	0,00	0,00	---
21	229,86	230	0,14	0,06	---

The three scenarios are compared as follows:



<u>4 Grid:</u>

Also for the fourth grid there are not unacceptable voltage drop values.

The results of the three scenarios follow:

4 Grid: Ideal Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	---
26	229,95	230	0,05	0,02	---
1	229,50	230	0,50	0,22	---

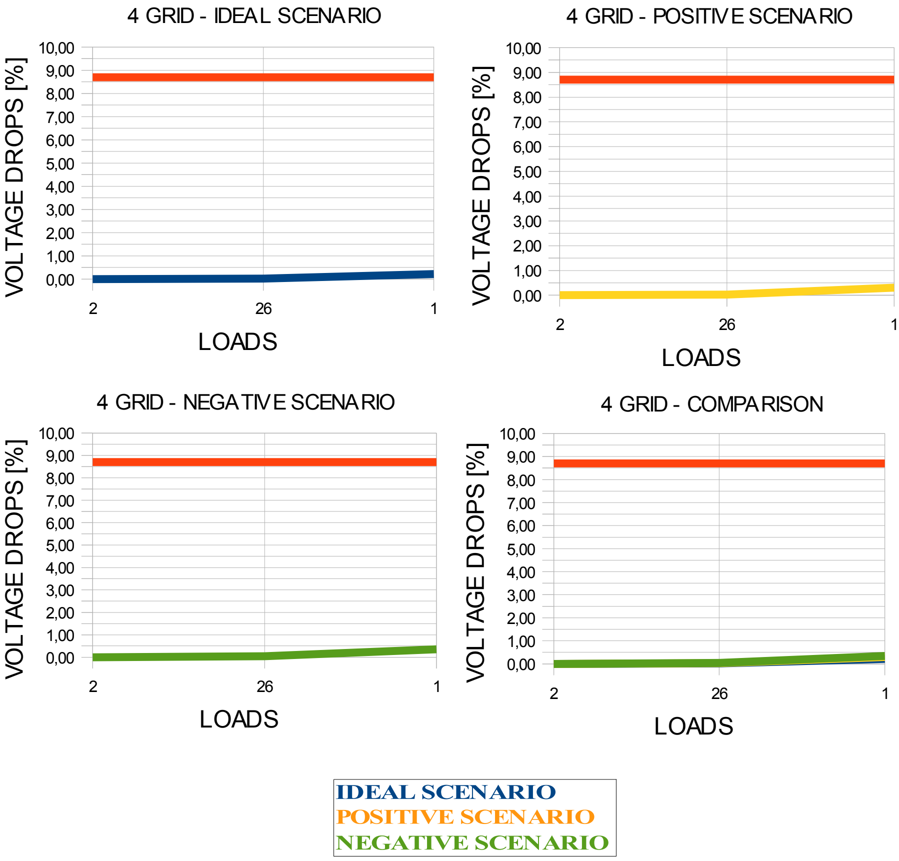
4 Grid: Positive Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	---
26	229,93	230	0,07	0,03	---
1	229,31	230	0,69	0,30	---

4 Grid: Negative Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	---
26	229,90	230	0,10	0,04	---
1	229,20	230	0,80	0,35	

The scenarios are compared below:



Concerning the individual grids, there are no problems connected the voltage drops, since there is no any cable infrastructure that connects the generator(s) and the load, so the load voltage is always 230 V, as for the generator and the battery.

Hybrid Generation System - Low Demand Case:

In this case there are eleven loads supplied by eleven 100 W photovoltaic panels, without any cable infrastructure, and a grid placed in the center of the community.

Individual Grid:

There are no voltage drops concerning the 11 individual wind generators: in this case, it is not worthwhile to consider different scenarios, and there is no difference between Ideal, Positive and Negative Scenarios, since the voltage is always 230 V.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
1	230,00	230	0,00	0	---

Main Grid:

The main grid analysis results are more interesting; there are no unacceptable values for the three considered scenarios, and the solution found by the GRECDH Team can be considered fully satisfactory.

Main Grid: Ideal Scenario

The voltage drops are lower than 8,70%: the highest is 3,85% (load 5), but it can be considered a very good value (load 5 has a high voltage, 221,15 V).

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
20	230,00	230	0,00	0,00	---
10	221,85	230	8,15	3,54	---
11	221,57	230	8,43	3,67	---
25	221,16	230	8,84	3,84	---
5	221,15	230	8,85	3,85	---
12	222,25	230	7,75	3,37	---
13	222,60	230	7,40	3,22	---
23	222,53	230	7,47	3,25	---
14	223,62	230	6,38	2,77	---
15	225,13	230	4,87	2,12	---
24	225,21	230	4,79	2,08	---
16	226,32	230	3,68	1,60	---
17	226,22	230	3,78	1,64	---
18	227,55	230	2,45	1,07	---
19	227,91	230	2,09	0,91	---

Main Grid: Positive Scenario

Considering a power factor of 0,90, the voltage drops increase, but remain lower than 8,70% for each load. Load 5 has a lower voltage value than in the previous case (218,78 V), and the voltage drop results 4,88%.

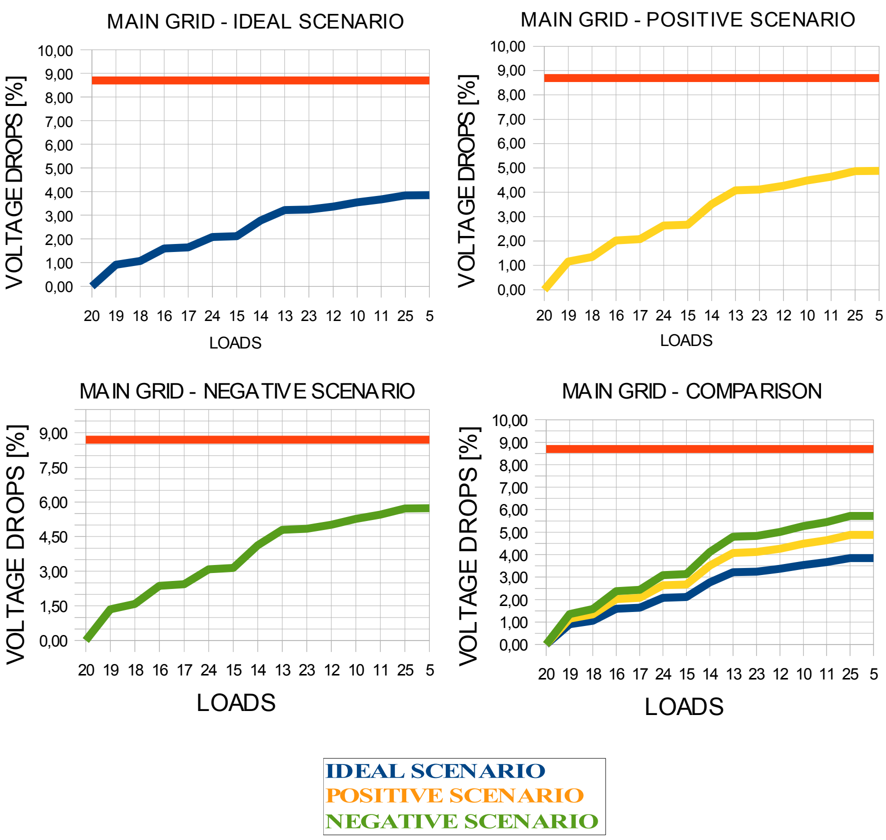
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
20	230,00	230	0,00	0,00	---
10	219,67	230	10,33	4,49	---
11	219,32	230	10,68	4,64	---
25	218,79	230	11,21	4,87	---
5	218,78	230	11,22	4,88	---
12	220,19	230	9,81	4,27	---
13	220,62	230	9,38	4,08	---
23	220,53	230	9,47	4,12	---
14	221,92	230	8,08	3,51	---
15	223,85	230	6,15	2,67	---
24	223,95	230	6,05	2,63	---
16	225,35	230	4,65	2,02	---
17	225,22	230	4,78	2,08	---
18	226,90	230	3,10	1,35	---
19	227,35	230	2,65	1,15	

Main Grid: Negative Scenario

Considering a low electronic devices efficiency, the voltage drops increase even more, but remain lower than 8,70%: load 5 has a 5,73% voltage drop, higher than the ideal case (3,85%), but it can be considered a satisfactory value.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
20	230,00	230	0,00	0,00	---
10	217,88	230	12,12	5,27	---
11	217,47	230	12,53	5,45	---
25	216,84	230	13,16	5,72	---
5	216,83	230	13,17	5,73	---
12	218,48	230	11,52	5,01	---
13	218,98	230	11,02	4,79	---
23	218,88	230	11,12	4,83	---
14	220,52	230	9,48	4,12	---
15	222,78	230	7,22	3,14	---
24	222,90	230	7,10	3,09	---
16	224,54	230	5,46	2,37	---
17	224,39	230	5,61	2,44	---
18	226,36	230	3,64	1,58	---
19	226,88	230	3,12	1,36	---

Here the three cases resume:



Wind Generation System - High Demand Case:

There are four microgrids to consider in this scenario: three of them do not show any problem concerning voltage drops, as they connect a small number of loads, while the remainder shows high values in the Negative scenario.

1 Grid:

This grid doesn't show any high voltage drop values, since the microgrid is not very big, and supplies just three loads.

1 Grid: Ideal Scenario

The highest voltage drop is 2,23%.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
7	230,00	230	0,00	0,00	---
8	225,89	230	4,11	1,79	---
9	224,87	230	5,13	2,23	---

1 Grid: Positive Scenario

In the Positive scenario, the highest voltage drop increases but it is much lower than 8,70% threshold.

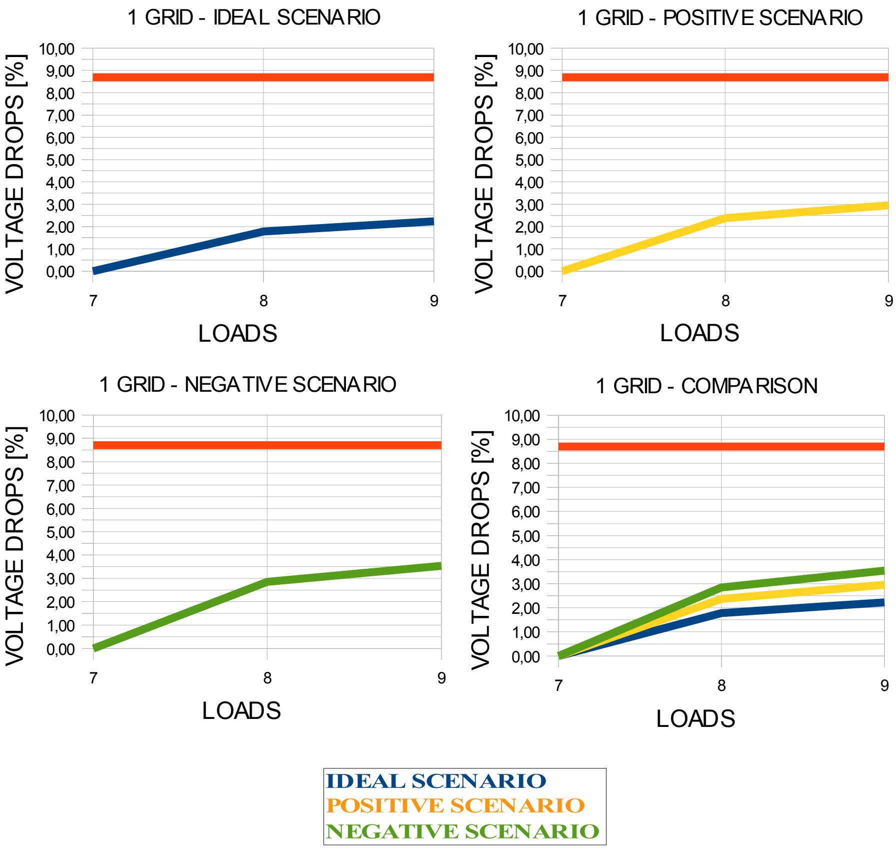
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
7	230,00	230	0,00	0,00	---
8	224,55	230	5,45	2,37	---
9	223,21	230	6,79	2,95	---

1 Grid: Negative Scenario

Considering a power factor of 0,75, the voltage drops increase, but the highest of them is very low even in this scenario (3,54%).

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
7	230,00	230	0,00	0,00	---
8	223,45	230	6,55	2,85	---
9	221,86	230	8,14	3,54	---

The three scenarios are compared below:



2 Grid:

The second microgrid also connects three loads and employs just one wind generator: the obtained results are similar to the case just commented.

2 Grid: Ideal Scenario

The voltage drops are very low in the Ideal Scenario (the highest is just 0,84%).

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	---
26	228,13	230	1,87	0,81	---
1	228,07	230	1,93	0,84	---

2 Grid: Positive Scenario

Load 1 voltage drop increases up to 1,10% in the Positive Scenario:

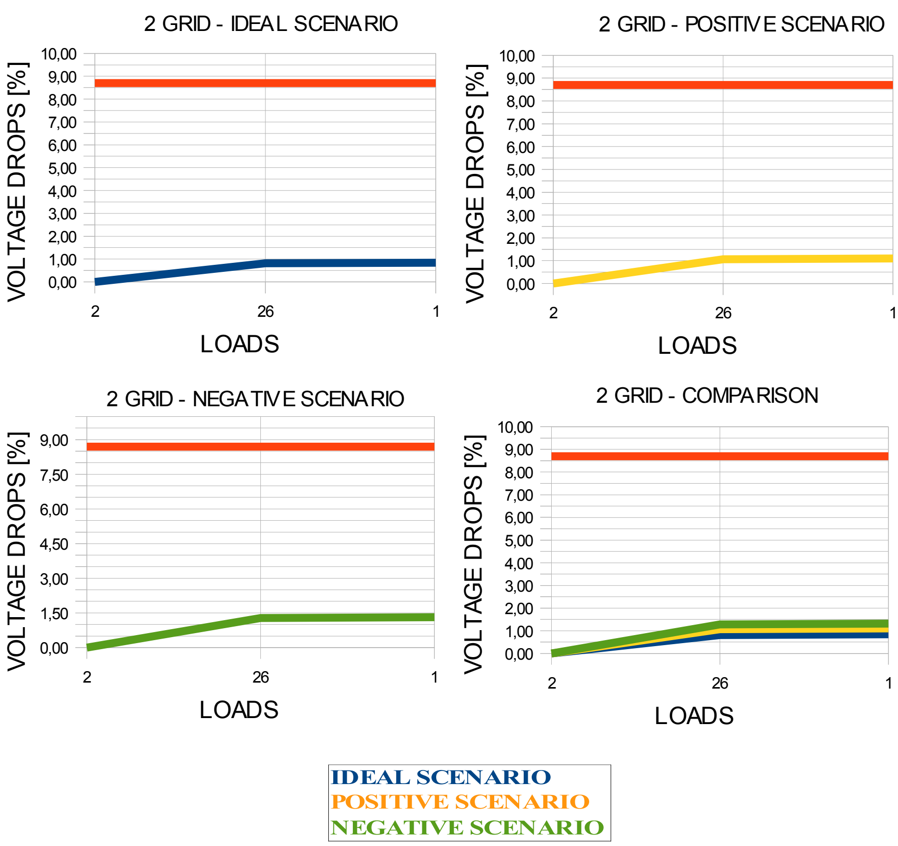
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	---
26	227,55	230	2,45	1,07	---
1	227,47	230	2,53	1,10	---

2 Grid: Negative Scenario

Even considering a power factor equal to 0,75, the voltage drops are very low:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	---
26	227,07	230	2,93	1,27	---
1	226,98	230	3,02	1,31	---

Here is the three scenarios resume:



3 Grid:

The third grid is more interesting from an electrical point of view: it connects 15 loads, and it presents significant differences when considering the three reactive power scenarios.

3 Grid: Ideal Scenario

Load 11 has the highest voltage drop in the ideal case: 5,52%.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
20	230,00	230	0,00	0,00	---
21	227,00	230	3,00	1,30	---
22	226,85	230	3,15	1,37	---
19	226,46	230	3,54	1,54	---
18	225,85	230	4,15	1,80	---
16	223,82	230	6,18	2,69	---
17	223,62	230	6,38	2,77	---
24	222,08	230	7,92	3,44	---
15	221,95	230	8,05	3,50	---
14	219,73	230	10,27	4,47	---
13	218,29	230	11,71	5,09	---
23	218,16	230	11,84	5,15	---
12	217,89	230	12,11	5,27	---
10	217,49	230	12,51	5,44	---
11	217,31	230	12,69	5,52	---

3 Grid: Positive Scenario

Load 11 voltage drop increases up to almost 7%, value close to the 8% security threshold.

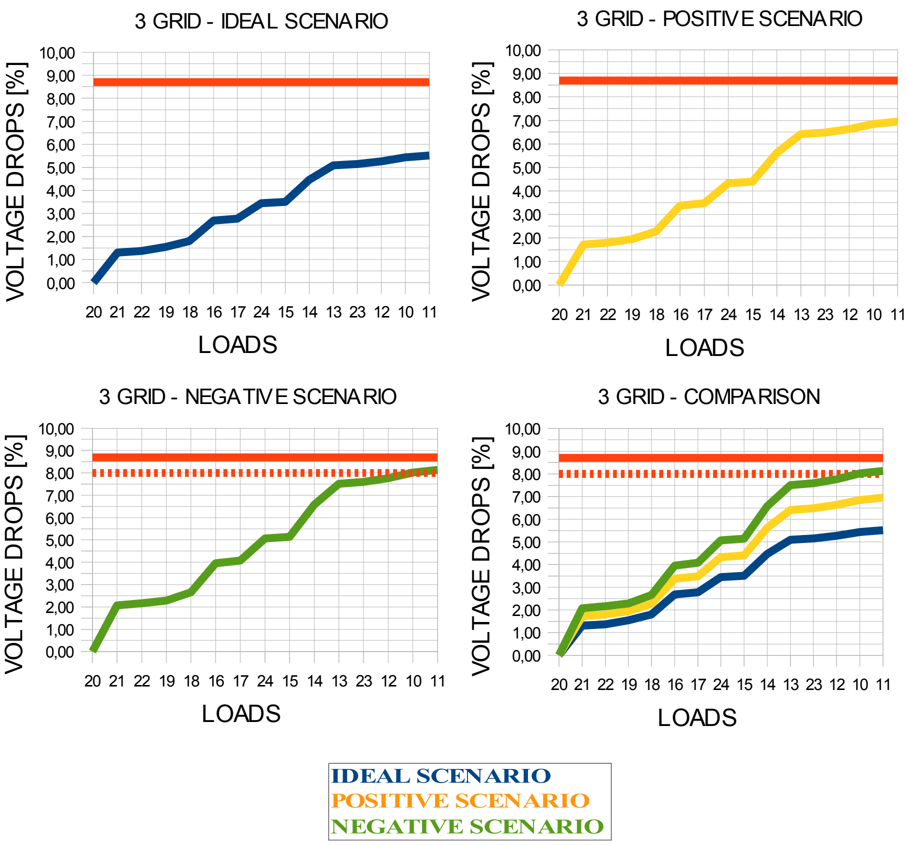
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
20	230,00	230	0,00	0,00	---
21	226,04	230	3,96	1,72	---
22	225,85	230	4,15	1,80	---
19	225,53	230	4,47	1,94	---
18	224,78	230	5,22	2,27	---
16	222,24	230	7,76	3,37	---
17	221,99	230	8,01	3,48	---
24	220,05	230	9,95	4,33	---
15	219,89	230	10,11	4,40	---
14	217,07	230	12,93	5,62	---
13	215,25	230	14,75	6,41	---
23	215,09	230	14,91	6,48	---
12	214,75	230	15,25	6,63	---
10	214,24	230	15,76	6,85	---
11	214,01	230	15,99	6,95	---

3 Grid: Negative Scenario

In this case load 10 and load 11 are labeled as “Close to Limit”, because their voltage drops are higher than 8%. it is interesting notice that in the ideal case these voltage drops were just 5,50%.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
20	230,00	230	0,00	0,00	---
21	225,24	230	4,76	2,07	---
22	225,02	230	4,98	2,17	---
19	224,75	230	5,25	2,28	---
18	223,89	230	6,11	2,66	---
16	220,91	230	9,09	3,95	---
17	220,62	230	9,38	4,08	---
24	218,35	230	11,65	5,07	---
15	218,17	230	11,83	5,14	---
14	214,87	230	15,13	6,58	---
13	212,73	230	17,27	7,51	---
23	212,54	230	17,46	7,59	---
12	212,15	230	17,85	7,76	---
10	211,56	230	18,44	8,02	CLOSE TO LIMIT
11	211,30	230	18,70	8,13	CLOSE TO LIMIT

The three scenarios are resumed below:



4 Grid:

The fourth grid connects five loads and do not show any problem connected to high voltage drops. The three scenario results are commented below.

4 Grid: Ideal Scenario

The highest voltage drop is 3,97% (load 3).

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
25	230,00	230	0,00	0,00	---
5	225,67	230	4,33	1,88	---
4	222,33	230	7,67	3,33	---
6	220,93	230	9,07	3,94	---
3	220,88	230	9,12	3,97	---

4 Grid: Positive Scenario

Load 3 voltage drop increases up to 5,17% considering a 0,90 power factor.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
25	230,00	230	0,00	0,00	---
5	224,38	230	5,62	2,44	---
4	220,03	230	9,97	4,33	---
6	218,19	230	11,81	5,13	---
3	218,12	230	11,88	5,17	---

4 Grid: Negative Scenario

Even in the Negative scenario, load 3 has 215,86 V, a value that's higher than the security threshold.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
25	230,00	230	0,00	0,00	---
5	223,31	230	6,69	2,91	---
4	218,14	230	11,86	5,16	---
6	215,94	230	14,06	6,11	---
3	215,86	230	14,14	6,15	---

Hybrid Generation System - High Demand Case:

There are two grids to consider for this solution: the first one shows unacceptable values for the three reactive power scenarios, while the second one is satisfactory. Notice that this is the only case in which the Ideal Scenario solution is unsuitable, due to the loads' high power and to the several connection cables deployed. There is a proposed solution to solve such voltage troubles in chapter 3.

1 Grid:

As just commented, this grid shows several problems connected to voltage drops, since just 1 load out of 18 performs suitably.

1 Grid: Ideal Scenario

The unacceptable voltage drops are in a range from 8,16 to 15,91%; just load 25 has an acceptable value, because it is placed close to the two 2000 W generators.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
25	224,28	230	5,72	2,49	—
11	**211,23**	**230**	**18,77**	**8,16**	**TOO HIGH**
5	**209,66**	**230**	**20,34**	**8,84**	**TOO HIGH**
10	**208,85**	**230**	**21,15**	**9,20**	**TOO HIGH**
4	**208,62**	**230**	**21,38**	**9,30**	**TOO HIGH**
12	**206,44**	**230**	**23,56**	**10,24**	**TOO HIGH**
13	**204,96**	**230**	**25,04**	**10,89**	**TOO HIGH**
23	**204,83**	**230**	**25,17**	**10,94**	**TOO HIGH**
14	**202,33**	**230**	**27,67**	**12,03**	**TOO HIGH**
15	**199,32**	**230**	**30,68**	**13,34**	**TOO HIGH**
24	**199,19**	**230**	**30,81**	**13,40**	**TOO HIGH**
16	**197,83**	**230**	**32,17**	**13,99**	**TOO HIGH**
17	**197,65**	**230**	**32,35**	**14,07**	**TOO HIGH**
18	**196,93**	**230**	**33,07**	**14,38**	**TOO HIGH**
19	**196,73**	**230**	**33,27**	**14,47**	**TOO HIGH**
20	**195,96**	**230**	**34,04**	**14,80**	**TOO HIGH**
22	**193,28**	**230**	**36,72**	**15,97**	**TOO HIGH**
21	**193,41**	**230**	**36,59**	**15,91**	**TOO HIGH**

1 Grid: Positive Scenario

In this scenario, voltage drops increase up to 19,58%.

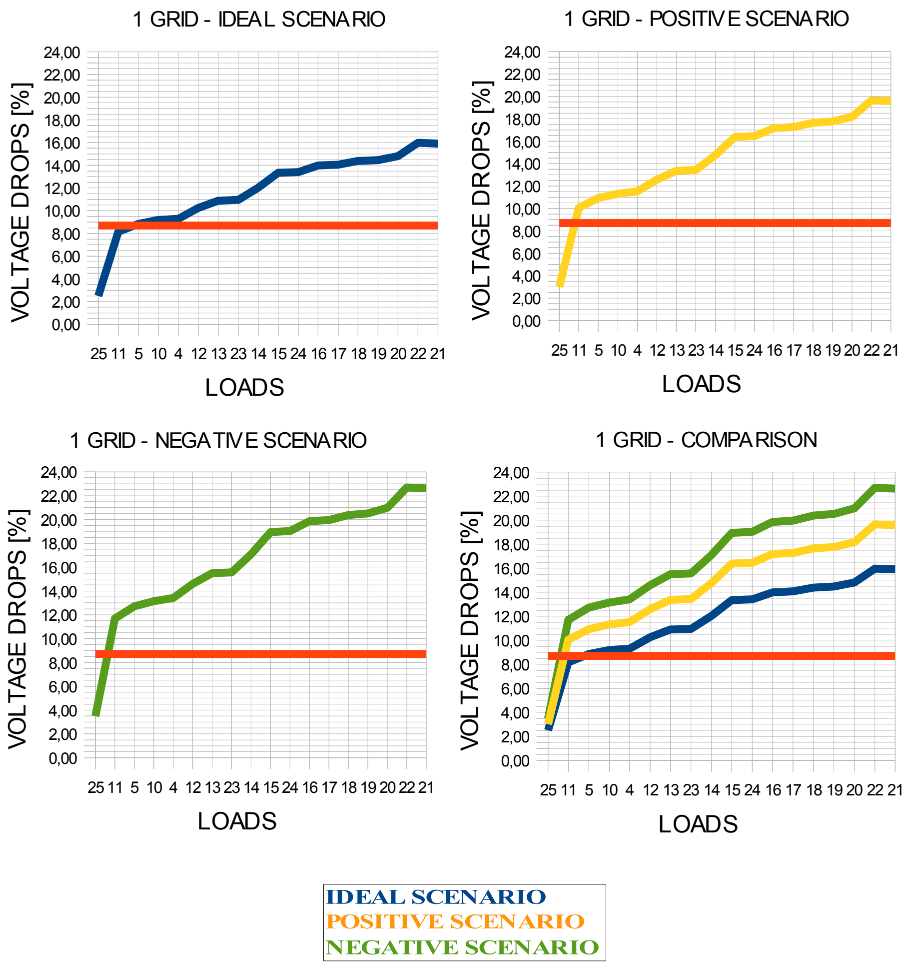
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
25	223,08	230	6,92	3,01	—
11	206,88	230	23,12	10,05	TOO HIGH
5	204,87	230	25,13	10,93	TOO HIGH
10	203,99	230	26,01	11,31	TOO HIGH
4	203,52	230	26,48	11,51	TOO HIGH
12	201,06	230	28,94	12,58	TOO HIGH
13	199,26	230	30,74	13,37	TOO HIGH
23	199,11	230	30,89	13,43	TOO HIGH
14	196,03	230	33,97	14,77	TOO HIGH
15	192,32	230	37,68	16,38	TOO HIGH
24	192,16	230	37,84	16,45	TOO HIGH
16	190,49	230	39,51	17,18	TOO HIGH
17	190,28	230	39,72	17,27	TOO HIGH
18	189,40	230	40,60	17,65	TOO HIGH
19	189,16	230	40,84	17,76	TOO HIGH
20	188,21	230	41,79	18,17	TOO HIGH
22	184,81	230	45,19	19,65	TOO HIGH
21	184,97	230	45,03	19,58	TOO HIGH

1 Grid: Negative Scenario

In the less favorable case, loads' voltage drops vary from 3,48 to 22,61%: it is evident this grid cannot work suitably if its architecture was maintained

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
25	221,99	230	8,01	3,48	—
11	203,12	230	26,88	11,69	TOO HIGH
5	200,76	230	29,24	12,71	TOO HIGH
10	199,80	230	30,20	13,13	TOO HIGH
4	199,17	230	30,83	13,40	TOO HIGH
12	196,44	230	33,56	14,59	TOO HIGH
13	194,39	230	35,61	15,48	TOO HIGH
23	194,22	230	35,78	15,56	TOO HIGH
14	190,70	230	39,30	17,09	TOO HIGH
15	186,43	230	43,57	18,94	TOO HIGH
24	186,26	230	43,74	19,02	TOO HIGH
16	184,35	230	45,65	19,85	TOO HIGH
17	184,11	230	45,89	19,95	TOO HIGH
18	183,11	230	46,89	20,39	TOO HIGH
19	182,85	230	47,15	20,50	TOO HIGH
20	181,76	230	48,24	20,97	TOO HIGH
22	177,83	230	52,17	22,68	TOO HIGH
21	178,00	230	52,00	22,61	TOO HIGH

The three cases resume below:



<u>2 Grid:</u>

The other grid connects just three loads, and it is not problematic regarding voltage drops.

2 Grid: Ideal Scenario

Load 1 has a voltage drop equal to just 0,84%.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	—
26	228,13	230	1,87	0,81	—
1	228,07	230	1,93	0,84	—

2 Grid: Positive Scenario

Load 1 voltage drop increases up to 1,10 in Positive Scenario.

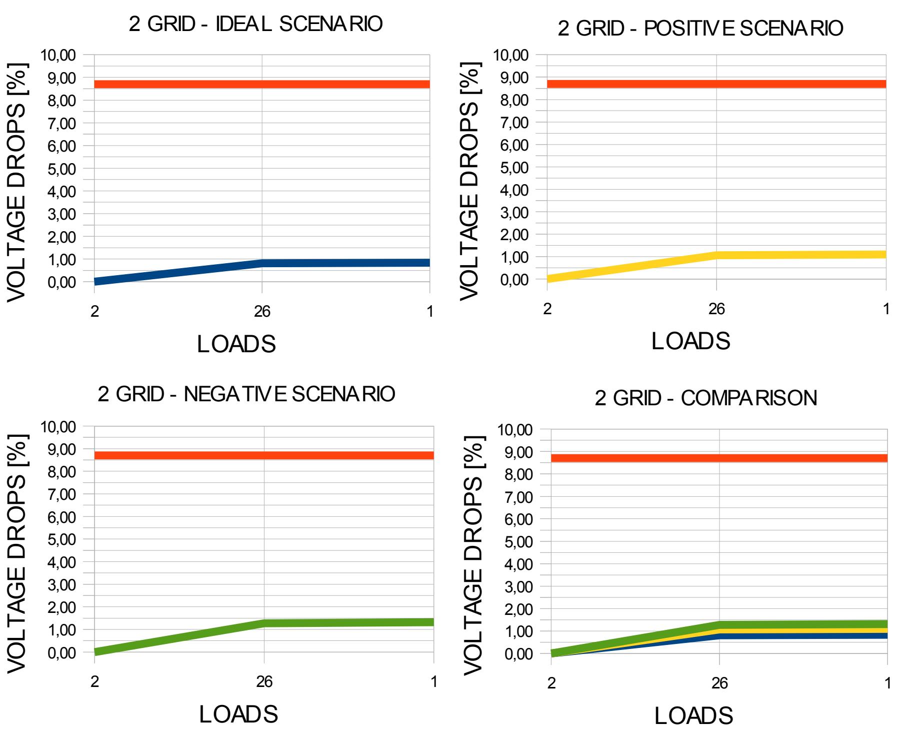
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	—
26	227,55	230	2,45	1,07	—
1	227,47	230	2,53	1,10	—

2 Grid: Negative Scenario

Even in the less favorable scenario, all the loads have acceptable voltage values.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	—
26	227,07	230	2,93	1,27	—
1	226,98	230	3,02	1,31	—

The three scenarios are compared below:



IDEAL SCENARIO
POSITIVE SCENARIO
NEGATIVE SCENARIO

This solution employs also individual generators directly connected to the loads: as commented before, there are no problems concerning voltage drops for such systems.

2.5 El Alumbre: microgrids preliminary analysis description

Let's take into consideration the results obtained for El Alumbre, concerning both Low and High Demand Scenarios: a solution concerning just Wind Energy is described first, then the Hybrid solution employing both wind and solar energy follows.

Wind Energy System - Low Demand Case:

The software found the cheapest solution to be a configuration in which there is a microgrid in the center of the community, connecting 9 houses loads, the school and the medical center. A 2000 W wind Generator is employed (indicated as A4 in the figure), and 8 batteries are required to store energy (7 type B4 and 1 type B2 in the figure). Of course, a regulator (R4) and an inverter (I4) are required by the wind generator to produce energy at the given system frequency.
Furthermore, 24 individual 100 W wind generators are required, and they are placed next to 24 individual loads; as well as for the previous case, a regulator (R1) and an inverter (I1) for each generator are required, and a smaller battery (B1) is also required for each generator.

Here is the scheme of the area; the coordinates (x;y) are expressed in meters.

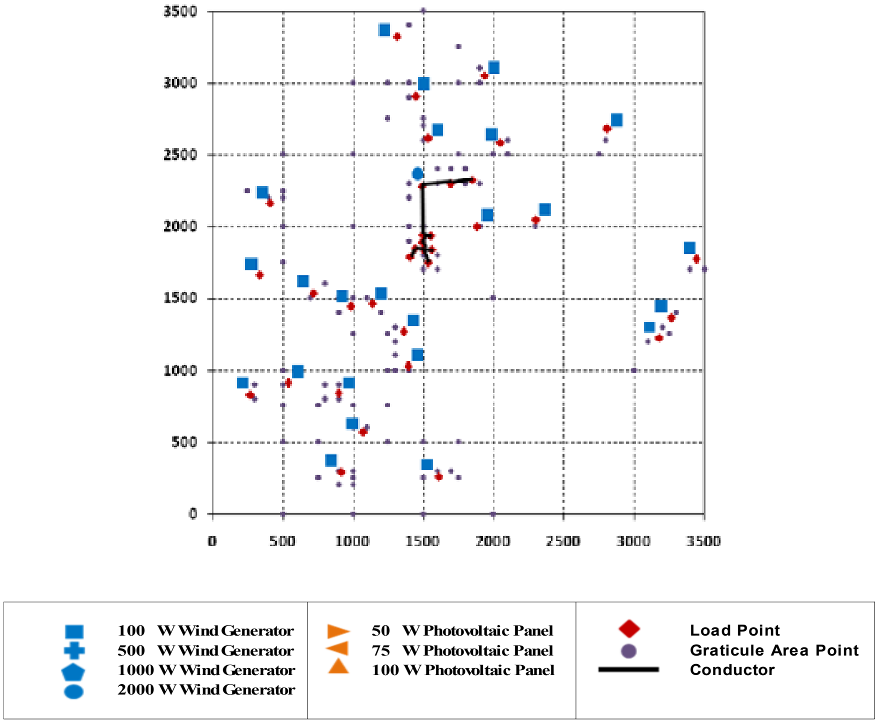


Figure 2.46: Low demand, wind generation - El Alumbre

Here is the main grid scheme, in which there are 11 loads, 1 2000 W generator, 1 regulator, 1 inverter and 8 batteries. The numbers identify the loads.

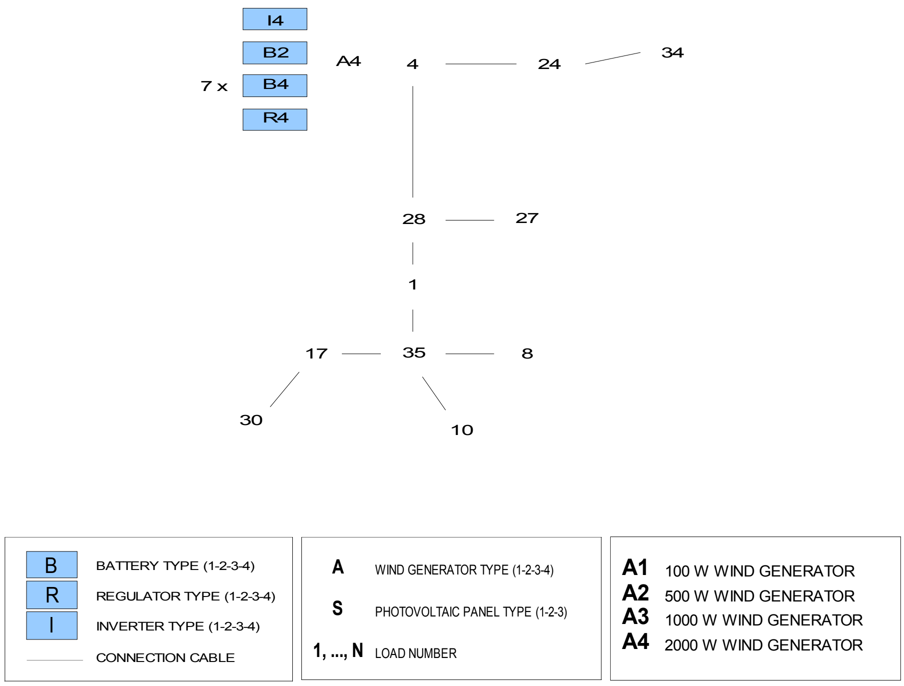


Figure 2.47: Main Grid scheme - Low demand, wind generation - El Alumbre

In the electrical grid scheme there are cables connecting the loads one another, and the generator to the battery bank. Here is the electrical scheme of the grid, where “B eq” is considered as the equivalent battery of the 8 batteries required by the grid:

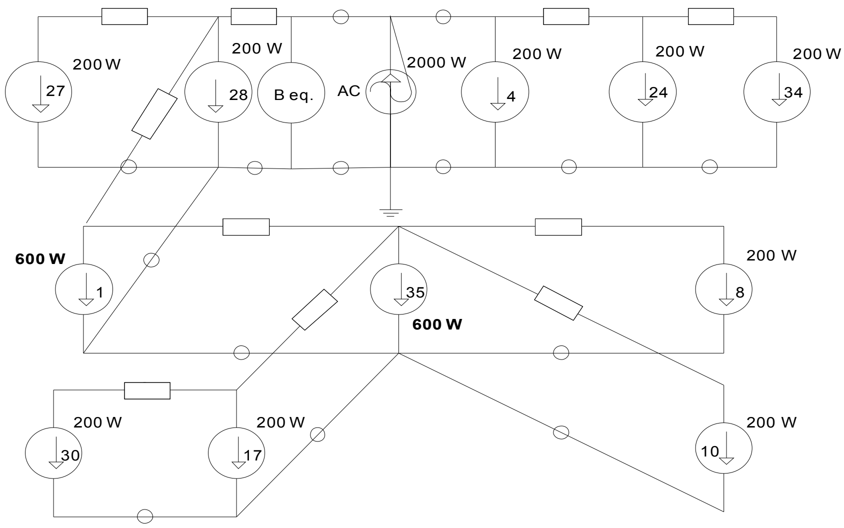


Figure 2.48: Main Grid electrical scheme - Low demand, wind generation - El Alumbre

As already exposed, this solution requires also 24 individual generators (100 W Power each), that are placed next to 24 loads. The grid scheme for load number 2 is reported as an example, and it is the same for the others 23 individual systems. In such system, there are one 100 W Wind Generator (A1), 1 battery (B1), 1 inverter (I1) and one regulator device (R1).

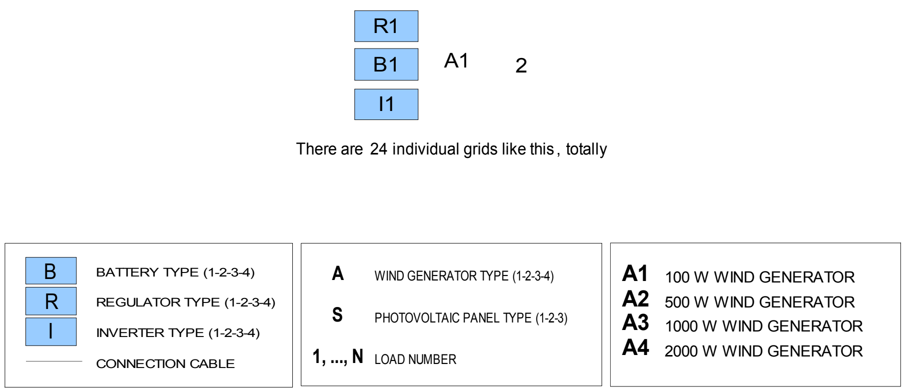


Figure 2.49: Individual Grid scheme - Low demand, wind generation - El Alumbre

Here is the electrical grid for the individual system above.

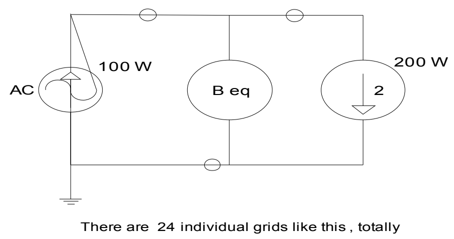


Figure 2.50: Individual Electrical Grid scheme - Low demand, wind generation - El Alumbre

Hybrid Generation System - Low Demand Case:

This solution employs both wind and photovoltaic generators, with just a grid in the center of the area, that supplies seven houses, a school and a the medical center using a 2000 W wind generator. Furthermore, 26 individual 100 W photovoltaic generators are required, placed next to 26 loads, without a grid or cable infrastructure.

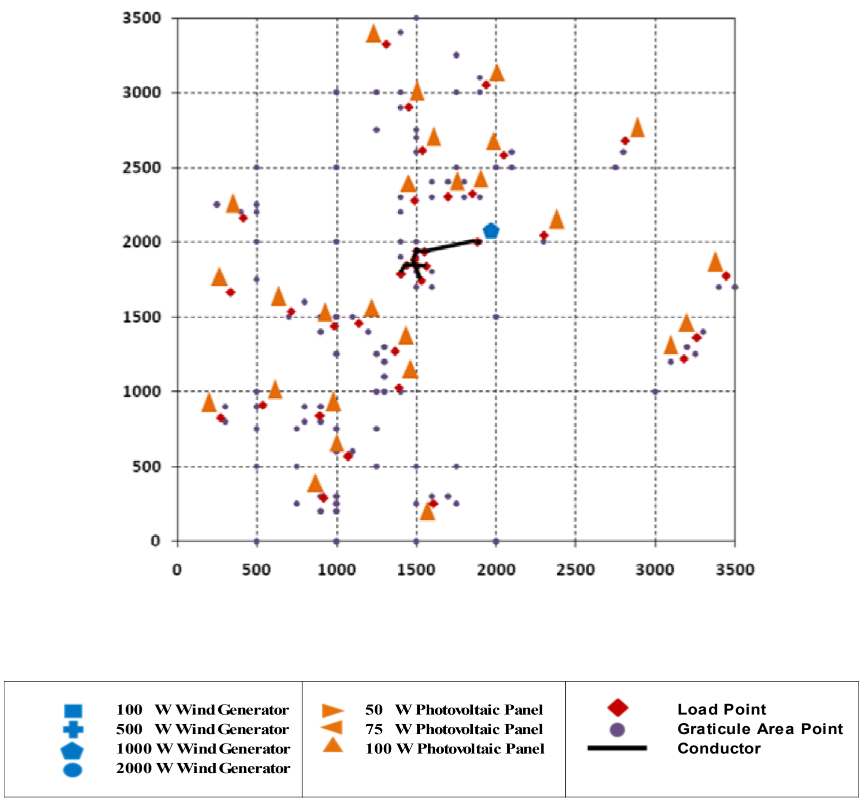


Figure 2.51: Low demand, hybrid generation – El Alumbre

Main Grid:

Here is the main grid architecture, with 8 batteries next to the 2000 W generator, 1 regulator and 1 inverter. The wind generator is placed in point 44, and it is connected to load 14.

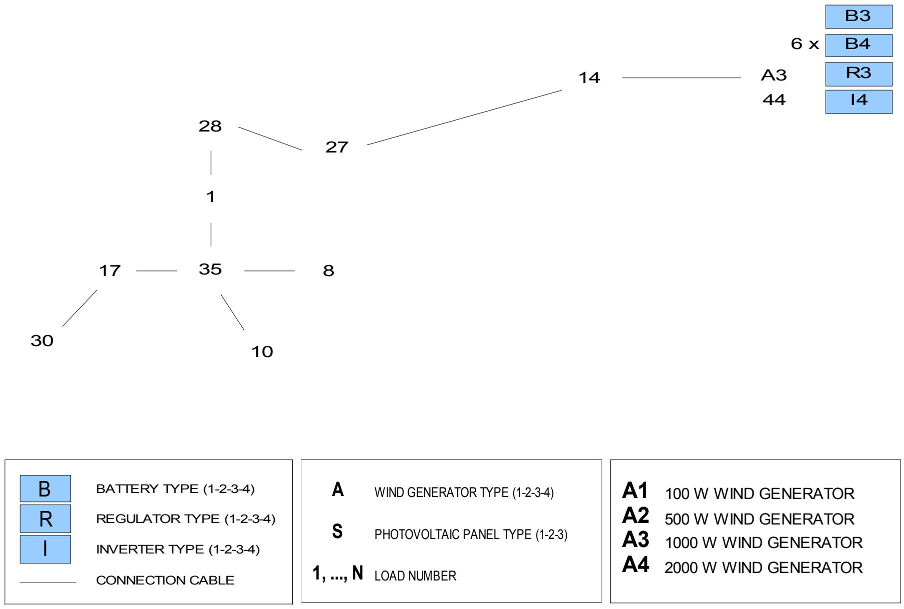


Figure 2.52: Main Grid scheme - Low demand, hybrid generation – El Alumbre

Here is the electrical scheme of the micro grid: B eq is considered as the equivalent battery of the 8 batteries.

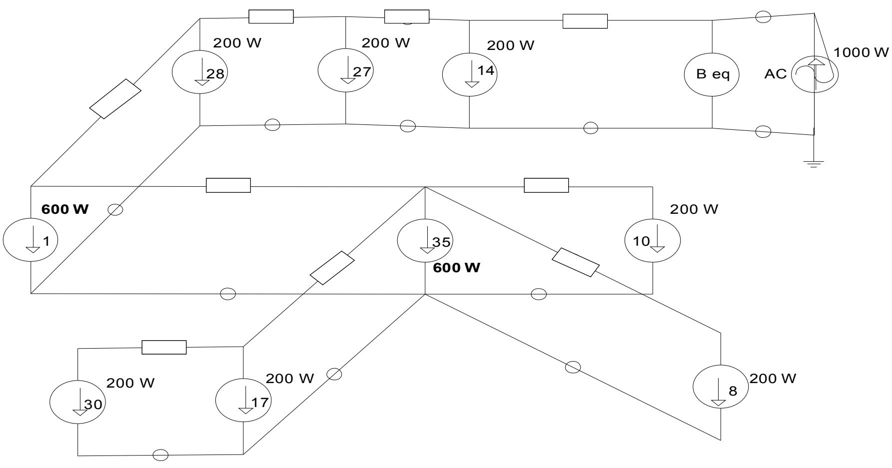


Figure 2.53: Main Grid Electrical scheme - Low demand, hybrid generation – El Alumbre

<u>Individual Grid:</u>

Also 26 individual 100 W photovoltaic generators are required in this solution; the scheme and the electrical grid is the same reported in the wind generation case.

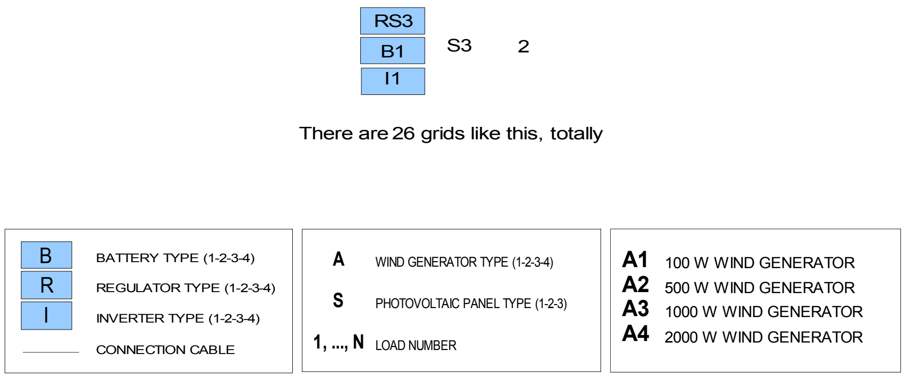


Figure 2.54: Individual Grid scheme - Low demand, hybrid generation – El Alumbre

Wind Generation System - High Demand Case:

In this solution four microgrids are required to supply the total loads demand: the two biggest are in the center of the area, employing two 2000 W wind generator, where there are the school and the health center; the third one connects 3 houses employing a 500 W generator and the fourth connects 5 houses with a 1000 W generator. Moreover, there are three houses supplied by six 100 W generator (2 generators each), and five loads supplied by five 100 W generators.

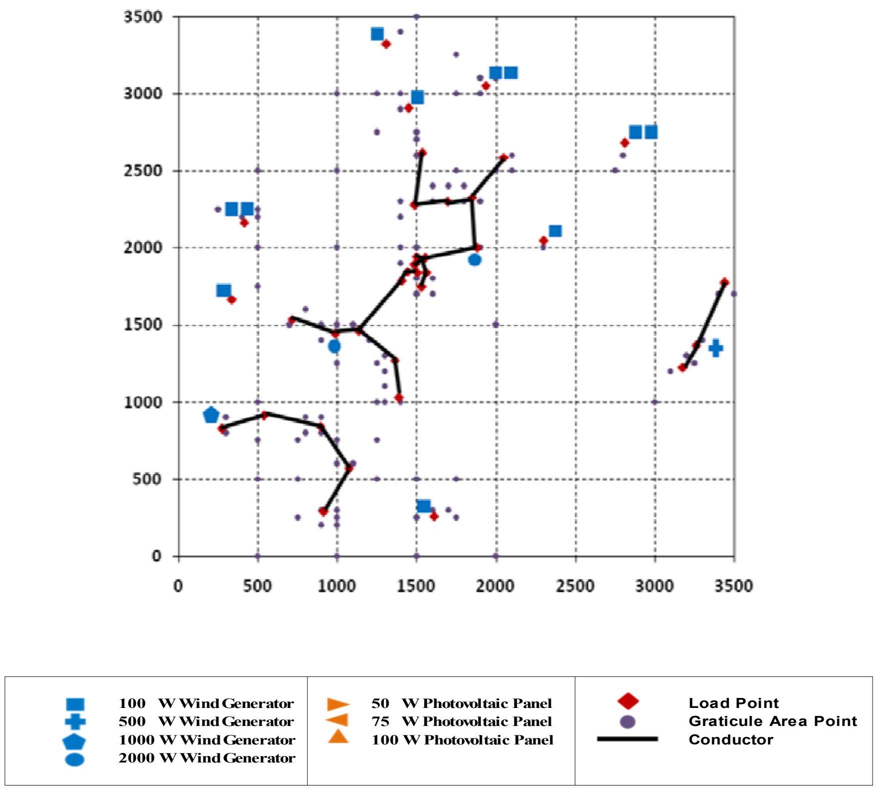


Figure 2.55: High demand, wind generation - El Alumbre

First Grid:

Let's analyze into detail the four microgrids; here is the first one, with a huge battery bank (12 B4 batteries and 1 B3 battery), three inverters for the 2000 W wind Generator, and one regulator.

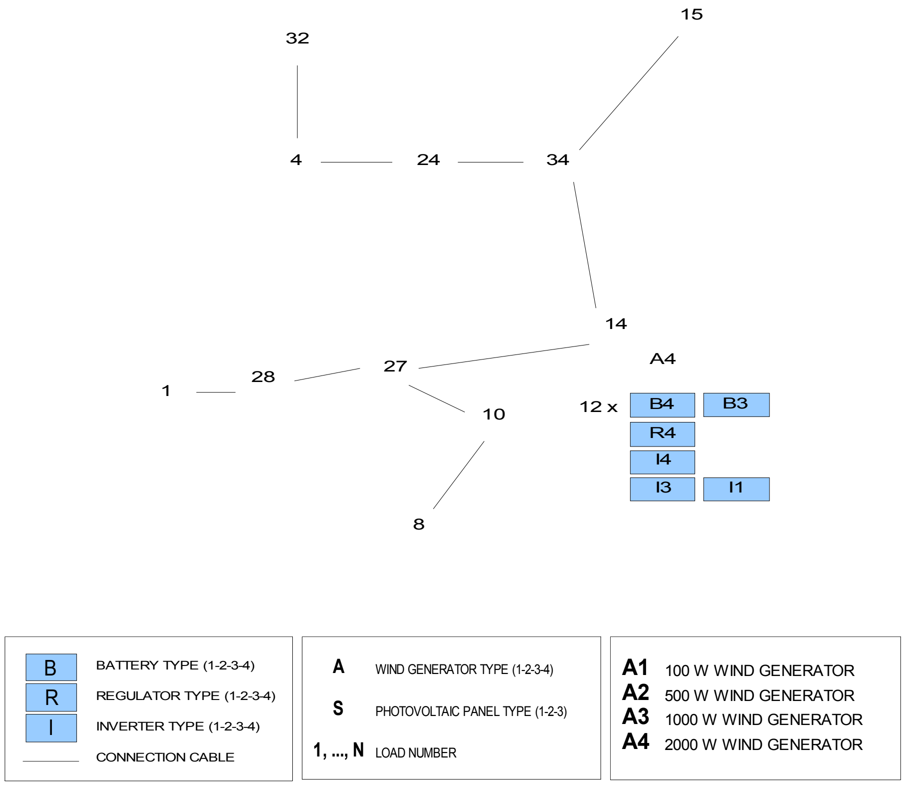


Figure 2.56: First Grid Scheme - High demand, wind generation - El Alumbre

Here is the electrical scheme of the microgrid: Beq is the battery standing for the 13 employed batteries. All the loads have 400 W of power, except the school (number 1) that has 1200 W.

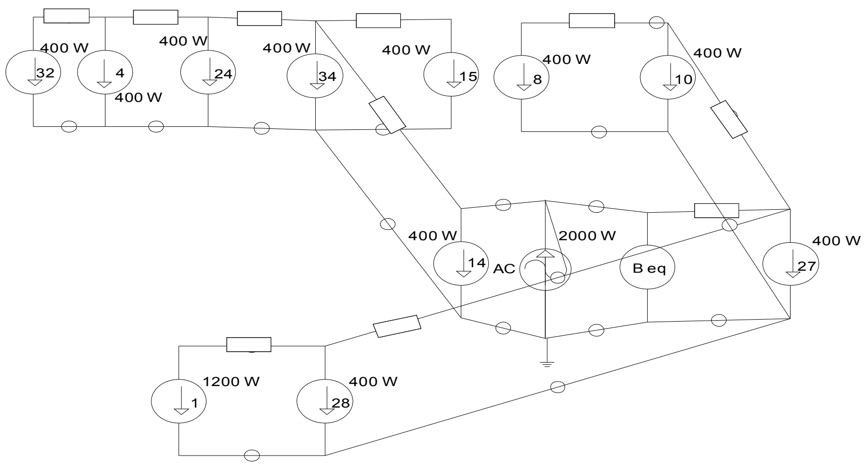


Figure 2.57: First Grid Electrical Scheme - High demand, wind generation - El Alumbre

Second Grid:

Here is the second grid scheme: as for the first grid, there is a 2000 W generator, with 10 batteries, one regulator and two inverters.

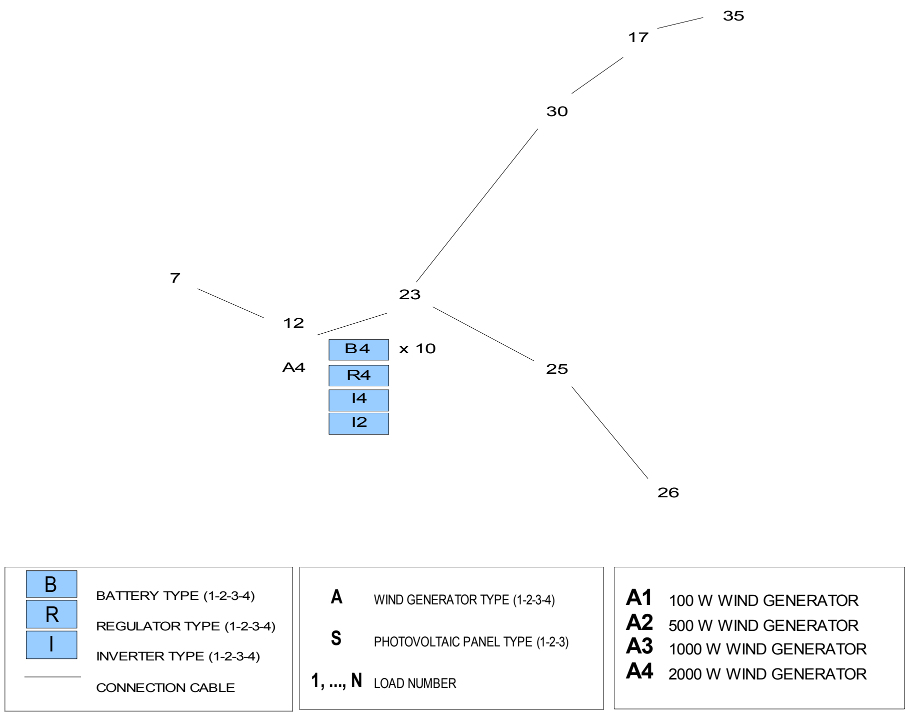


Figure 2.58: Second Grid Scheme - High demand, wind generation - El Alumbre

Here is the second grid electrical scheme: all the loads have 400 W of power (they require 560 kWh per day), except the Health Center (load 35) that has 1200 W of electrical power and requires 1950 kWh per day.

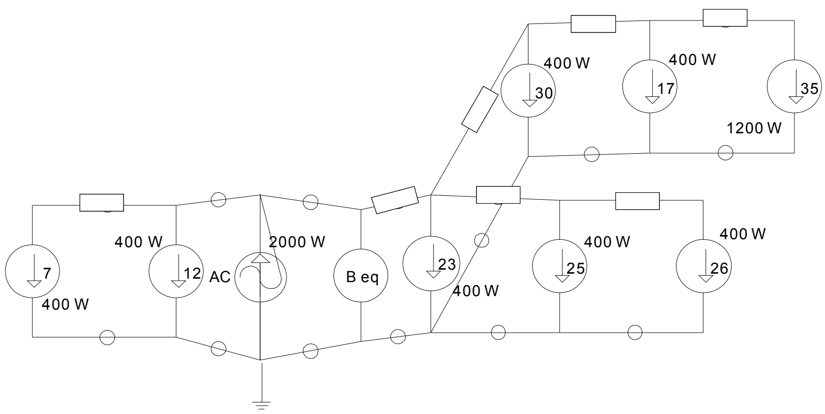


Figure 2.59: Second Grid Electrical Scheme - High demand, wind generation - El Alumbre

Third Grid:

The third grid employs a 500 W wind generator, three batteries, one regulator and one inverter. The three loads are houses, so the electrical power to consider is 400 W.

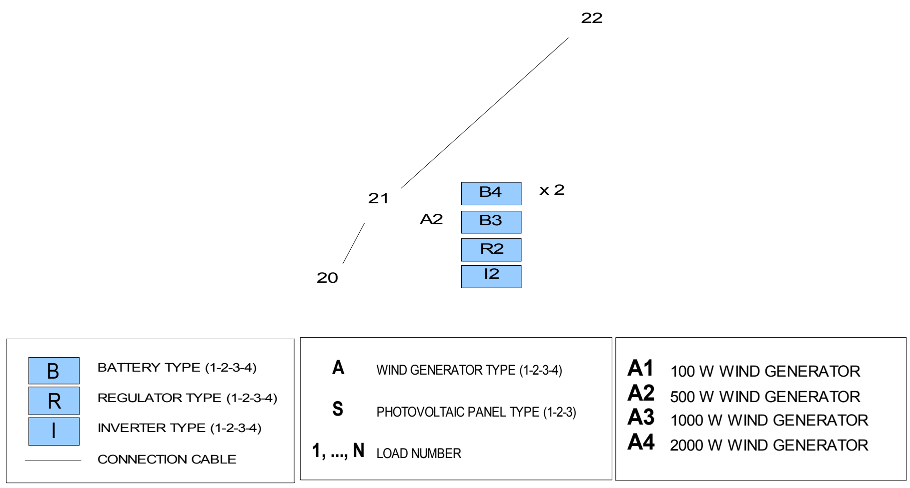


Figure 2.60: Third Grid Scheme - High demand, wind generation - El Alumbre

Here is the electrical grid scheme for the commented microgrid:

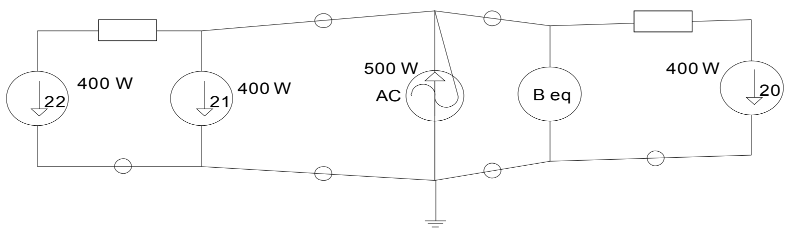


Figure 2.61: Third Grid Electrical Scheme - High demand, wind generation - El Alumbre

Fourth Grid:

Finally, here is the fourth grid, that employs a 1000 W wind generator, five batteries, one regulator and one inverter. The five loads in the grid have 400 W of electrical power and require 560 kWh per day.

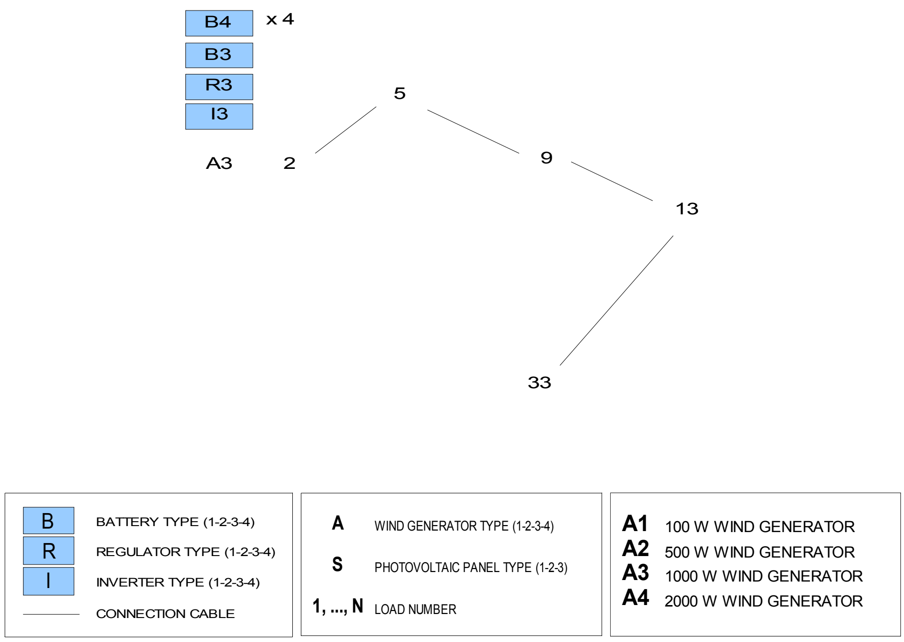


Figure 2.62: Fourth Grid Scheme - High demand, wind generation - El Alumbre

Here is the electrical scheme:

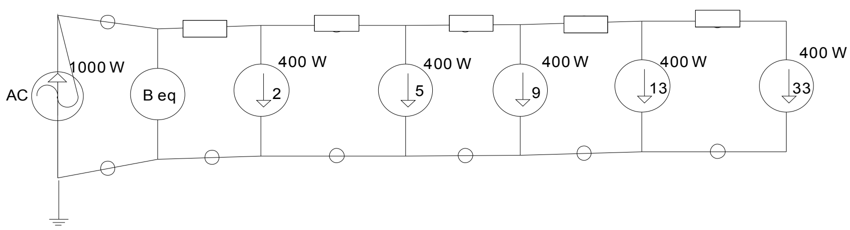


Figure 2.63: Fourth Grid Electrical Scheme - High demand, wind generation - El Alumbre

Finally, there are two types of individual grids that don't employ any cable infrastructure; all of them can store energy in a battery, and supply just a house:

- Type 1 (3 grids): two 100 W wind generators supply an individual 400 W load.
- Type 2 (5 grids): just one 100 W wind generator supplies an individual 400 W load

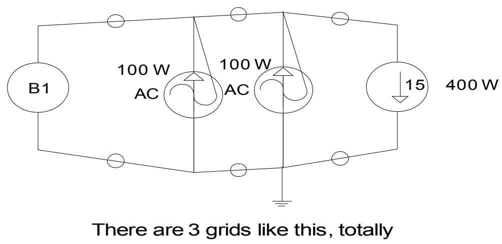


Figure 2.64: Individual Load (Type 1) Electrical Scheme - High demand, wind generation - El Alumbre

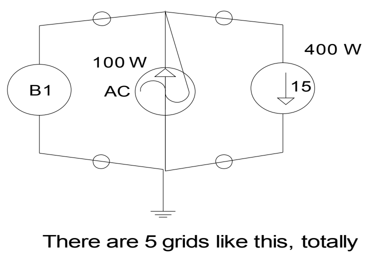


Figure 2.65: Individual Load (Type 2) Electrical Scheme - High demand, wind generation - El Alumbre

Hybrid Generation System - High Demand Case:

This solution is similar to the previous one (Wind Energy Generation), and maintains two big grids in the central part of the community; the third one results smaller, connecting just two loads (three in the previous solution). There are six 50 W photovoltaic panels and eight 100 W ones, supplying energy to the loads without any cable infrastructure (named individual solutions) and one of 50 W panels is in the third grid together with two small wind generators (100 W). it is interesting to note that the second grid is the same built in the previous solution, while the first one, the biggest, is very similar and connects the same loads. Here is the community map:

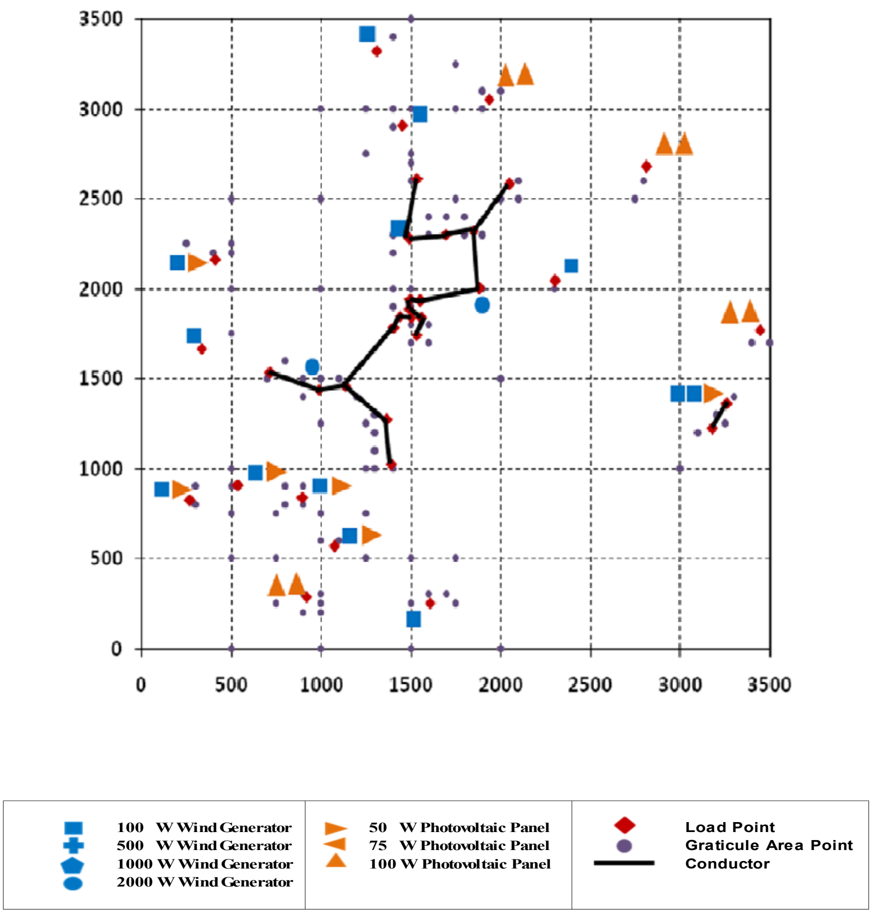


Figure 2.66: High demand, hybrid generation - El Alumbre

First Grid:

The first grid employs just one 2000 W wind generator, as in the Wind Generation Solution, with 13 batteries, 3 inverters and 1 regulator. The loads supplied are the same, all 400 W of electrical power and one 1200 W.

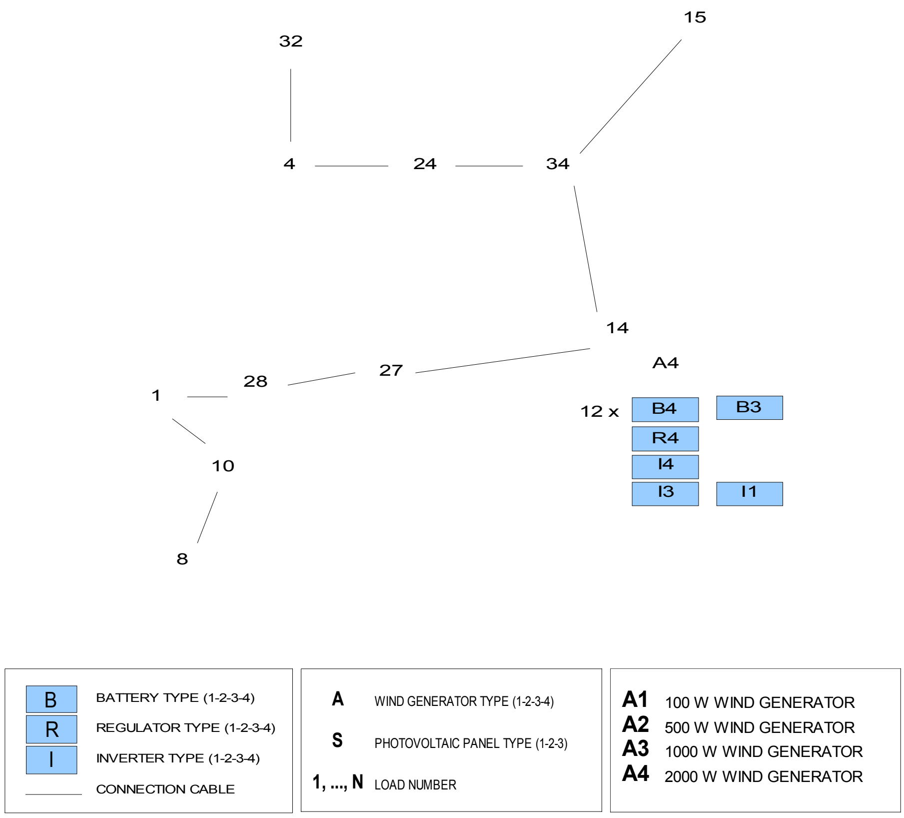


Figure 2.67: First Grid Scheme - High demand, hybrid generation - El Alumbre

Here is the first grid electrical scheme:

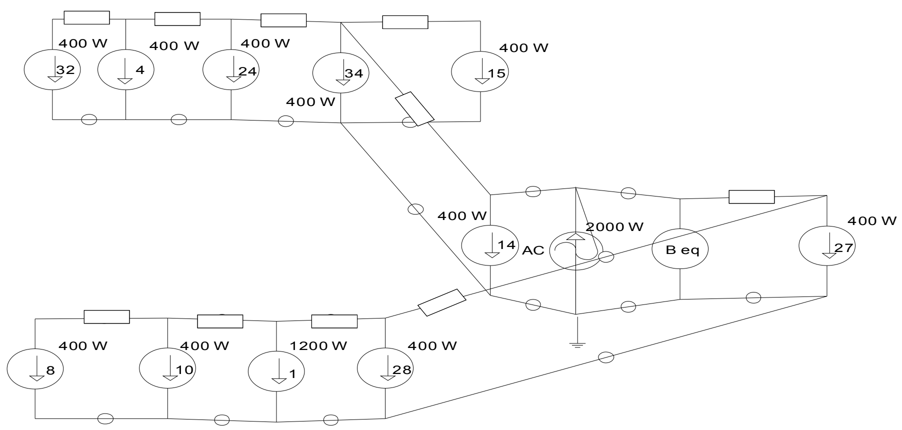


Figure 2.68: First Grid Electrical Scheme - High demand, hybrid generation - El Alumbre

Second Grid:

The second grid is the same commented for the Wind Generation System case:

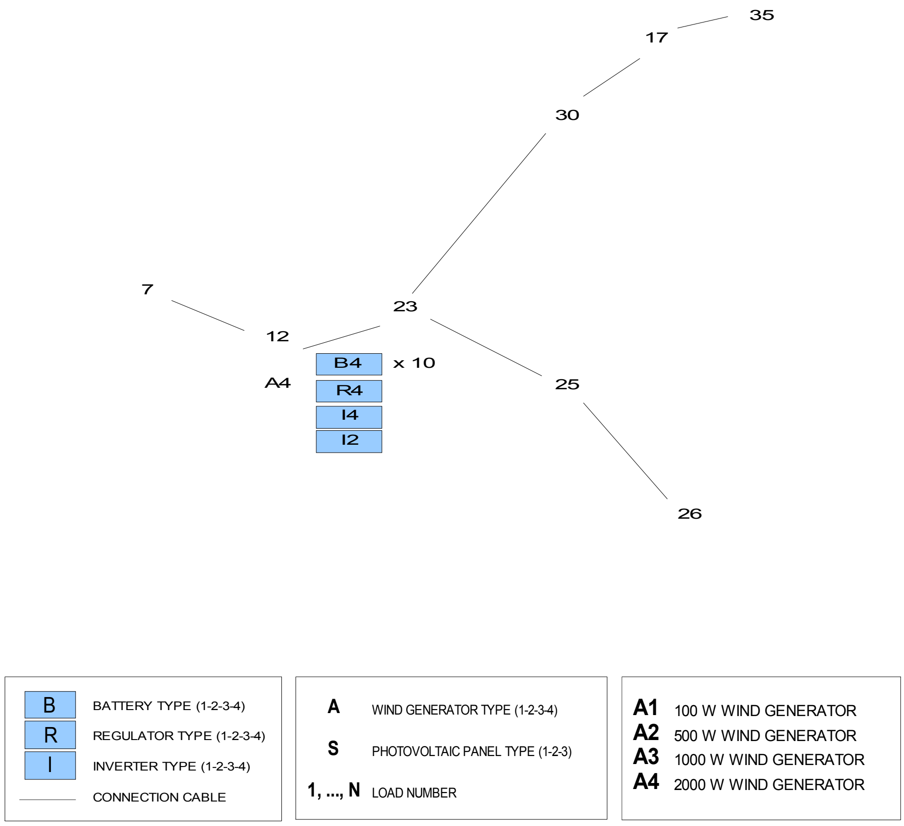


Figure 2.69: Second Grid Scheme - High demand, hybrid generation - El Alumbre

Here is the second grid electrical scheme:

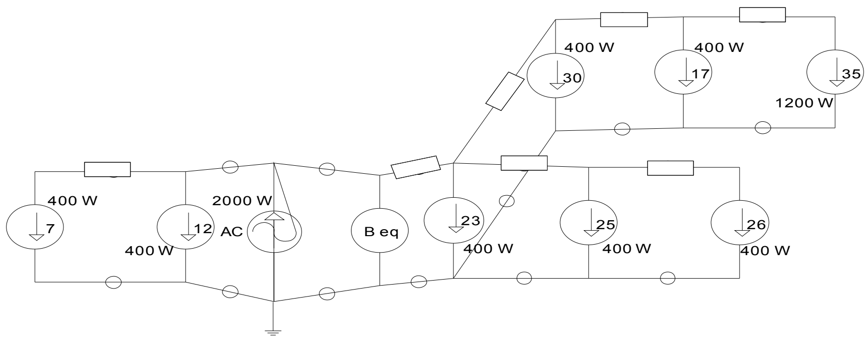


Figure 2.70: Second Grid Electrical Scheme - High demand, hybrid generation - El Alumbre

Third Grid:

The third grid is the smallest, and employs 2 wind generators (100 W), and one photovoltaic panel (50 W): the loads supplied are just two, 400 W of electrical power each. The batteries are two, and furthermore there are three inverters and one regulator device.

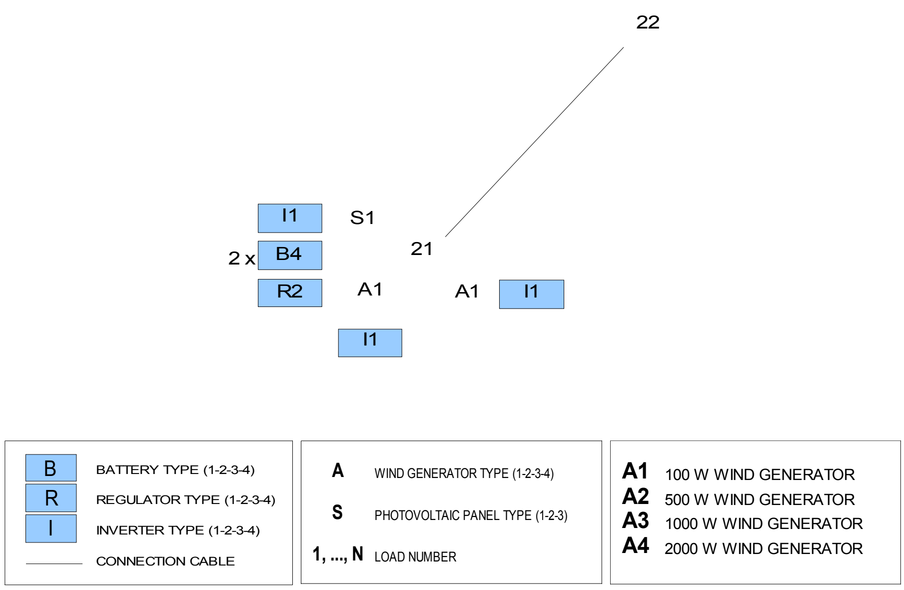


Figure 2.71: Third Grid Scheme - High demand, hybrid generation - El Alumbre

Here is the electrical scheme for the mentioned grid: the loads have 400 W of electrical power.

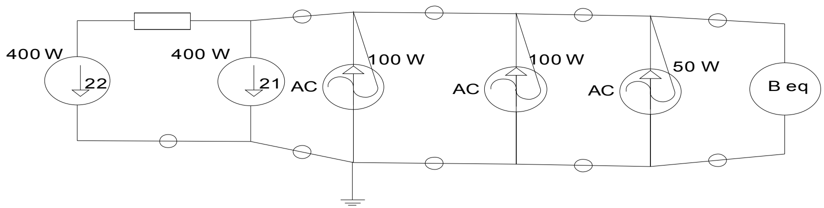


Figure 2.72: Third Grid Electrical Scheme - High demand, hybrid generation - El Alumbre

Finally, there are 3 different types of individual grids, that do not employ any cable infrastructure and supply just one load (a house); all of them can store the overproduced energy in a battery.

These grids are:

- Type 1 (5 grids): one 100 W wind generator supplies a 400 W load.
- Type 2 (5 grids): one 100 W wind generator and a 50 W photovoltaic panel supply a 400 W load.
- Type 3 (4 loads): two 100 W photovoltaic panels supply a 400 W load.

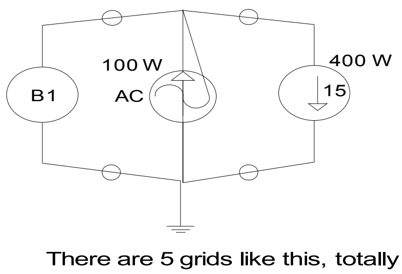


Figure 2.73: Individual Load (Type 1) Electrical Scheme - High demand, hybrid generation - El Alumbre

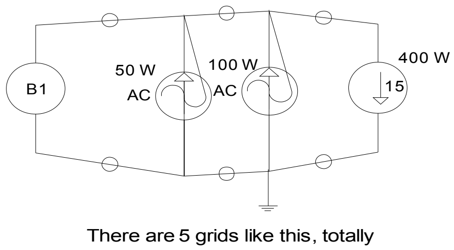


Figure 2.74: Individual Load (Type 2) Electrical Scheme - High demand, hybrid generation - El Alumbre

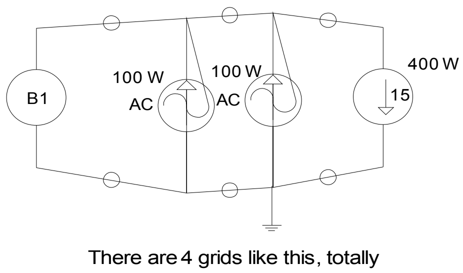


Figure 2.75: Individual Load (Type 3) Electrical Scheme - High demand, hybrid generation - El Alumbre

2.5.1 El Alumbre: Voltage Drops Analysis

After calculating the cable resistance and the cable inductance values, it is possible to run the circuit simulation in Simulink-Matlab Environment. The software allows for the calculation of the voltage values at each grid node, or rather at each load in the grid. Expecting a voltage value between 210 and 230 V, as GRECDH Team supposed in the preliminary analysis, it is pretty easy to calculate the voltage drop, that has to be lower than 8,70%. it is interesting to notice how this restriction is always respected in the ideal scenario modeled by UPC Team (cos φ=1, no reactive power in the loads), while in the Positive (cos φ=0,90) and Negative (cos φ=0,75) scenarios this is not always verified.

In this paragraph there is an accurate cable analysis, that calculates the voltage drops for all the grids regarding the different considered scenarios. The proposed solutions to solve some of the problems connected to the grid voltage drops are in the Chapter 3.

<u>Wind Energy System - Low Demand Case:</u>

In this case there is just a grid that feed several loads in the center of the area, and others individual systems without any cable infrastructure.

<u>Main Grid:</u>

There are no problems connected to excessive voltage drop values in this grid, even considering the Negative Scenario.

Main Grid: Ideal Scenario

All the loads have suitable voltage values, since the lowest value is 218,30 V.

POINT	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
1	219,58	230	10,42	4,53	---
10	218,62	230	11,38	4,95	---
17	218,47	230	11,53	5,01	---
24	228,97	230	1,03	0,45	---
27	220,76	230	9,24	4,02	---
28	220,88	230	9,12	3,97	---
8	218,53	230	11,47	4,99	---
30	218,30	230	11,70	5,09	---
34	228,61	230	1,39	0,60	---
35	218,75	230	11,25	4,89	---
4	230,00	230	0,00	0,00	---

Main Grid: Positive Scenario

Considering a relatively small amount of reactive power, the voltage values decrease sightly, but they remain satisfactory (the lowest is 214,89 V)

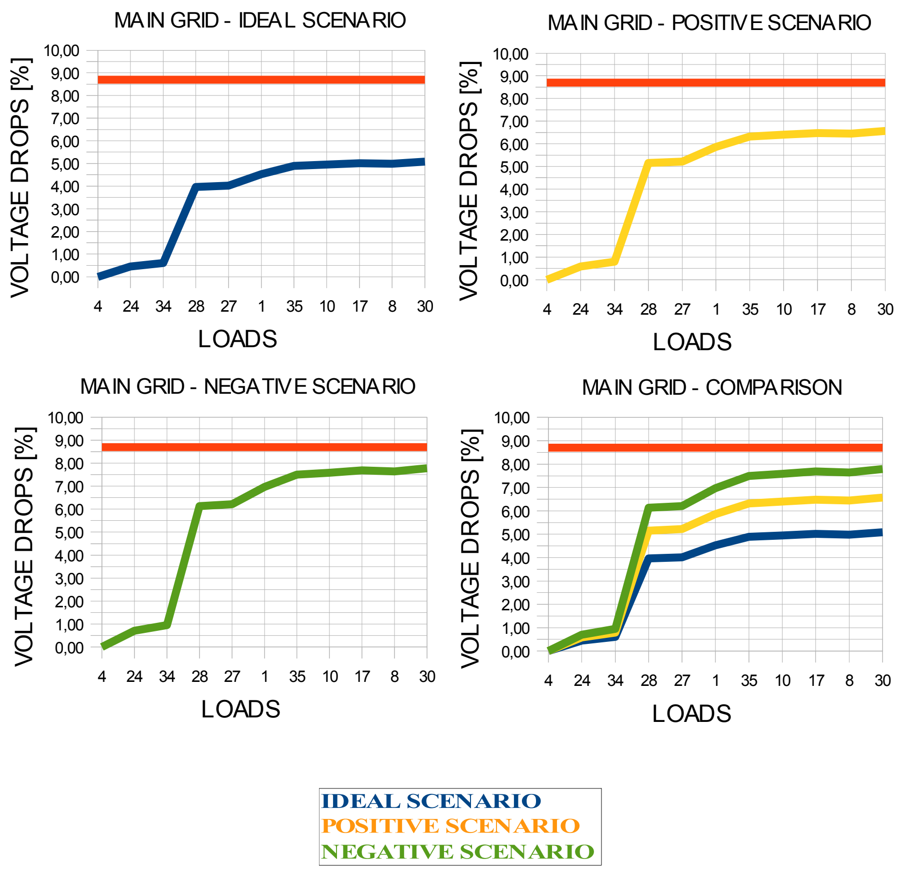
POINT	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
1	216,51	230	13,49	5,87	---
10	215,29	230	14,71	6,40	---
17	215,10	230	14,90	6,48	---
24	228,65	230	1,35	0,59	---
27	218,00	230	12,00	5,22	---
28	218,16	230	11,84	5,15	---
8	215,18	230	14,82	6,44	---
30	214,89	230	15,11	6,57	---
34	228,17	230	1,83	0,80	---
35	215,46	230	14,54	6,32	---
4	230,00	230	0,00	0,00	---

Main Grid: Negative Scenario

Even in Negative Scenario, the grid performance is acceptable.

POINT	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
1	213,97	230	16,03	6,97	---
10	212,56	230	17,44	7,58	---
17	212,33	230	17,67	7,68	---
24	228,38	230	1,62	0,70	---
27	215,72	230	14,28	6,21	---
28	215,90	230	14,10	6,13	---
8	212,42	230	17,58	7,64	---
30	212,09	230	17,91	7,79	---
34	227,81	230	2,19	0,95	---
35	212,75	230	17,25	7,50	---
4	230,00	230	0,00	0,00	---

The three scenario results are resumed here:



Individual Grid:

As exposed in the previous paragraph, there are no voltage drop problems concerning the individual loads supplied by individual generators (wind or photovoltaic). As no cable is employed in this type of structure, and the load and the generator are placed one next to the other, the voltage at the load is 230 V in the three considered scenarios.

Hybrid Generation System - Low Demand Case:

Also in this solution there is a grid in the center of the area, and several individual generation systems to feed the remainder loads.

Main Grid:

The grid performs suitably for Ideal and Positive Scenario, while there are several problems in the Negative case. Here are the three scenarios description.:

Main Grid: Ideal Scenario

Load 30 has the highest voltage drop (5,93%), that is acceptable.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	229,39	230	0,61	0,27	---
27	220,27	230	9,73	4,23	---
28	218,92	230	11,08	4,82	---
1	217,63	230	12,37	5,38	---
35	216,81	230	13,19	5,73	---
8	216,59	230	13,41	5,83	---
10	216,68	230	13,32	5,79	---
17	216,53	230	13,47	5,86	---
30	216,37	230	13,63	5,93	---

Main Grid: Positive Scenario

Considering an amount of reactive power in the grid, five loads have voltage drops higher than 7%, but the grid performance is acceptable since all the loads voltage values are higher than 210 V.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES

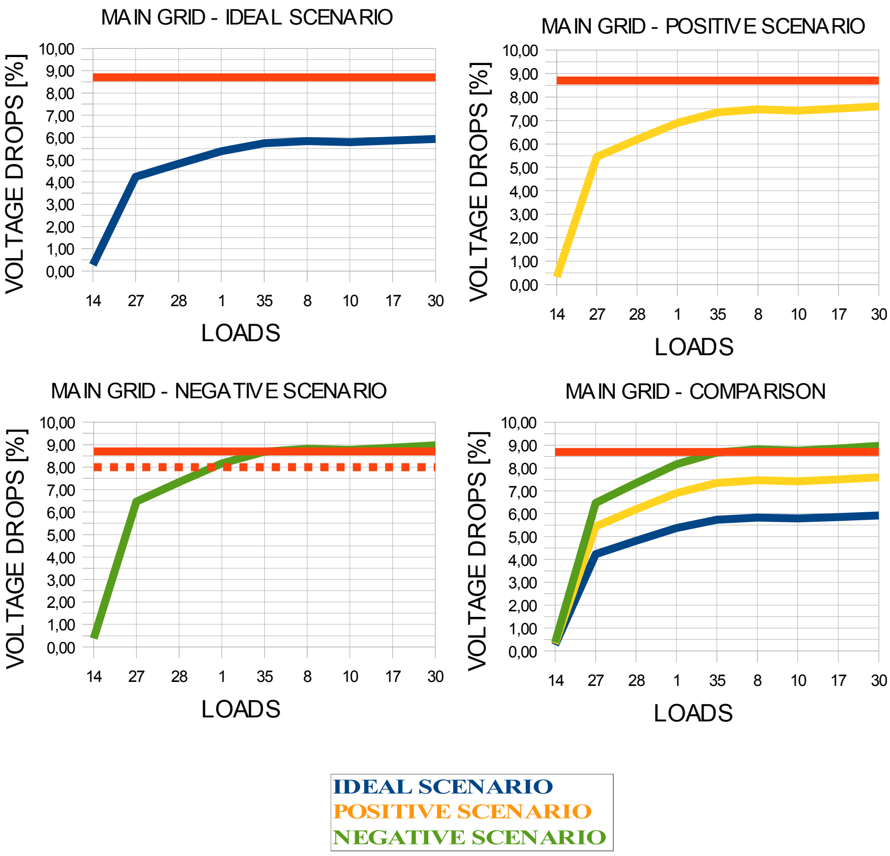
14	229,25	230	0,75	0,33	---
27	217,46	230	12,54	5,45	---
28	215,76	230	14,24	6,19	---
1	214,13	230	15,87	6,90	---
35	213,10	230	16,90	7,35	---
8	212,82	230	17,18	7,47	---
10	212,93	230	17,07	7,42	---
17	212,74	230	17,26	7,50	---
30	212,53	230	17,47	7,60	---

Main Grid: Negative Scenario

When power factor is 0,75, four loads have unacceptable voltage values, and furthermore two loads have worrying values and are labeled as "Close to limit"

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	229,14	230	0,86	0,37	---
27	215,12	230	14,88	6,47	---
28	213,14	230	16,86	7,33	---
1	211,23	230	18,77	8,16	CLOSE TO LIMIT
35	210,03	230	19,97	8,68	CLOSE TO LIMIT
8	209,71	230	20,29	8,82	TOO HIGH
10	209,84	230	20,16	8,77	TOO HIGH
17	209,62	230	20,38	8,86	TOO HIGH
30	209,37	230	20,63	8,97	TOO HIGH

Here is the results resume:



<u>Individual Grid:</u>

As commented for other individual grids, there is no any voltage drop when the load is connected directly to the generator.

Wind Generation System - High Demand Case:

In this case there are four grids: grid 1 and grid 2 are the biggest, and are very interesting concerning the voltage drops analysis, while the remainder are small and do not show considerable problems.

1 Grid:

The first Grid connects 11 loads, including the school.

1 Grid: Ideal Scenario

In this scenario there are no considerable problems due to voltage drops: the highest value is 5,83% (load 32), and the voltage value measured by Simulink Software in this load is 216,60 V.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	222,10	230	7,90	3,43	---
15	220,70	230	9,30	4,04	---
24	220,00	230	10,00	4,35	---
27	219,30	230	10,70	4,65	---
10	218,50	230	11,50	5,00	---
28	218,40	230	11,60	5,04	---
8	218,10	230	11,90	5,17	---
4	218,10	230	11,90	5,17	---
1	217,60	230	12,40	5,39	---
32	216,60	230	13,40	5,83	---

1 Grid: Positive Scenario

Neither in the Positive scenario are there are significant problems concerning voltage drops: the highest drop is 7,57%, but the voltage value in load 32 is 212,60 V.

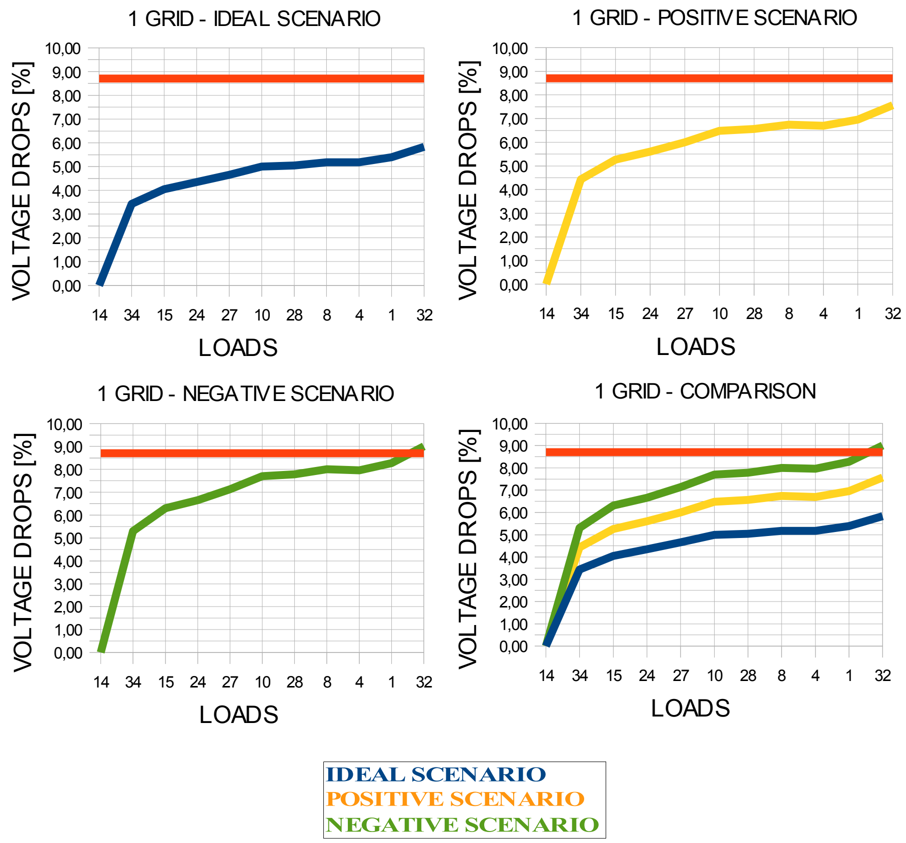
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	219,80	230	10,20	4,43	---
15	217,90	230	12,10	5,26	---
24	217,10	230	12,90	5,61	---
27	216,20	230	13,80	6,00	---
10	215,10	230	14,90	6,48	---
28	214,90	230	15,10	6,57	---
8	214,50	230	15,50	6,74	---
4	214,60	230	15,40	6,70	---
1	214,00	230	16,00	6,96	---
32	212,60	230	17,40	7,57	---

1 Grid: Negative Scenario

In the Negative scenario (cos φ=0,75), there are two loads that present a very high voltage drop: in load 1, it is 8,26%, so considered "Close to Limit", and in load 32 it is 9%, that's too high because the voltage value is in this case lower than 210 V (209,30 V).

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	217,80	230	12,20	5,30	---
15	215,50	230	14,50	6,30	---
24	214,70	230	15,30	6,65	---
27	213,60	230	16,40	7,13	---
10	212,30	230	17,70	7,70	---
28	212,10	230	17,90	7,78	---
8	211,60	230	18,40	8,00	---
4	211,70	230	18,30	7,96	---
1	**210,98**	**230**	**19,02**	**8,27**	**CLOSE TO LIMIT**
32	**209,30**	**230**	**20,70**	**9,00**	**TOO HIGH**

Here the three cases resume:



<u>2 Grid:</u>

The second grid connects 8 load, including the health center. Although it connects just eight loads, it presents more high voltage drop values in the Positive and Negative scenarios, because of the high cables length.

2 Grid: Ideal Scenario

In this case there are low voltage drops: the highest is 7,43% for the health center, that has a sufficient voltage value (212,90 V).

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	228,60	230	1,40	0,61	---
23	224,40	230	5,60	2,43	---
25	221,70	230	8,30	3,61	---
26	220,60	230	9,40	4,09	---
30	215,00	230	15,00	6,52	---
17	213,70	230	16,30	7,09	---
35	212,90	230	17,10	7,43	---

2 Grid: Positive Scenario

Considering an amount of reactive power, two loads present a high voltage drop value (load 17 and 35), while load 30 has 210,70 V, very close to the 210 V threshold.

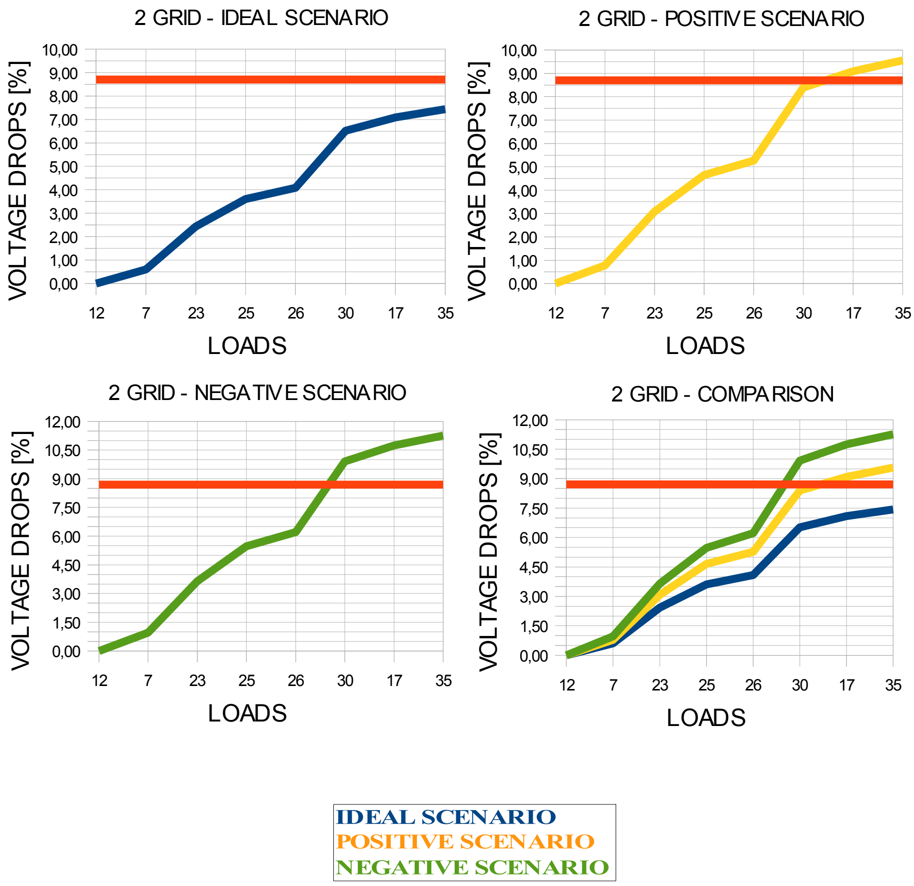
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	228,20	230	1,80	0,78	---
23	222,90	230	7,10	3,09	---
25	219,30	230	10,70	4,65	---
26	217,90	230	12,10	5,26	---
30	**210,70**	**230**	**19,30**	**8,39**	**CLOSE TO LIMIT**
17	**209,10**	**230**	**20,90**	**9,09**	**TOO HIGH**
35	**208,00**	**230**	**22,00**	**9,57**	**TOO HIGH**

2 Grid: Negative Scenario

In the Negative scenario, the three cited loads do not have the required voltage value, and the highest voltage drop is 11,26%.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	227,80	230	2,20	0,96	---
23	221,60	230	8,40	3,65	---
25	217,40	230	12,60	5,48	---
26	215,70	230	14,30	6,22	---
30	**207,20**	**230**	**22,80**	**9,91**	**TOO HIGH**
17	**205,30**	**230**	**24,70**	**10,74**	**TOO HIGH**
35	**204,10**	**230**	**25,90**	**11,26**	**TOO HIGH**

The three scenarios are resumed below:



<u>3 Grid:</u>

The third grid connects just three loads, in the east part of El Alumbre. There are no considerable voltage drops, because of the small extension of the grid.

3 Grid: Ideal Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
21	230,00	230	0,00	0,00	---
20	229,20	230	0,80	0,35	---
22	227,80	230	2,20	0,96	---

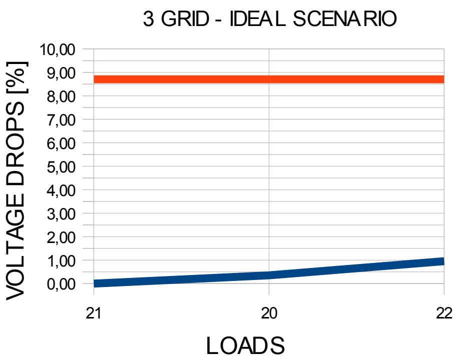
3 Grid: Positive Scenario

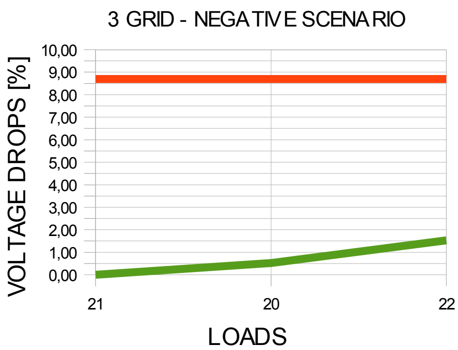
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
21	230,00	230	0,00	0,00	---
20	229,00	230	1,00	0,43	---
22	227,10	230	2,90	1,26	---

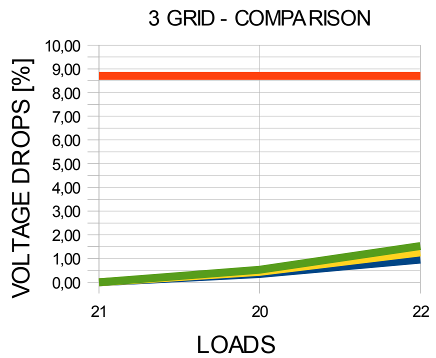
3 Grid: Negative Scenario

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
21	230,00	230	0,00	0,00	---
20	228,80	230	1,20	0,52	---
22	226,50	230	3,50	1,52	---

The three cases are compared here:







IDEAL SCENARIO
POSITIVE SCENARIO
NEGATIVE SCENARIO

4 Grid:

The fourth grid connects five loads and, as the third one, doesn't show considerable voltage drop values, due to its reduced geographical extension.

4 Grid: Ideal Scenario

If reactive power is not considered, as in the preliminary analysis, the voltage drops do not reach even 1%.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	---
5	229,20	230	0,80	0,35	---
9	228,60	230	1,40	0,61	---
13	228,50	230	1,50	0,65	---
33	228,30	230	1,70	0,74	---

4 Grid: Positive Scenario

Considering a 0,9 power factor, the voltage drops measured during the software simulation sightly increase.

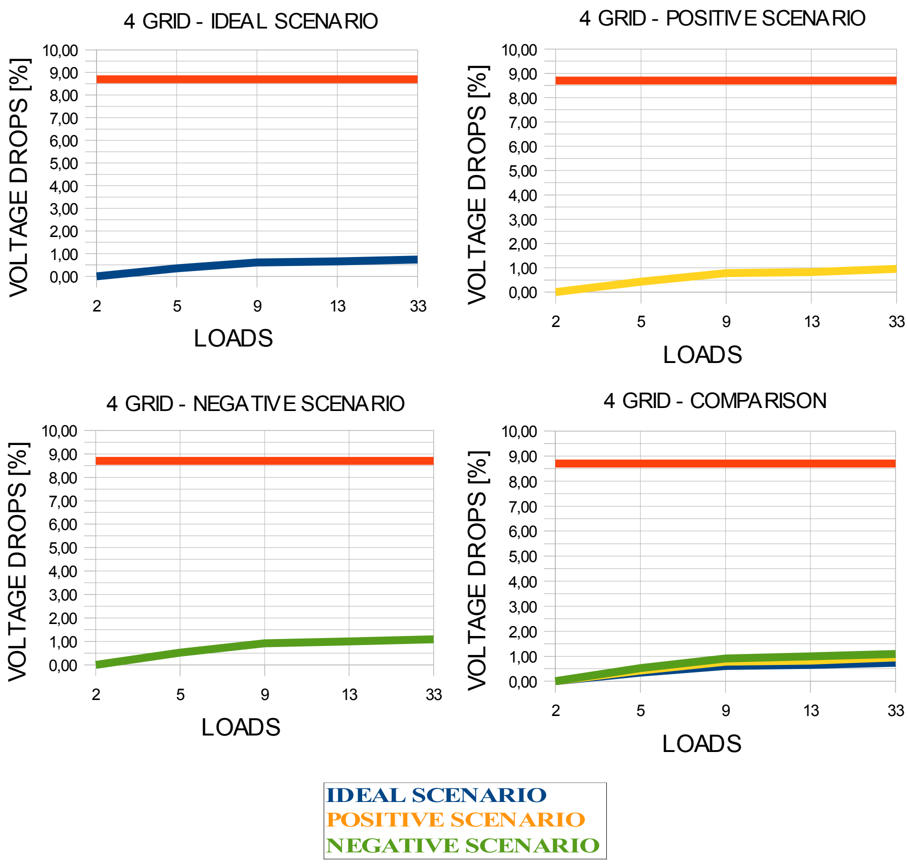
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	---
5	229,00	230	1,00	0,43	---
9	228,20	230	1,80	0,78	---
13	228,10	230	1,90	0,83	---
33	227,80	230	2,20	0,96	---

4 Grid: Negative Scenario

In the third considered scenario, some of the voltage drops reach 1%, but they are also in this case very low.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	230,00	230	0,00	0,00	---
5	228,80	230	1,20	0,52	---
9	227,90	230	2,10	0,91	---
13	227,70	230	2,30	1,00	---
33	227,50	230	2,50	1,09	---

Here is the three cases resume: there is no an evident difference between the three scenarios.



Hybrid Generation System - High Demand Case:

In this solution there are three grids: the first is very similar to the first grid in the Wind Generation System commented above, and connects the same loads; the second is exactly the same considered in the previous case, and finally the third one connects just two loads, and is interesting because it employs two 100 W Wind Generators and one 50 W photovoltaic panel.

1 Grid:

There are no problems if no reactive power is considered in the grid, while some of the loads do not have required values when power factor decreases.

1 Grid: Ideal Scenario

There are no problems concerning the voltage drops measured by Simulink; the highest value is 6,35%, but load 8 has 215,40 V.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	222,10	230	7,90	3,43	---
15	220,70	230	9,30	4,04	---
24	220,00	230	10,00	4,35	---
27	219,40	230	10,60	4,61	---
4	218,10	230	11,90	5,17	---
28	217,90	230	12,10	5,26	---
1	216,60	230	13,40	5,83	---
32	216,60	230	13,40	5,83	---
10	215,80	230	14,20	6,17	---
8	215,40	230	14,60	6,35	---

1 Grid: Positive Scenario

In the Positive scenario, load 8 voltage drop reaches a dangerous value, labeled as “Close to limit” because it is higher than the 8% threshold considered. Anyway the voltage value is 211,20 V.

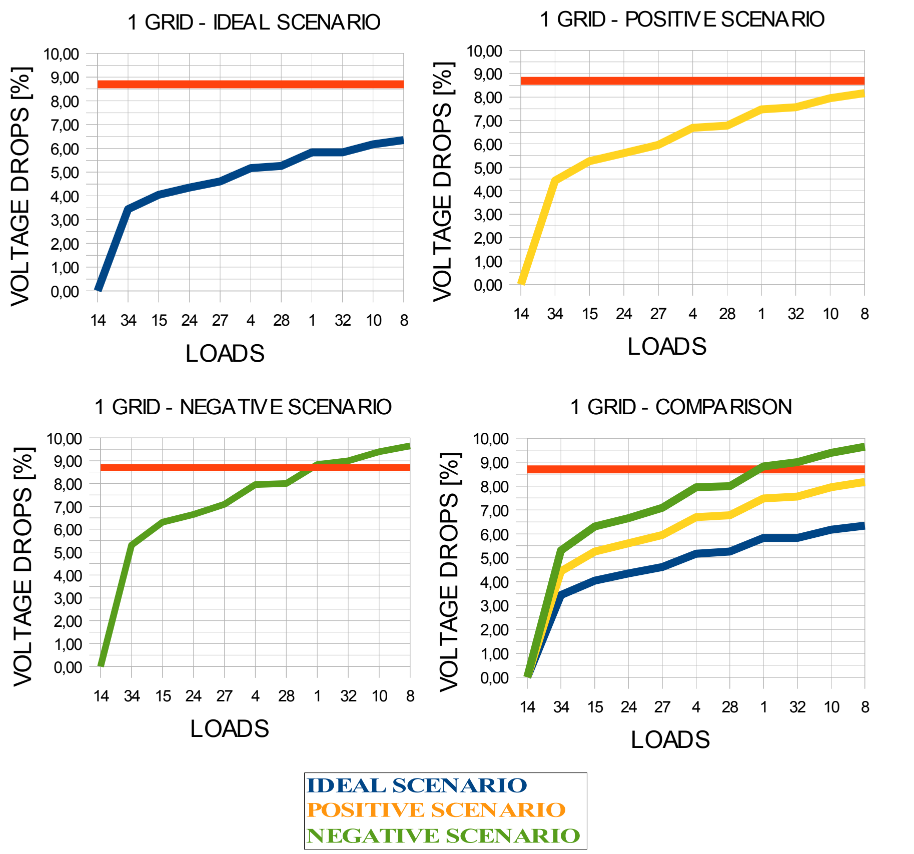
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	219,80	230	10,20	4,43	---
15	217,90	230	12,10	5,26	---
24	217,10	230	12,90	5,61	---
27	216,30	230	13,70	5,96	---
4	214,60	230	15,40	6,70	---
28	214,40	230	15,60	6,78	---
1	212,80	230	17,20	7,48	---
32	212,60	230	17,40	7,57	---
10	211,70	230	18,30	7,96	---
8	**211,20**	**230**	**18,80**	**8,17**	**CLOSE TO LIMIT**

1 Grid: Negative Scenario

In the Negative scenario, as expected, load 8 voltage drop is too high (9,65%), and furthermore load 1 and load 10 voltage drops are also higher than 8,70% limit.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	217,80	230	12,20	5,30	---
15	215,50	230	14,50	6,30	---
24	214,70	230	15,30	6,65	---
27	213,70	230	16,30	7,09	---
4	211,70	230	18,30	7,96	---
28	211,60	230	18,40	8,00	---
1	**209,70**	**230**	**20,30**	**8,83**	**TOO HIGH**
32	**209,30**	**230**	**20,70**	**9,00**	**TOO HIGH**
10	**208,40**	**230**	**21,60**	**9,39**	**TOO HIGH**
8	**207,80**	**230**	**22,20**	**9,65**	**TOO HIGH**

The figure below shows clearly the difference between the three described scenarios:



<u>2 Grid:</u>

The second grid is the same commented above in the Wind Generation System.

2 Grid: Ideal Scenario

There are no problems concerning voltage drops for the Ideal Scenario:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	228,60	230	1,40	0,61	---
23	224,40	230	5,60	2,43	---
25	221,70	230	8,30	3,61	---
26	220,60	230	9,40	4,09	---
30	215,00	230	15,00	6,52	---
17	213,70	230	16,30	7,09	---
35	212,90	230	17,10	7,43	---

2 Grid: Positive Scenario

Load 17 and 35 have low voltage values, 209,10 V and 208 V. Load 30 is labeled as "Close to limit".

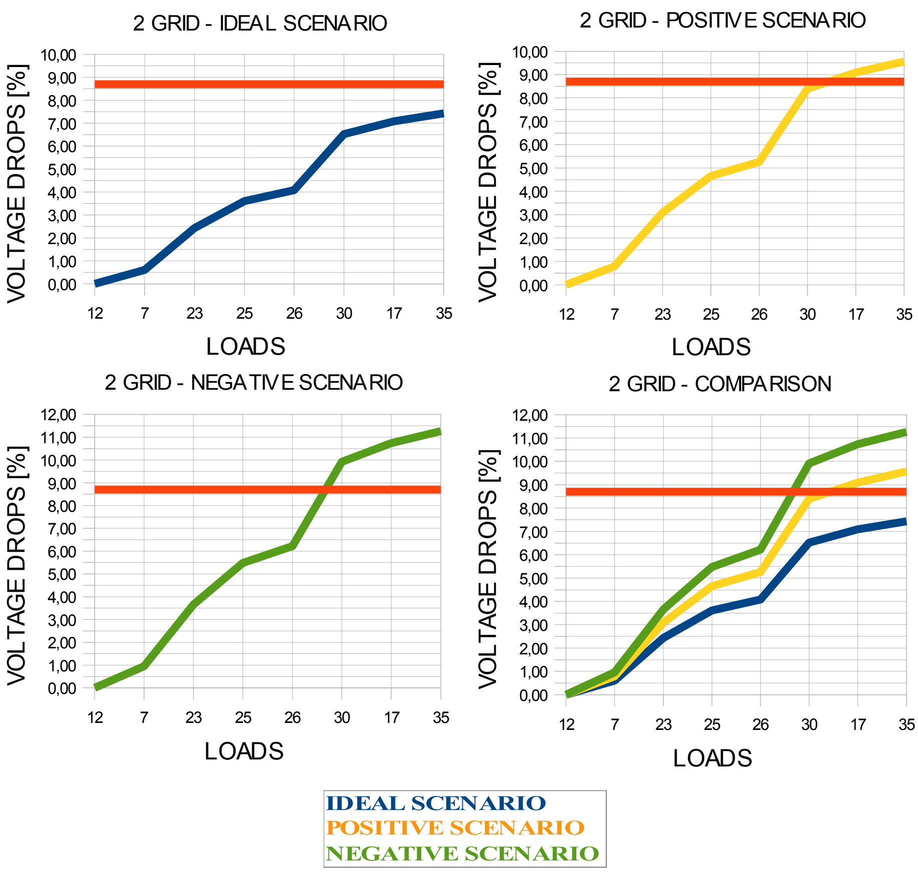
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	228,20	230	1,80	0,78	---
23	222,90	230	7,10	3,09	---
25	219,30	230	10,70	4,65	---
26	217,90	230	12,10	5,26	---
30	**210,70**	**230**	**19,30**	**8,39**	**CLOSE TO LIMIT**
17	**209,10**	**230**	**20,90**	**9,09**	**TOO HIGH**
35	**208,00**	**230**	**22,00**	**9,57**	**TOO HIGH**

2 Grid: Negative Scenario

In this scenario three loads don't have the required voltage value.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	227,80	230	2,20	0,96	---
23	221,60	230	8,40	3,65	---
25	217,40	230	12,60	5,48	---
26	215,70	230	14,30	6,22	---
30	**207,20**	**230**	**22,80**	**9,91**	**TOO HIGH**
17	**205,30**	**230**	**24,70**	**10,74**	**TOO HIGH**
35	**204,10**	**230**	**25,90**	**11,26**	**TOO HIGH**

It is evident reactive power has a strong influence on grid performance:



<u>3 Grid:</u>

This grid is very small, and it connects just two loads. There are no troubles concerning voltage drops.

3 Grid: Ideal Scenario

Load 22 has 229,20 V voltage value.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
21 22	230,00 229,20	230 230	0,00 0,80	0,00 0,35	--- ---

3 Grid: Positive Scenario

In this case its voltage decreases to 229 V.

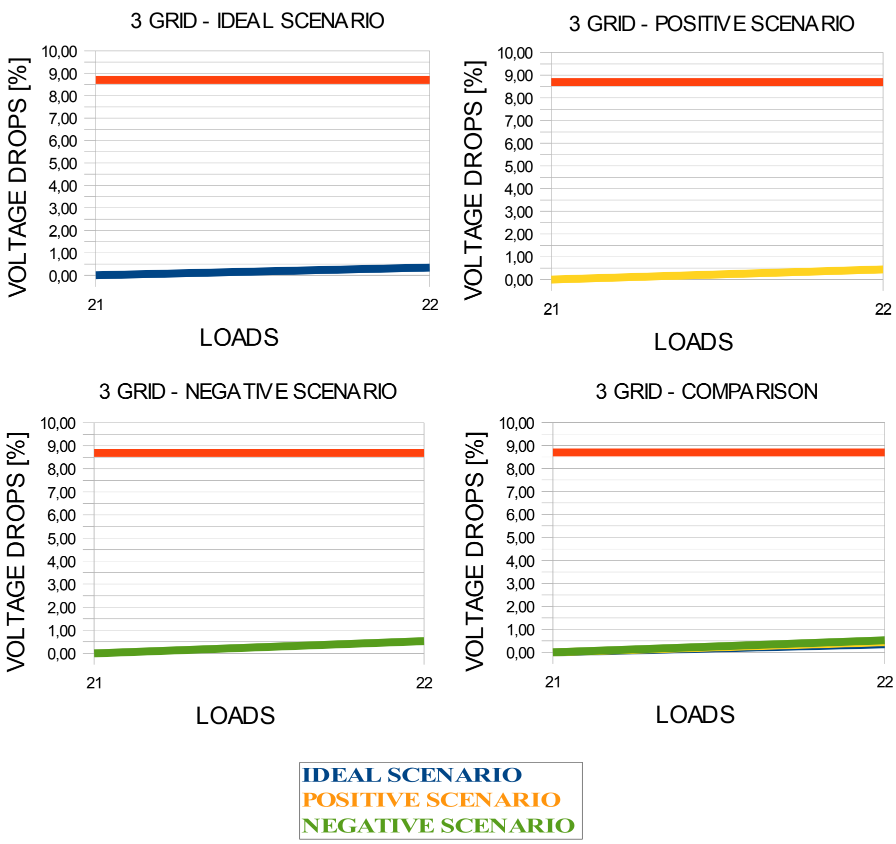
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
21	230,00	230	0,00	0,00	---
22	229,00	230	1,00	0,43	---

3 Grid: Negative Scenario

In this case, the voltage is 228,80 V.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
21	230,00	230	0,00	0,00	---
22	228,80	230	1,20	0,52	---

As shown in the figure, the three performances are very similar:



3. Proposed solutions to decrease voltage drops

As commented in the previous chapter, some of the analyzed microgrids have not the required voltage (between 210 and 230 V) at each load, because of the different values of reactive power the loads were supposed to have in the Positive and Negative scenarios. In this chapter there are the results of several simulations, in collaboration with CITCEA Department, run in a Simulink-Matlab Environment that consider different connection cables, bigger than AWG 7 used in the preliminary simulation; by using cables with a bigger section, the voltage drops decrease, and the required voltages are reached in all cases. Of course a bigger cable is more expensive than a AWG 7, because it requires more material: the economic aspect is also considered in this chapter, so for each proposed solution an extra-budget is calculated.

GRECDH Team supposed to use AWG (American Wire Gauge) cables in the preliminary study: here are the cables sections, expressed in mm²:

AWG Cables	
AWG	Section [mm²]
14	2,10
13	2,60
12	3,30
11	4,20
10	5,30
9	6,60
8	8,40
7	10,50
6	13,30
5	16,80
4	21,10
3	26,70
2	33,60
1	42,40

GRECDH Team used only AWG 7 cables in the preliminary model, although two cable parameters were known (concerning AWG 7 and AWG 6):

AMERICAN WIRE GAUGE (AWG) CABLE				
AWG	SECTION [mm²]	RESISTANCE [Ω / m]	MAX CURRENT [A]	COST / METER [$ / m]
7	10,50	0,00271	89	4,90
6	13,30	0,00215	101	5,10

Cables AWG 7 and AWG 6 are unsuitable to solve all the voltage problems risen during the analysis: because of that, the resistance / meter values, the maximum current values and the cost for each cable are calculated. The resistivity for the conductor material (Aluminum) is easily calculated:

$$\rho = \frac{R * S}{L}$$

Where R is the resistance [Ω], S the section [m²] and L the cable length [m]; of course the resistivity ρ is expressed in [Ω * m]. For cable AWG 7, resistivity is 0,028455 [μΩ * m], and for AWG 6 is 0,028595 [μΩ * m]: so it is possible considering the average of these values as resistivity value for next cases: 0,028525 [μΩ * m]. The resistance values for the remainders AWG cables are calculated as follow:

$$R = \frac{\rho * L}{S}$$

The obtained values are in the table, while in the graphics there are the resistance (expressed in Ω) and electric conductance values (expressed in Siemens) in function of the cable sections:

AWG	SECTION [mm²]	RESISTANCE [Ω / m]
7	**10,50**	**0,00271**
6	**13,30**	**0,00215**
5	16,80	0,00170
4	21,10	0,00135
3	26,70	0,00107
2	33,60	0,00085
1	42,40	0,00067

AWG	SECTION [mm²]	CONDUCTANCE [S / m]
7	**10,50**	**369,00**
6	**13,30**	**465,12**
5	16,80	588,96
4	21,10	739,70
3	26,70	936,02
2	33,60	1177,91
1	42,40	1486,42

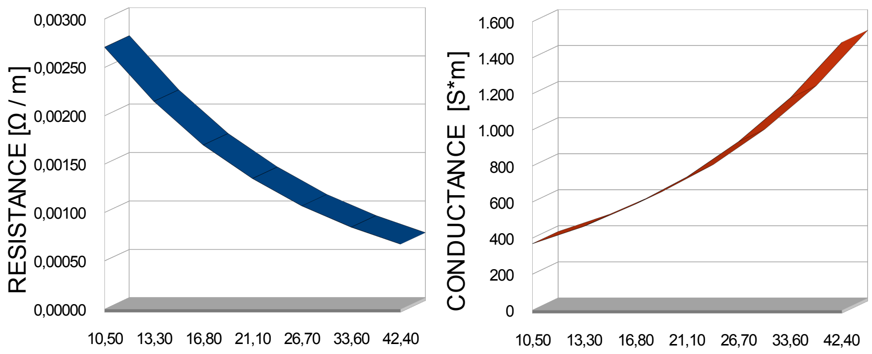


Figure 3.1: [Resistance / meter] and [Conductance * meter] for different cables

Maximum currents for AWG 7 and AWG 6 were also known in the preliminary analysis: 89 A for AWG 7 and 101 A for AWG 6. The remaining values are calculated by an interpolation of these values: the starting step considers that AWG 7 can conduct 89 A and AWG 6 101: the ratio AWG 7 / AWG 6 is 0,88119. The AWG 5 value is calculated using this formula:

AWG 5 Max Current = AWG 6 Max Current * 0,88119

And so on with the others AWG cables; notice that these are approximated values, but the currents there are in the analyzed microgrids are not so high for the cables used as conductors (between 1 and 15 A). That's why this approximation can be accepted:

AWG	SECTION [mm²]	MAX CURRENT [A]
7	**10,50**	**89**
6	**13,30**	**101**
5	16,80	114
4	21,10	129
3	26,70	146
2	33,60	164
1	42,40	186

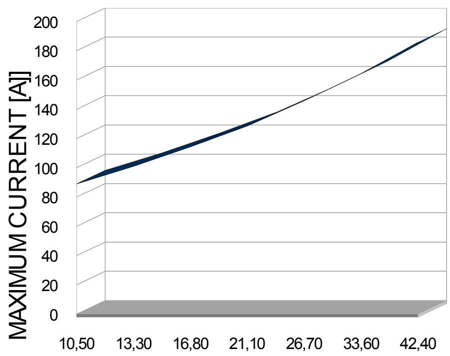


Figure 3.2: Maximum Current for different section cables

GRECDH Team calculated a cost per meter to obtain a total cable cost for each found solution. This cost is calculated taking into account both fixed and variable costs: the AWG 7 cost/meter is 4,90 $/m, and AWG 6 is 5,10 $/m as shown above. The variable cost concerns the quantity of material used for each cable, evidently proportional to the cable section, while fixed cost concerns others costs, like posts, cost of work etc... By a simple analysis of the available data, it is evident that for each meter the fixed cost is 4,15 $/m and the variable cost is 0,07 $/cm^3. Each cable has a fixed cost equal to $ 4,90, and a variable cost that varies (proportional to material used), as shown below:

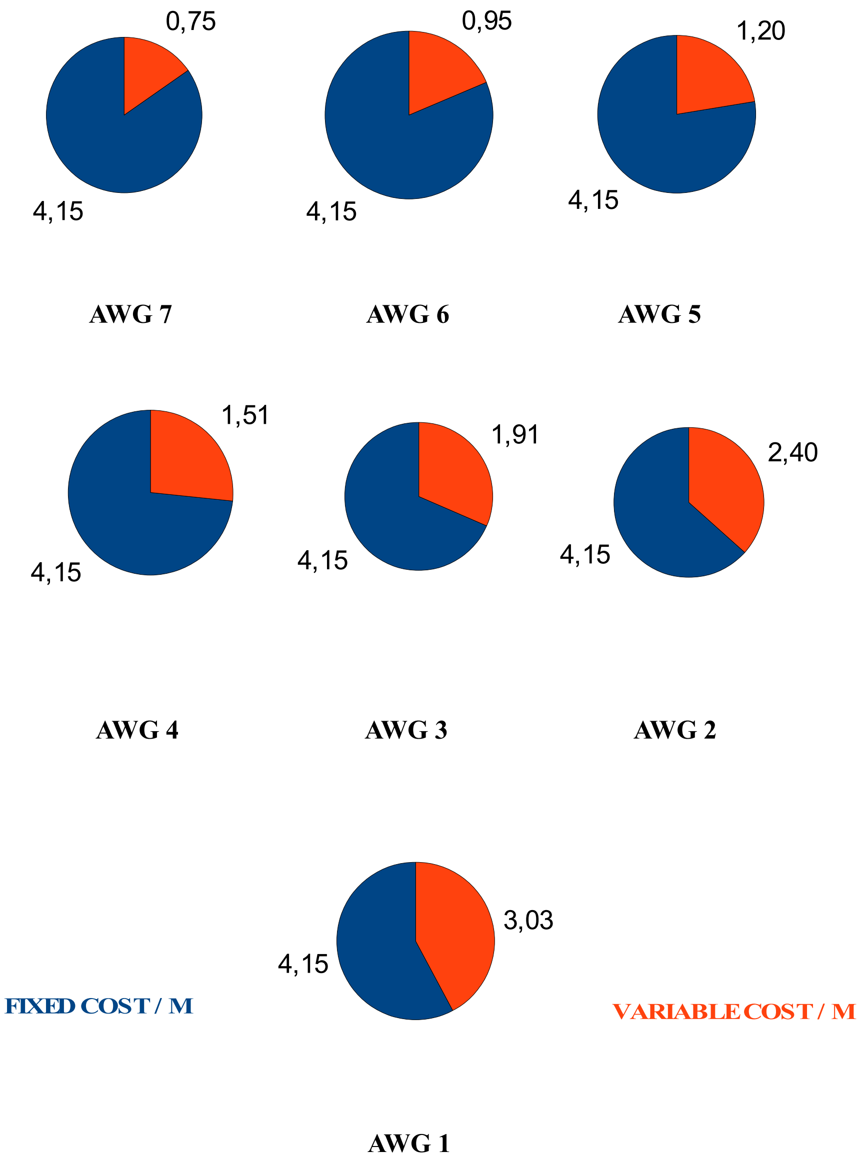


Figure 3.3: Fixed and Variable Cost for each cable type [$/m]

Variable / total cost ratio is about 15% for AWG 7 cables, while it is about 27% for AWG 4 and increase up to 42% for AWG 1.

All the cable costs are collected in the table below:

AWG	SECTION [mm^2]	VOLUME / m [cm^3]	FIXED COST [$]	VARIABLE COST [$ / cm^3]	COST / m [$ / m]	EXTRA COST [$ / m]
7	**10,50**	**10,50**	**4,15**	**0,07**	**4,90**	---
6	**13,30**	**13,30**			**5,10**	0,20
5	16,80	16,80			5,35	0,45
4	21,10	21,10			5,66	0,76
3	26,70	26,70			6,06	1,16
2	33,60	33,60			6,55	1,65
1	42,40	42,40			7,18	2,28

It is evident that cable total cost per meter is proportional to cable section:

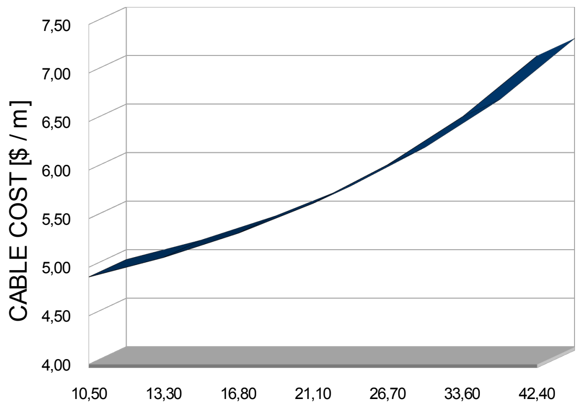


Figure 3.4: Cable cost for different cable types

The extra cost is calculated as the difference between each cable total cost per meter and the AWG 7 cost per meter, because in the preliminary analysis all the employed cables were AWG 7. For instance, a proposed solution requires 100 meters of AWG 5 cable instead of AWG 7, so the total cost is:

100 m * 5,35 $ / m = $ 535

while the **extra cost** to consider is:

100 m * 0,45 $ / m = $ 45

Finally, here are all the electrical parameters and the costs concerning seven AWG cables:

AMERICAN WIRE GAUGE (AWG) CABLE				
AWG	SECTION [mm²]	RESISTANCE [Ω / m]	MAX CURRENT [A]	COST / METER [$ / m]
7	**10,50**	**0,00271**	**89**	**4,90**
6	**13,30**	**0,00215**	**101**	**5,10**
5	16,80	0,00170	114	5,35
4	21,10	0,00135	129	5,66
3	26,70	0,00107	146	6,06
2	33,60	0,00085	164	6,55
1	42,40	0,00067	186	7,18

The simulations results commented in the previous chapter are useful because they identify those grids that need bigger cables to decrease the voltage drops and to increase the stability of the grid itself: in this chapter solutions are proposed concerning the Positive and Negative Scenarios.

3.1 Proposed solutions for Positive scenario

There are no problems concerning Alto Peru analysis in Positive Scenario. Simulations regarding El Alumbre show that voltage drops are too high in three grids, all of them in the High Demand Case, in which the electrical power is 400 W for houses and 1200 W for the school and for the health center.

First Grid:

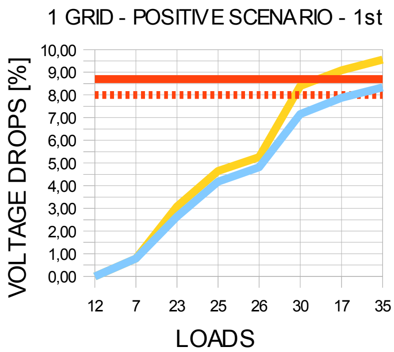
The first analyzed case concerns the "Second grid in the Wind Generation Case, High Demand": here are the results obtained in the preliminary simulation, using AWG 7 cables:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	228,20	230	1,80	0,78	---
23	222,90	230	7,10	3,09	---
25	219,30	230	10,70	4,65	---
26	217,90	230	12,10	5,26	---
30	210,70	230	19,30	8,39	CLOSE TO LIMIT
17	209,10	230	20,90	9,09	TOO HIGH
35	208,00	230	22,00	9,57	TOO HIGH

The resolution process requires several steps: two cables are considered in the first step of the analysis: the first is the longest (424 meters), and connects loads 23 and 30, while the second connects loads 12 and 23: they are replaced by two AWG 6 cables, that have a section of 13,30 mm², instead of 10,50 mm² used in the preliminary analysis. Here are the step 1 results:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	228,20	230	1,80	0,78	---
23	223,94	230	6,06	2,63	---
25	220,40	230	9,60	4,17	---
26	218,94	230	11,06	4,81	---
30	213,53	230	16,47	7,16	---
17	211,88	230	18,12	7,88	---
35	210,82	230	19,18	8,34	CLOSE TO LIMIT

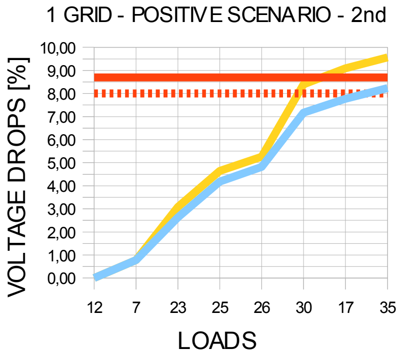
POSITIVE SCENARIO SOLUTION
PROPOSED SOLUTION



Load 30 and Load 17 have now acceptable voltage values, thanks to the lower resistance value of AWG 6 cable: their voltage drops decrease, and are lower than 8% security threshold. Load 35, instead, is labeled as "Close to limit", because the voltage drops is higher than 8%; in step 2 cable 30 – 17 (almost 74 meters) is AWG 6: load 35 voltage drop decreases, but it is still considered "Close to limit":

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	228,20	230	1,80	0,78	---
23	223,94	230	6,06	2,63	---
25	220,39	230	9,61	4,18	---
26	218,93	230	11,07	4,81	---
30	213,52	230	16,48	7,17	---
17	212,13	230	17,87	7,77	---
35	211,07	230	18,93	8,23	CLOSE TO LIMIT

POSITIVE SCENARIO SOLUTION
PROPOSED SOLUTION



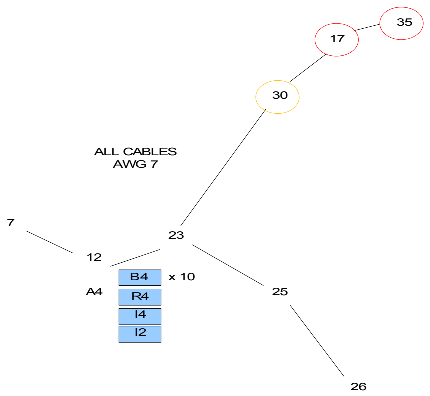
In step 3 AWG 5 is used for 12 – 23 connection cable, while 23-30 cable and cable 30-17 remain AWG 6. No more steps are required now because all the voltage drops are acceptable:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	228,20	230	1,80	0,78	---
23	224,84	230	5,16	2,24	---
25	221,28	230	8,72	3,79	---
26	219,81	230	10,19	4,43	---
30	214,38	230	15,62	6,79	---
17	212,98	230	17,02	7,40	---
35	211,92	230	18,08	7,86	---

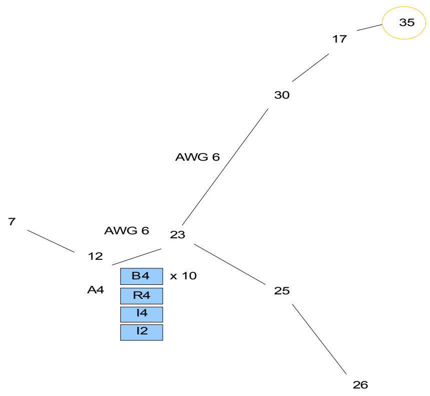
POSITIVE SCENARIO SOLUTION
PROPOSED SOLUTION

The four steps are resumed here:

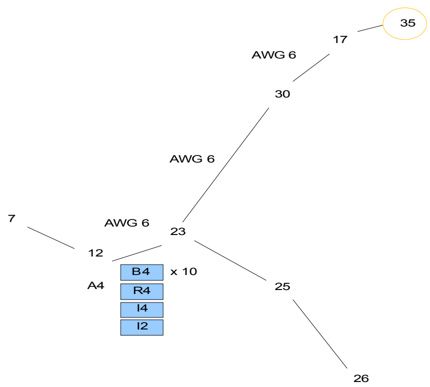
Step 0:



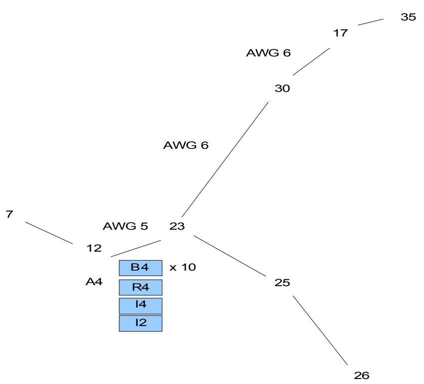
Step 1:



Step 2:



Step 3:



TOO HIGH

CLOSE TO LIMIT

The extra costs to consider for the proposed solution are in the table below: the third step extra cost is $ 169,54.

PROPOSED SOLUTION	CONNECTION POINTS	CABLE LENGTH [m]	CABLE TYPE [AWG]	CABLE SECTION [mm²]	EXTRA COST [$ / m]	CABLE EXTRA COST [$]	TOTAL EXTRA COST [$]
1st	12 – 23 23 – 30	155,35 424,19	AWG 6 AWG 6	13,30 13,30	0,20 0,20	31,07 84,84	*115,91*
2nd	12 – 23 23 – 30 30 – 17	155,35 424,19 73,99	AWG 6 AWG 6 AWG 6	13,30 13,30 13,30	0,20 0,20 0,20	31,07 84,84 14,80	*130,71*
3rd	**12 – 23 23 – 30 30 – 17**	**155,35 424,19 73,99**	**AWG 5 AWG 6 AWG 6**	**16,80 13,30 13,30**	**0,45 0,20 0,20**	**69,91 84,84 14,8**	**169,54**

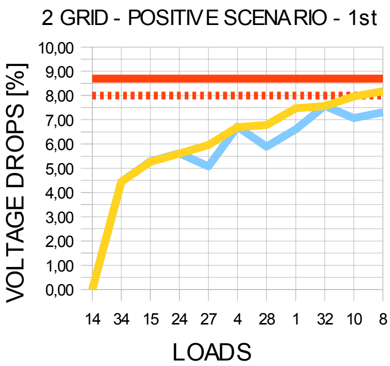
Second Grid:

The second considered grid is the "First Grid in Hybrid Generation Case, High Demand": load 8 has 211,20 V, so is labeled as "Close to limit".

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	219,80	230	10,20	4,43	---
15	217,90	230	12,10	5,26	---
24	217,10	230	12,90	5,61	---
27	216,30	230	13,70	5,96	---
4	214,60	230	15,40	6,70	---
28	214,40	230	15,60	6,78	---
1	212,80	230	17,20	7,48	---
32	212,60	230	17,40	7,57	---
10	211,70	230	18,30	7,96	---
8	211,20	230	18,80	8,17	CLOSE TO LIMIT

In Step 1, cable 14 – 27 (336 meters) is replaced with an AWG 6 cable: the simulation results are in the table below.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	219,80	230	10,20	4,43	---
15	217,85	230	12,15	5,28	---
24	217,09	230	12,91	5,61	---
27	218,32	230	11,68	5,08	---
4	214,56	230	15,44	6,71	---
28	216,46	230	13,54	5,89	---
1	214,81	230	15,19	6,6	---
32	212,57	230	17,43	7,58	---
10	213,74	230	16,26	7,07	---
8	213,18	230	16,82	7,31	---

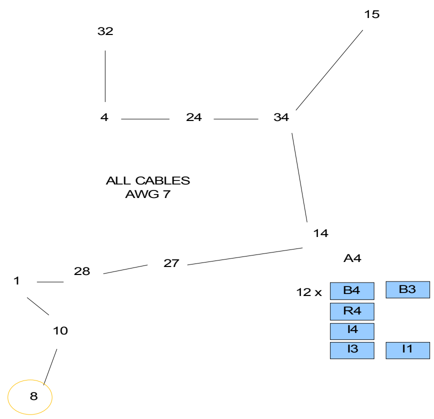


POSITIVE SCENARIO SOLUTION
PROPOSED SOLUTION

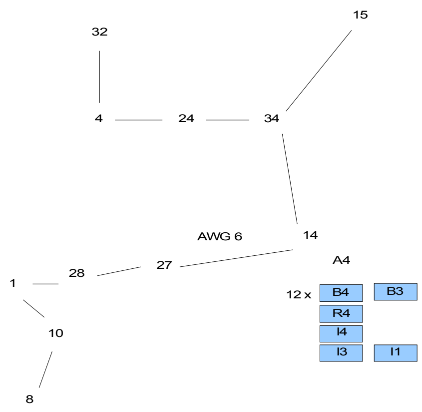
Load 8 has now 213,18 V, but also load 27, 28, 1 and 10 perform better, having higher voltage values; it would have been possible to change cable 8 – 10 (99 meters), but this would have not increased the voltage values for loads 27, 28, 1 and 10, even if it would have solved the problem in load 8. This is very positive for microgrid stability, and more importantly the extra cost required is very low:

PROPOSED SOLUTION	CONNECTION POINTS	CABLE LENGTH [m]	CABLE TYPE [AWG]	CABLE SECTION [mm²]	EXTRA COST [$ / m]	CABLE EXTRA COST [$]	TOTAL EXTRA COST [$]
1st	14 – 27	336,14	AWG 6	13,30	0,20	67,23	67,23

Step 0:



Step 1:



TOO HIGH
CLOSE TO LIMIT

Third Grid:

This is the “Second Grid in Hybrid Generation System, High Demand Scenario”. This grid is exactly the same grid considered in the Wind Generation System, high demand Scenario, described as first grid. The required extra cost is $ 169,54.

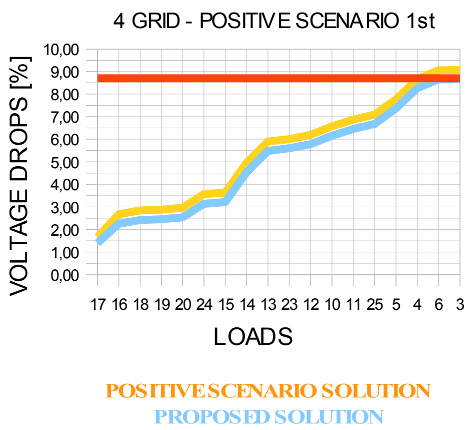
Fourth Grid:

This is the “Second Grid” in the Wind Generation System, Low Demand Scenario in Alto Peru: the preliminary analysis shows that two loads have a too high voltage drop, while another is labeled as “Close to limit”.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	226,17	230	3,83	1,67	---
16	223,84	230	6,16	2,68	---
18	223,45	230	6,55	2,85	---
19	223,38	230	6,62	2,88	---
20	223,19	230	6,81	2,96	---
24	221,80	230	8,20	3,57	---
15	221,64	230	8,36	3,63	---
14	218,60	230	11,40	4,96	---
13	216,43	230	13,57	5,90	---
23	216,18	230	13,82	6,01	---
12	215,76	230	14,24	6,19	---
10	214,89	230	15,11	6,57	---
11	214,21	230	15,79	6,87	---
25	213,69	230	16,31	7,09	---
5	212,14	230	17,86	7,77	---
4	**210,06**	**230**	**19,94**	**8,67**	**CLOSE TO LIMIT**
6	**209,17**	**230**	**20,83**	**9,06**	**TOO HIGH**
3	**209,14**	**230**	**20,86**	**9,07**	**TOO HIGH**

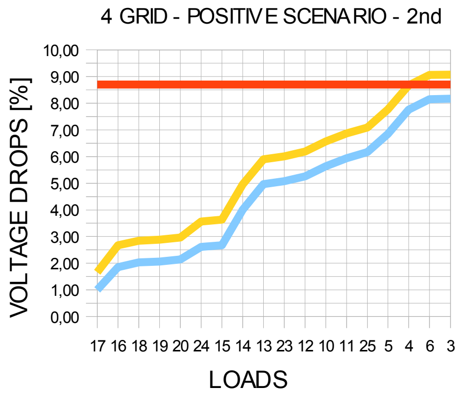
In the first step, cables 73 – 17 and 17 – 16 are replaced by two AWG 6 cables: these cables are the closest to the generator, so all the load voltage drops decrease, but three loads do not have acceptable voltage drop values.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	226,78	230	3,22	1,4	---
16	224,82	230	5,18	2,25	---
18	224,43	230	5,57	2,42	---
19	224,36	230	5,64	2,45	---
20	224,17	230	5,83	2,53	---
24	222,77	230	7,23	3,14	---
15	222,61	230	7,39	3,21	---
14	219,56	230	10,44	4,54	---
13	217,37	230	12,63	5,49	---
23	217,13	230	12,87	5,60	---
12	216,71	230	13,29	5,78	---
10	215,83	230	14,17	6,16	---
11	215,15	230	14,85	6,46	---
25	214,63	230	15,37	6,68	---
5	213,07	230	16,93	7,36	---
4	210,98	230	19,02	8,27	CLOSE TO LIMIT
6	210,09	230	19,91	8,66	CLOSE TO LIMIT
3	210,06	230	19,94	8,67	CLOSE TO LIMIT



In the second step, 73 – 17 cable is replaced by AWG 5 cable: just two loads have not acceptable values:

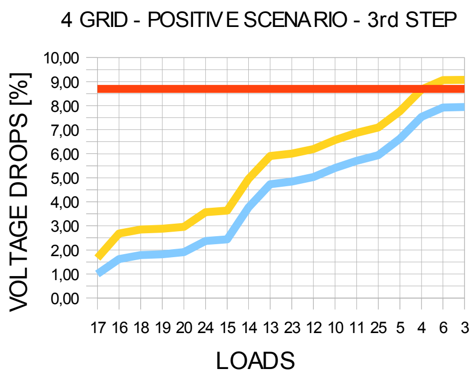
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	227,70	230	2,30	1,00	---
16	225,73	230	4,27	1,86	---
18	225,33	230	4,67	2,03	---
19	225,26	230	4,74	2,06	---
20	225,07	230	4,93	2,14	---
24	224,00	230	6,00	2,61	---
15	223,85	230	6,15	2,67	---
14	220,78	230	9,22	4,01	---
13	218,58	230	11,42	4,97	---
23	218,33	230	11,67	5,07	---
12	217,91	230	12,09	5,26	---
10	217,03	230	12,97	5,64	---
11	216,34	230	13,66	5,94	---
25	215,81	230	14,19	6,17	---
5	214,25	230	15,75	6,85	---
4	212,15	230	17,85	7,76	---
6	211,25	230	18,75	8,15	CLOSE TO LIMIT
3	211,22	230	18,78	8,17	CLOSE TO LIMIT



POSITIVE SCENARIO SOLUTION
PROPOSED SOLUTION

It is evident that another step is required: also cable 17 – 16 cable is now replaced by AWG 5, and the Matlab-Simulink simulation gives satisfactory results:

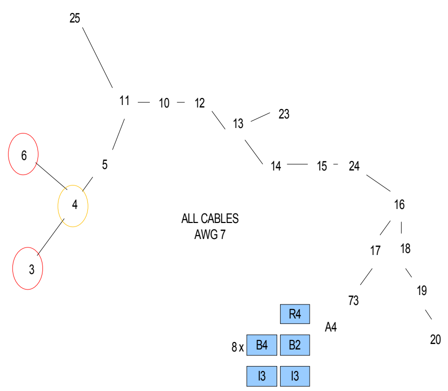
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	227,69	230	2,31	1,00	—
16	226,28	230	3,72	1,62	—
18	225,89	230	4,11	1,79	—
19	225,82	230	4,18	1,82	—
20	225,63	230	4,37	1,9	—
24	224,55	230	5,45	2,37	—
15	224,40	230	5,60	2,43	—
14	221,32	230	8,68	3,77	—
13	219,11	230	10,89	4,73	—
23	218,86	230	11,14	4,84	—
12	218,44	230	11,56	5,03	—
10	217,56	230	12,44	5,41	—
11	216,87	230	13,13	5,71	—
25	216,34	230	13,66	5,94	—
5	214,77	230	15,23	6,62	—
4	212,67	230	17,33	7,53	---
6	211,77	230	18,23	7,93	---
3	211,74	230	18,26	7,94	---



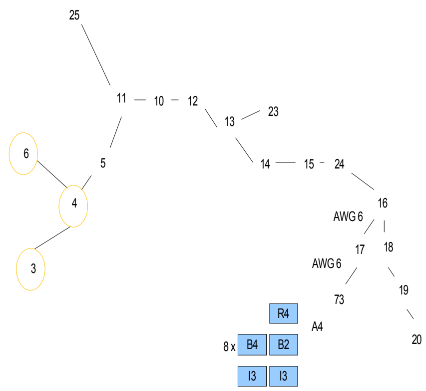
POSITIVE SCENARIO SOLUTION
PROPOSED SOLUTION

Here is the three steps resume:

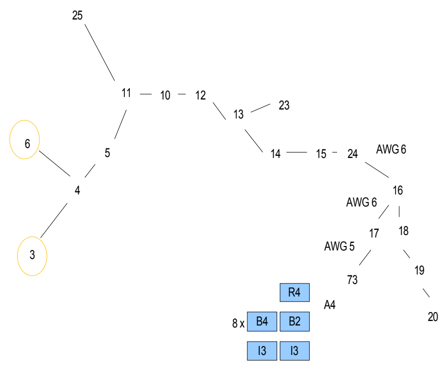
Step 0:



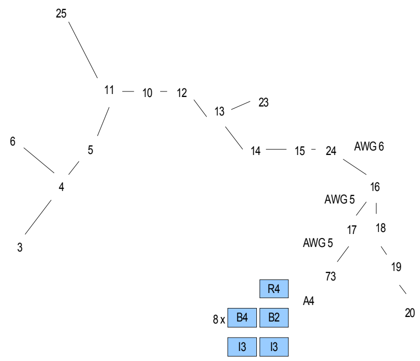
Step 1:



Step 2:



Step 3:



TOO HIGH

CLOSE TO LIMIT

The extra cost for the third step is however very low, $ 59,07.

PROPOSED SOLUTION	CONNECTION POINTS	CABLE LENGTH [m]	CABLE TYPE [AWG]	CABLE SECTION [mm²]	EXTRA COST [$ / m]	CABLE EXTRA COST [$]	TOTAL EXTRA COST [$]
1st	73 – 17 17 – 16	66,60 43,22	AWG 6 AWG 6	13,30 13,30	0,20 0,20	13,32 8,64	*21,96*
2nd	73 – 17 17 – 16 16 – 24	66,60 43,22 48,27	AWG 5 AWG 6 AWG 6	16,80 13,30 13,30	0,45 0,20 0,20	29,97 8,64 9,65	*48,27*
3rd	**73 – 17** **17 – 16** **16 – 24**	**66,60** **43,22** **48,27**	**AWG 5** **AWG 5** **AWG 6**	**16,80** **16,80** **13,30**	**0,45** **0,45** **0,20**	**29,97** **19,45** **9,65**	***59,07***

The total extra cost for the 4 considered grids is $ 465,38.

POSITIVE SCENARIO

	1st GRID	2nd GRID	3rd GRID	4th GRID	TOTAL EXTRA COST [$]
EXTRA COST [$]	169,54	67,23	169,54	59,07	**465,38**

3.2 Proposed solutions for Negative scenario

There are 7 microgrids that do not reach the required voltage for each load. it is interesting to notice that just two of them belongs to the Low Demand Scenario cases group, but they require a limited number of steps to solve all the voltage problems.

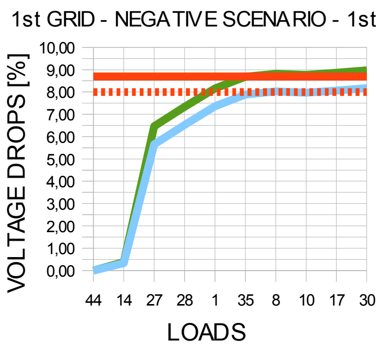
First Grid:

The first grid taken into consideration is the "Main grid in Hybrid Generation System, Low Demand Scenario"; here are the voltage drop values measured in the preliminary analysis:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
44	230,00	230	0,00	0,00	---
14	229,14	230	0,86	0,37	---
27	215,12	230	14,88	6,47	---
28	213,14	230	16,86	7,33	---
1	**211,23**	**230**	**18,77**	**8,16**	**CLOSE TO LIMIT**
35	**210,03**	**230**	**19,97**	**8,68**	**CLOSE TO LIMIT**
8	**209,71**	**230**	**20,29**	**8,82**	**TOO HIGH**
10	**209,84**	**230**	**20,16**	**8,77**	**TOO HIGH**
17	**209,62**	**230**	**20,38**	**8,86**	**TOO HIGH**
30	**209,37**	**230**	**20,63**	**8,97**	**TOO HIGH**

In the first proposed solution, the cable 44 – 14 (20 meters) and 27 – 14 (336 meters) are AWG 6 cables: the voltage drops in the cited loads decrease, all of them are lower than 8,70%, but are not higher than the 8% security threshold.

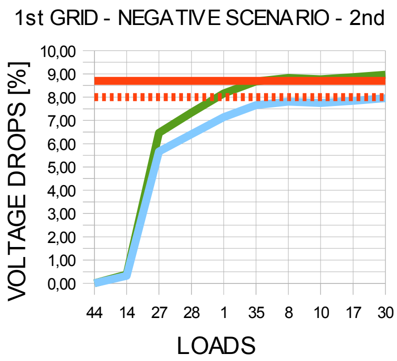
POINT	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	229,26	230	0,74	0,32	---
27	217,00	230	13,00	5,65	---
28	215,00	230	15,00	6,52	---
1	213,08	230	16,92	7,36	---
35	211,86	230	18,14	7,89	---
8	**211,54**	**230**	**18,46**	**8,03**	**CLOSE TO LIMIT**
10	211,67	230	18,33	7,97	---
17	**211,45**	**230**	**18,55**	**8,07**	**CLOSE TO LIMIT**
30	**211,20**	**230**	**18,80**	**8,17**	**CLOSE TO LIMIT**



NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION

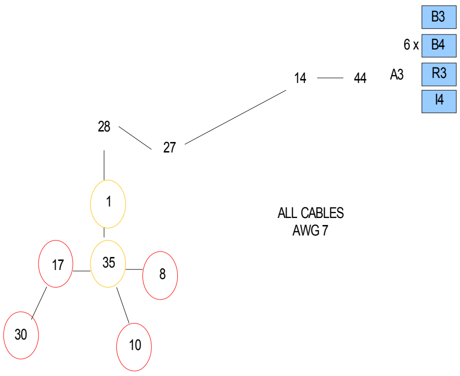
Another solution is required, that's the step 2 shown here: also cable 27 – 28 is an AWG 6 cable, and the simulation results are satisfactory.

POINT	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
44	230,00	230	0,00	0,00	—
14	229,26	230	0,74	0,32	—
27	216,97	230	13,03	5,67	—
28	215,25	230	14,75	6,41	—
1	213,59	230	16,41	7,13	---
35	212,38	230	17,62	7,66	---
8	212,05	230	17,95	7,80	---
10	212,18	230	17,82	7,75	---
17	211,96	230	18,04	7,84	---
30	211,71	230	18,29	7,95	---

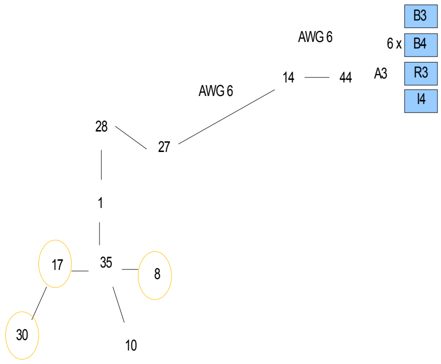


NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION

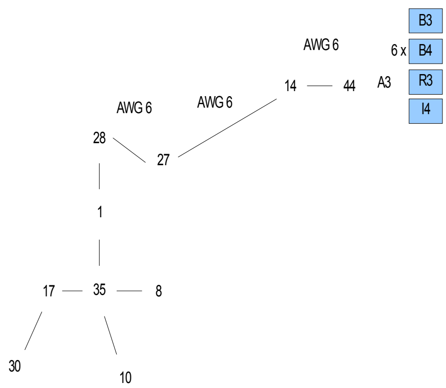
Step 0:



Step 1:



Step 2:



TOO HIGH
CLOSE TO LIMIT

This solution is satisfactory and the extra cost is just $ 82,36. Here is the extra cost table:

PROPOSED SOLUTION	CONNECTION POINTS	CABLE LENGTH [m]	CABLE TYPE [AWG]	CABLE SECTION [mm²]	EXTRA COST [$ / m]	CABLE EXTRA COST [$]	TOTAL EXTRA COST [$]
1st	44 – 14	20,71	AWG 6	13,30	0,20	4,14	
	27 – 14	336,14	AWG 6	13,30	0,20	67,23	71,37
2nd	**44 – 14**	**20,71**	**AWG 6**	**13,30**	**0,20**	**4,14**	
	27 – 14	**336,14**	**AWG 6**	**13,30**	**0,20**	**67,23**	
	27 – 28	**54,95**	**AWG 6**	**13,30**	**0,20**	**10,99**	**82,36**

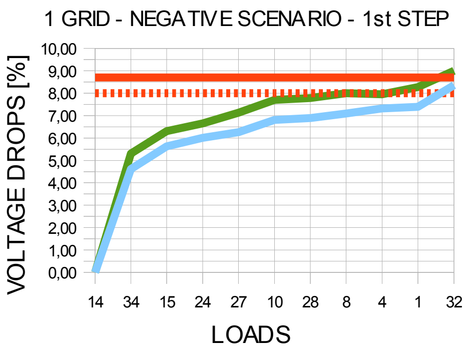
<u>Second Grid:</u>

The second considered microgrid is the "First Grid, Wind Generation System, High Demand Scenario": here are the voltage drop values of the preliminary analysis:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	217,80	230	12,20	5,30	---
15	215,50	230	14,50	6,30	---
24	214,70	230	15,30	6,65	---
27	213,60	230	16,40	7,13	---
10	212,30	230	17,70	7,70	---
28	212,10	230	17,90	7,78	---
8	211,60	230	18,40	8,00	---
4	211,70	230	18,30	7,96	---
1	**210,98**	**230**	**19,02**	**8,27**	**CLOSE TO LIMIT**
32	**209,30**	**230**	**20,70**	**9,00**	**TOO HIGH**

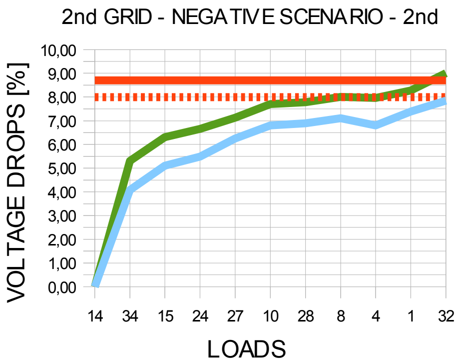
Load 32 has a too high voltage drop value, and moreover load 1 has just 210,98 V, very close to 210 V threshold. So, in the first proposed solution (step 1) the cables 14 – 34 (344 meters) and 14 – 27 (336 meters) are replaced with two AWG 6 cables: the simulation returns these results:

POINT	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	219,39	230	10,61	4,61	---
15	217,05	230	12,95	5,63	---
24	216,17	230	13,83	6,01	---
27	215,62	230	14,38	6,25	---
10	214,34	230	15,66	6,81	---
28	214,16	230	15,84	6,89	---
8	213,67	230	16,33	7,10	---
4	213,16	230	16,84	7,32	---
1	213,00	230	17,00	7,39	—
32	**210,77**	**230**	**19,23**	**8,36**	**CLOSE TO LIMIT**



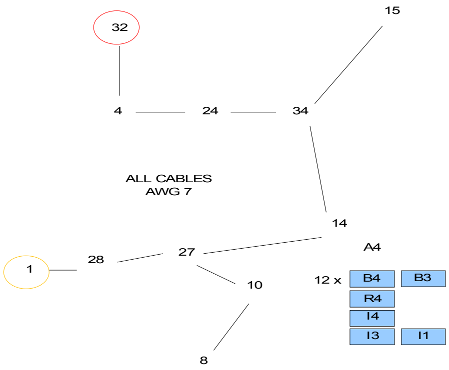
Load 32 voltage drop decreases, but it is not lower than 8%. So, a next step is required, by replacing cable 14 – 34 with an AWG 5 cable:

POINT	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	220,61	230	9,39	4,08	---
15	218,26	230	11,74	5,10	---
24	217,38	230	12,62	5,49	---
27	215,62	230	14,38	6,25	---
10	214,34	230	15,66	6,81	---
28	214,16	230	15,84	6,89	---
8	213,67	230	16,33	7,10	---
4	214,35	230	15,65	6,80	---
1	213,00	230	17,00	7,39	---
32	211,95	230	18,05	7,85	---

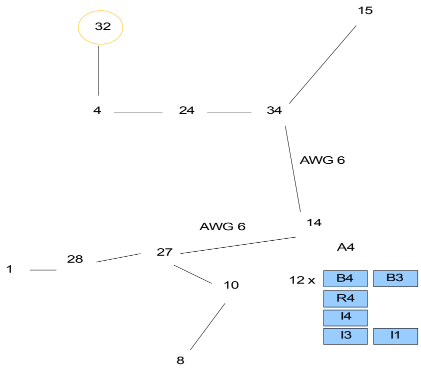


The measured values are satisfactory; here are the 2 steps:

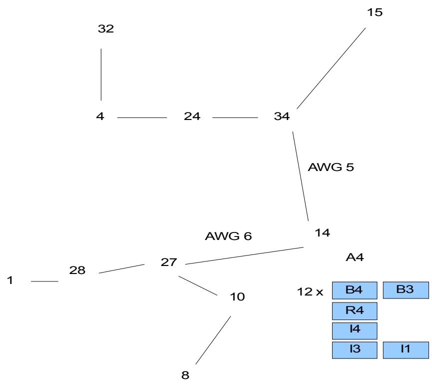
Step 0:



Step 1:



Step 2:



TOO HIGH

CLOSE TO LIMIT

The extra cost for the second proposed solution is $ 222,34 :

PROPOSED SOLUTION	CONNECTION POINTS	CABLE LENGTH [m]	CABLE TYPE [AWG]	CABLE SECTION [mm²]	EXTRA COST [$ / m]	CABLE EXTRA COST [$]	TOTAL EXTRA COST [$]
1st	14 – 34 14 – 27	344,69 336,14	AWG 6 AWG 6	13,30 13,30	0,20 0,20	68,94 67,23	136,17
2nd	**14 – 34** **14 – 27**	**344,69** **336,14**	**AWG 5** **AWG 6**	**16,80** **13,30**	**0,45** **0,20**	**155,11** **67,23**	**222,34**

<u>Third Grid:</u>

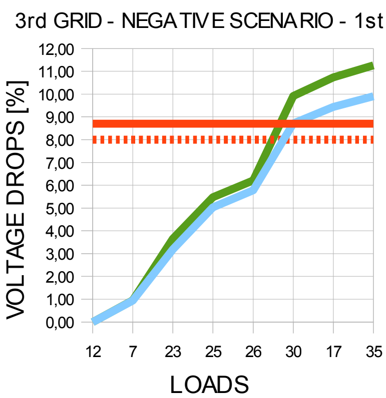
The third case taken into consideration is the “Second Grid in the Wind Generation System, High Demand Scenario”, and the results returned by the preliminary analysis follow: three loads have too high voltage drop values.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	227,80	230	2,20	0,96	---
23	221,60	230	8,40	3,65	---
25	217,40	230	12,60	5,48	---
26	215,70	230	14,30	6,22	---
30	**207,20**	**230**	**22,80**	**9,91**	**TOO HIGH**
17	**205,30**	**230**	**24,70**	**10,74**	**TOO HIGH**
35	**204,10**	**230**	**25,90**	**11,26**	**TOO HIGH**

The first solution to solve these problems previews to replace cables 23 – 30 (424 meters), 30 – 17 (74 meters), 17 – 35 (63 meters) and 12 – 23 (155 meters) by four AWG 6 cables, that have a 13,30 mm² section. The results follow:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	227,84	230	2,16	0,94	---
23	222,67	230	7,33	3,19	---
25	218,44	230	11,56	5,03	---
26	216,70	230	13,30	5,78	---
30	**209,96**	**230**	**20,04**	**8,71**	**TOO HIGH**
17	**208,29**	**230**	**21,71**	**9,44**	**TOO HIGH**
35	**207,23**	**230**	**22,77**	**9,90**	**TOO HIGH**

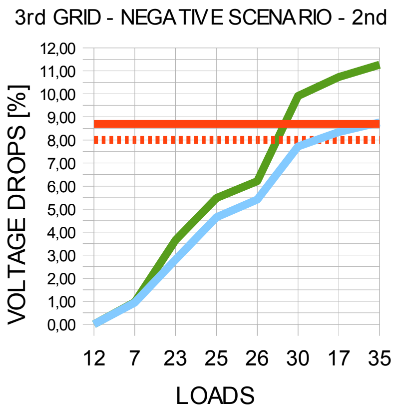
NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION



The obtained results are not satisfactory: so the cables are replaced with four AWG 5 cables, that have a 16,80 mm² section; the simulation results are:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	227,84	230	2,16	0,94	---
23	223,54	230	6,46	2,81	---
25	219,30	230	10,70	4,65	---
26	217,55	230	12,45	5,41	---
30	212,25	230	17,75	7,72	---
17	210,79	230	19,21	8,35	CLOSE TO LIMIT
35	209,85	230	20,15	8,76	TOO HIGH

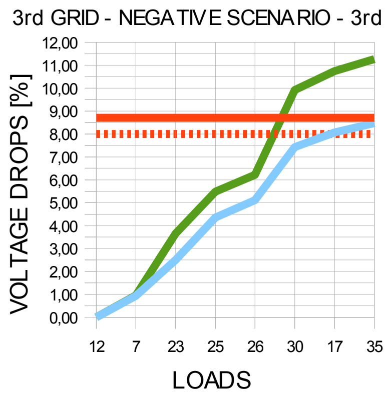
NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION



The voltage drops are not satisfactory: in the third proposed solution, the 12 – 23 cable (the closest to the wind generator) is replaced by an AWG 4 cable; the simulation results follow:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	227,84	230	2,16	0,94	---
23	224,25	230	5,75	2,50	---
25	219,99	230	10,01	4,35	---
26	218,24	230	11,76	5,11	---
30	212,92	230	17,08	7,43	---
17	211,45	230	18,55	8,07	CLOSE TO LIMIT
35	210,52	230	19,48	8,47	CLOSE TO LIMIT

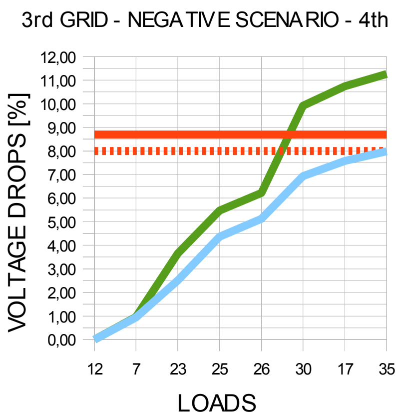
NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION



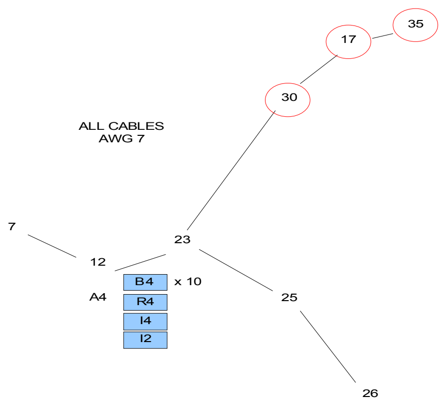
In the fourth step all the loads have at least 210,52 V, that can be considered a positive voltage value, but loads 17 and 35 are labeled as “Close to limit”; so a further step is required, by replacing also cable 23 – 30 by an AWG 4. The results obtained are better than the previous ones, and no further steps are required:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	230,00	230	0,00	0,00	---
7	227,84	230	2,16	0,94	---
23	224,22	230	5,78	2,51	---
25	219,97	230	10,03	4,36	---
26	218,22	230	11,78	5,12	---
30	214,06	230	15,94	6,93	---
17	212,59	230	17,41	7,57	---
35	211,64	230	18,36	7,98	---

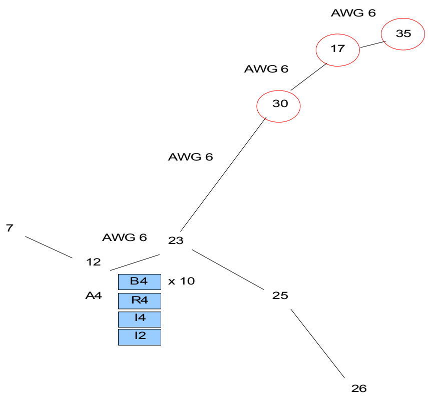
NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION



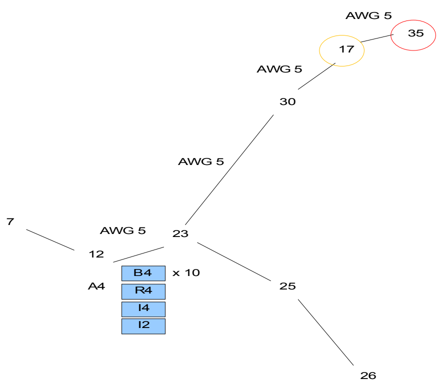
Step 0:



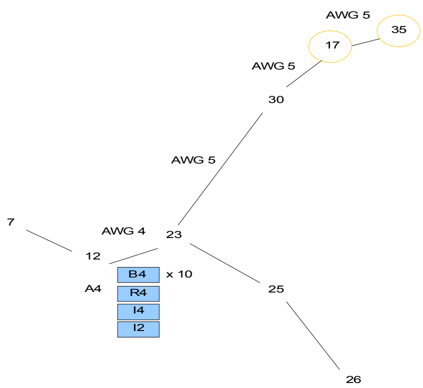
Step 1:



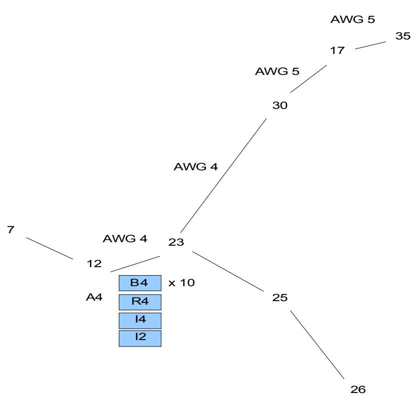
Step 2:



Step 3:



Step 4:



TOO HIGH
CLOSE TO LIMIT

This solution is the most expensive: the extra cost gradually increases step by step, from $ 143,40 (first step) to $ 502,30 for the last one.

PROPOSED SOLUTION	CONNECTION POINTS	CABLE LENGTH [m]	CABLE TYPE [AWG]	CABLE SECTION [mm²]	EXTRA COST [$ / m]	CABLE EXTRA COST [$]	TOTAL EXTRA COST [$]
1st	12 – 23	155,35	AWG 6	13,30	0,20	31,07	
	23 – 30	424,19	AWG 6	13,30	0,20	84,84	
	30 – 17	73,99	AWG 6	13,30	0,20	14,80	
	17 – 35	63,46	AWG 6	13,30	0,20	12,69	143,40
2nd	12 – 23	155,35	AWG 5	16,80	0,45	69,91	
	23 – 30	424,19	AWG 5	16,80	0,45	190,88	
	30 – 17	73,99	AWG 5	16,80	0,45	33,30	
	17 – 35	63,46	AWG 5	16,80	0,45	28,56	322,64
3rd	12 – 23	155,35	AWG 4	21,10	0,76	118,06	
	23 – 30	424,19	AWG 5	16,80	0,45	190,88	
	30 – 17	73,99	AWG 5	16,80	0,45	33,30	
	17 – 35	63,46	AWG 5	16,80	0,45	28,56	370,80
4th	**12 – 23**	**155,35**	**AWG 4**	**21,10**	**0,76**	**118,06**	
	23 – 30	**424,19**	**AWG 4**	**21,10**	**0,76**	**322,38**	
	30 – 17	**73,99**	**AWG 5**	**16,80**	**0,45**	**33,30**	
	17 – 35	**63,46**	**AWG 5**	**16,80**	**0,45**	**28,56**	**502,30**

<u>Fourth Grid:</u>

The fourth grid to be considered is the “Second grid in Hybrid Generation System, High Demand Scenario”; as commented before for the Positive Scenario, this grid is exactly the same just analyzed. So the grid extra cost to be spent to solve the voltage drop problems is $ 502,30.

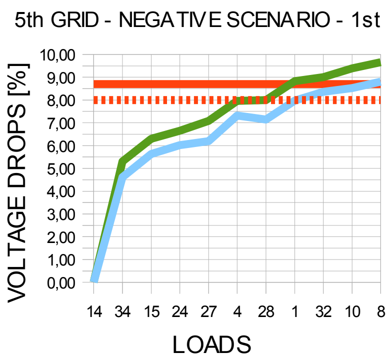
<u>Fifth Grid:</u>

Let's take into consideration the “First Grid in Hybrid Generation System, High Demand Scenario”. The voltage problems in the preliminary simulation concern 4 loads:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	217,80	230	12,20	5,30	---
15	215,50	230	14,50	6,30	---
24	214,70	230	15,30	6,65	---
27	213,70	230	16,30	7,09	---
4	211,70	230	18,30	7,96	---
28	211,60	230	18,40	8,00	---
1	**209,70**	**230**	**20,30**	**8,83**	**TOO HIGH**
32	**209,30**	**230**	**20,70**	**9,00**	**TOO HIGH**
10	**208,40**	**230**	**21,60**	**9,39**	**TOO HIGH**
8	**207,80**	**230**	**22,20**	**9,65**	**TOO HIGH**

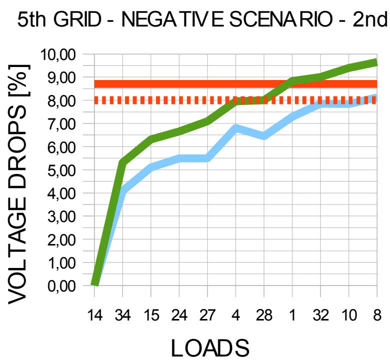
In the first proposed solution, cables 14 – 34 (344 meters) and 14 – 27 (336 meters) are replaced by two AWG 6 cables. The simulation results follow:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	219,39	230	10,61	4,61	---
15	217,05	230	12,95	5,63	---
24	216,17	230	13,83	6,01	---
27	215,74	230	14,26	6,20	---
4	213,16	230	16,84	7,32	---
28	213,57	230	16,43	7,14	---
1	211,66	230	18,34	7,97	---
32	210,77	230	19,23	8,36	CLOSE TO LIMIT
10	210,40	230	19,60	8,52	CLOSE TO LIMIT
8	209,74	230	20,26	8,81	TOO HIGH



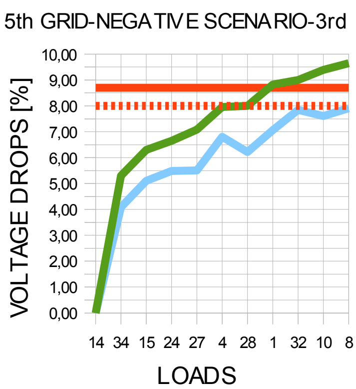
Load 8 has just 209,74 V; furthermore, loads 32 and 10 are labeled as “Close to limit”. So, in the second step, the two considered cables are replaced by two AWG 5 cables; the grid performance gets better:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	220,61	230	9,39	4,08	---
15	218,26	230	11,74	5,10	---
24	217,38	230	12,62	5,49	---
27	217,36	230	12,64	5,50	---
4	214,35	230	15,65	6,80	---
28	215,18	230	14,82	6,44	---
1	213,25	230	16,75	7,28	---
32	211,95	230	18,05	7,85	---
10	211,98	230	18,02	7,83	---
8	211,32	230	18,68	8,12	CLOSE TO LIMIT



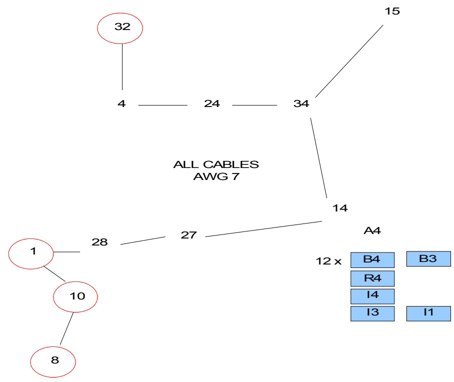
As shown in the table, load 8 has still a not satisfactory voltage value, and it is labeled as “Close to limit”. In the third and last step, cable 27 – 28 (almost 55 meters) is replaced by an AWG 6 cable: the microgrid has now at least 211,82 V at each load.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
14	230,00	230	0,00	0,00	---
34	220,61	230	9,39	4,08	---
15	218,26	230	11,74	5,10	---
24	217,38	230	12,62	5,49	---
27	217,34	230	12,66	5,50	---
4	214,35	230	15,65	6,80	---
28	215,69	230	14,31	6,22	---
1	213,76	230	16,24	7,06	---
32	211,95	230	18,05	7,85	---
10	212,49	230	17,51	7,61	---
8	211,82	230	18,18	7,90	---

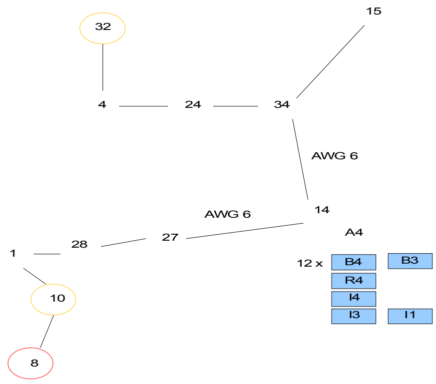


The three step are resumed:

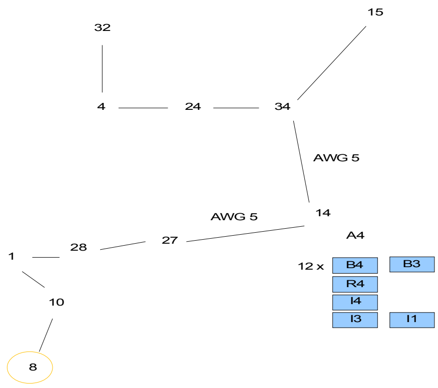
Step 0:



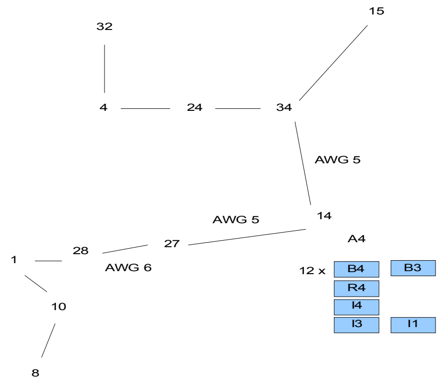
Step 1:



Step 2:



Step 3:



TOO HIGH
CLOSE TO LIMIT

The extra costs are shown in the table below:

PROPOSED SOLUTION	CONNECTION POINTS	CABLE LENGTH [m]	CABLE TYPE [AWG]	CABLE SECTION [mm²]	EXTRA COST [$ / m]	CABLE EXTRA COST [$]	TOTAL EXTRA COST [$]
1st	14 – 27	336,14	AWG 6	13,30	0,20	67,23	
	14 – 34	344,69	AWG 6	13,30	0,20	68,94	136,17
2nd	14 – 27	336,14	AWG 5	16,80	0,45	151,26	
	14 – 34	344,69	AWG 5	16,80	0,45	155,11	306,37
3rd	**14 – 27**	**336,14**	**AWG 5**	**16,80**	**0,45**	**151,26**	
	14 – 34	**344,69**	**AWG 5**	**16,80**	**0,45**	**155,11**	
	27 – 28	**54,95**	**AWG 6**	**13,30**	**0,20**	**10,99**	**317,36**

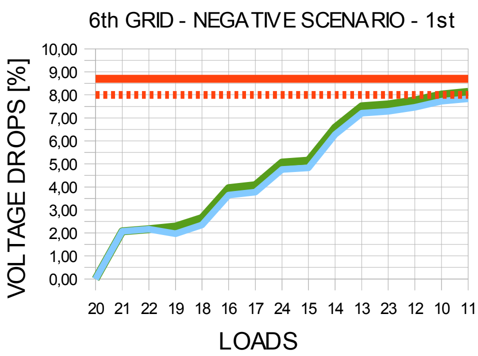
Sixth Grid:

The sixth analyzed grid belongs to the Alto Peru solutions group, and it is the "Third grid in Wind Generation System, High Demand Scenario". Two loads have voltage drops higher than 8%:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
20	230,00	230	0,00	0,00	---
21	225,24	230	4,76	2,07	---
22	225,02	230	4,98	2,17	---
19	224,75	230	5,25	2,28	---
18	223,89	230	6,11	2,66	---
16	220,91	230	9,09	3,95	---
17	220,62	230	9,38	4,08	---
24	218,35	230	11,65	5,07	---
15	218,17	230	11,83	5,14	---
14	214,87	230	15,13	6,58	---
13	212,73	230	17,27	7,51	---
23	212,54	230	17,46	7,59	---
12	212,15	230	17,85	7,76	---
10	211,56	230	18,44	8,02	CLOSE TO LIMIT
11	211,30	230	18,70	8,13	CLOSE TO LIMIT

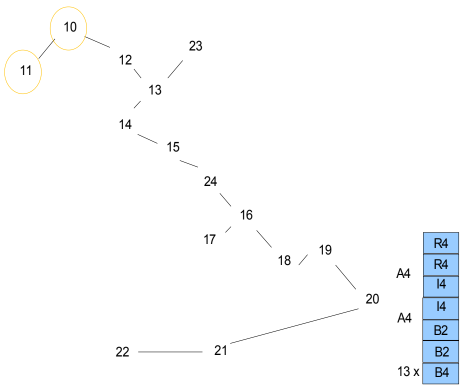
The first solution previews the replacing of the cable 20 – 19, that connects the generator (20) to the grid itself: the new cable is an AWG 6 cable, and thanks to it 12 loads voltage drops decrease: there are no problems now because all the voltage drops are lower than 8%.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
20	230,00	230	0,00	0,00	---
21	225,24	230	4,76	2,07	---
22	225,02	230	4,98	2,17	---
19	225,47	230	4,53	1,97	---
18	224,61	230	5,39	2,34	---
16	221,62	230	8,38	3,64	---
17	221,33	230	8,67	3,77	---
24	219,05	230	10,95	4,76	---
15	218,88	230	11,12	4,83	---
14	215,56	230	14,44	6,28	---
13	213,42	230	16,58	7,21	---
23	213,23	230	16,77	7,29	---
12	212,83	230	17,17	7,47	---
10	212,24	230	17,76	7,72	---
11	211,98	230	18,02	7,83	---

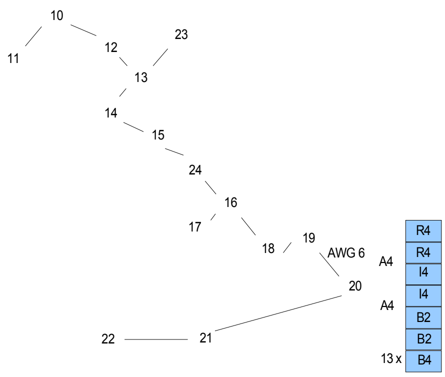


NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION

Step 0:



Step 1:



TOO HIGH
CLOSE TO LIMIT

The extra cost is just $ 12,89, since the replaced cable is just 64,45 meters:

PROPOSED SOLUTION	CONNECTION POINTS	CABLE LENGTH [m]	CABLE TYPE [AWG]	CABLE SECTION [mm²]	EXTRA COST [$ / m]	CABLE EXTRA COST [$]	TOTAL EXTRA COST [$]
1st	20 – 19	64,45	AWG 6	13,30	0,20	12,89	12,89

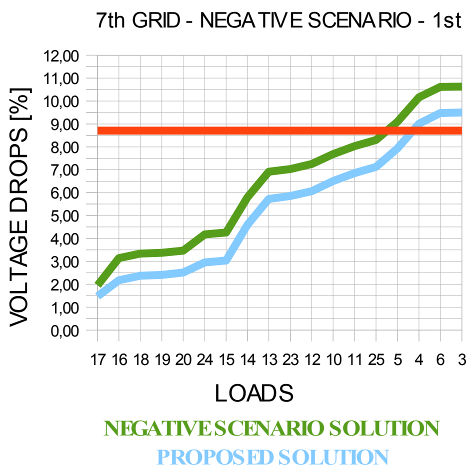
<u>Seventh Grid:</u>

The seventh considered case is the “Second Grid, Wind Generation System, Low Demand Scenario” in Alto Peru. The preliminary analysis shows two loads are labeled as “Close to limit”, while four loads have voltage drops higher than 8,70%. The generator is placed in point 73, that's close to load 17 (it has the lowest voltage drop indeed), and the commented loads are quite far from point 73.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	225,51	230	4,49	1,95	—
16	222,78	230	7,22	3,14	—
18	222,32	230	7,68	3,34	—
19	222,24	230	7,76	3,37	—
20	222,02	230	7,98	3,47	—
24	220,39	230	9,61	4,18	—
15	220,22	230	9,78	4,25	—
14	216,66	230	13,34	5,80	—
13	214,11	230	15,89	6,91	—
23	213,82	230	16,18	7,03	—
12	213,34	230	16,66	7,24	—
10	212,33	230	17,67	7,68	—
11	**211,54**	**230**	**18,46**	**8,03**	**CLOSE TO LIMIT**
25	**210,92**	**230**	**19,08**	**8,30**	**CLOSE TO LIMIT**
5	**209,10**	**230**	**20,90**	**9,09**	**TOO HIGH**
4	**206,64**	**230**	**23,36**	**10,16**	**TOO HIGH**
6	**205,59**	**230**	**24,41**	**10,61**	**TOO HIGH**
3	**205,56**	**230**	**24,44**	**10,63**	**TOO HIGH**

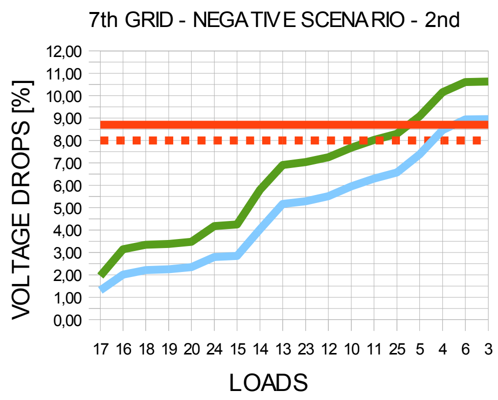
In the first step three AWG 5 cables are used for 73-17, 17-16 and 16-24 connection cables. Three loads have voltage drops higher than 8,70%.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	226,60	230	3,40	1,48	—
16	225,00	230	5,00	2,17	—
18	224,54	230	5,46	2,37	—
19	224,46	230	5,54	2,41	—
20	224,23	230	5,77	2,51	—
24	223,20	230	6,80	2,96	—
15	223,03	230	6,97	3,03	—
14	219,42	230	10,58	4,60	—
13	216,84	230	13,16	5,72	—
23	216,55	230	13,45	5,85	—
12	216,06	230	13,94	6,06	—
10	215,03	230	14,97	6,51	—
11	214,23	230	15,77	6,86	---
25	213,61	230	16,39	7,13	---
5	211,76	230	18,24	7,93	---
4	**209,27**	**230**	**20,73**	**9,01**	**TOO HIGH**
6	**208,21**	**230**	**21,79**	**9,47**	**TOO HIGH**
3	**208,17**	**230**	**21,83**	**9,49**	**TOO HIGH**



In step 2 the first cable (73-17) is replaced by an AWG 4 cable, while also 24-15 and 15-14 are AWG 5: the performance slightly improves, but loads 6 and 3 do not have acceptable voltage values.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	226,99	230	3,01	1,31	---
16	225,38	230	4,62	2,01	---
18	224,92	230	5,08	2,21	---
19	224,84	230	5,16	2,24	---
20	224,61	230	5,39	2,34	---
24	223,57	230	6,43	2,80	---
15	223,45	230	6,55	2,85	---
14	220,73	230	9,27	4,03	---
13	218,13	230	11,87	5,16	---
23	217,84	230	12,16	5,29	---
12	217,34	230	12,66	5,50	---
10	216,31	230	13,69	5,95	---
11	215,51	230	14,49	6,30	---
25	214,88	230	15,12	6,57	---
5	213,02	230	16,98	7,38	---
4	210,52	230	19,48	8,47	CLOSE TO LIMIT
6	209,45	230	20,55	8,93	TOO HIGH
3	209,42	230	20,58	8,95	TOO HIGH



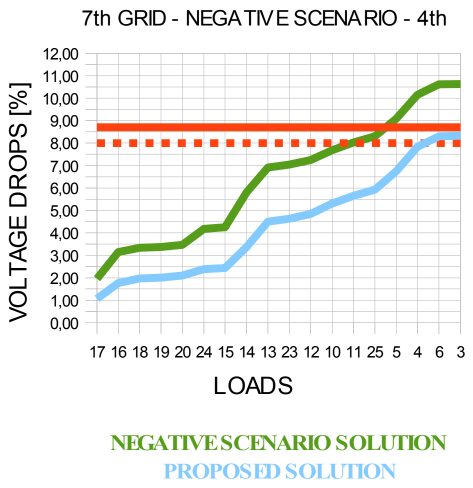
NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION

In step 3 the cable 73-17 is replaced by an AWG 3 cable, while all the remaining cables are now AWG 4: now all the loads have voltage drops lower than 8,70 %, but three of them are still labeled as “Close to limit”. This solution would be acceptable under the parameters the UPC Team chose in the preliminary analysis: anyway this paper assumes the security threshold would be 8%, that's why another step is required.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	227,31	230	2,69	1,17	---
16	225,49	230	4,51	1,96	---
18	225,03	230	4,97	2,16	---
19	224,95	230	5,05	2,20	---
20	224,72	230	5,28	2,30	---
24	223,90	230	6,10	2,65	---
15	223,78	230	6,22	2,70	---
14	221,38	230	8,62	3,75	---
13	218,77	230	11,23	4,88	---
23	218,48	230	11,52	5,01	---
12	217,98	230	12,02	5,23	---
10	216,95	230	13,05	5,67	---
11	216,14	230	13,86	6,03	---
25	215,52	230	14,48	6,30	---
5	213,65	230	16,35	7,11	---
4	**211,14**	**230**	**18,86**	**8,20**	**CLOSE TO LIMIT**
6	**210,07**	**230**	**19,93**	**8,67**	**CLOSE TO LIMIT**
3	**210,03**	**230**	**19,97**	**8,68**	**CLOSE TO LIMIT**

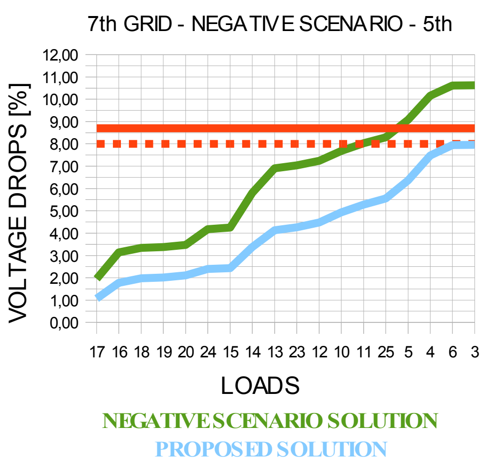
Although 73-17 cable is AWG 2 and the four remainders already considered are AWG 3, loads 6 and 3 still have voltage drops higher than 8%; notice that the voltage drops concerning the loads from 17 to 14 are very low (3,37% the highest), because these are the loads directly influenced by the cable changes commented up until step 4: the voltage drops increase in the other part of the grid, as the cables are AWG 7 as in the preliminary analysis.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	227,56	230	2,44	1,06	---
16	225,94	230	4,06	1,77	---
18	225,47	230	4,53	1,97	---
19	225,39	230	4,61	2,00	---
20	225,16	230	4,84	2,10	---
24	224,51	230	5,49	2,39	---
15	224,41	230	5,59	2,43	---
14	222,26	230	7,74	3,37	---
13	219,64	230	10,36	4,50	---
23	219,35	230	10,65	4,63	---
12	218,85	230	11,15	4,85	---
10	217,81	230	12,19	5,30	---
11	217,00	230	13,00	5,65	---
25	216,37	230	13,63	5,93	---
5	214,50	230	15,50	6,74	---
4	211,98	230	18,02	7,83	---
6	**210,91**	**230**	**19,09**	**8,30**	**CLOSE TO LIMIT**
3	**210,87**	**230**	**19,13**	**8,32**	**CLOSE TO LIMIT**

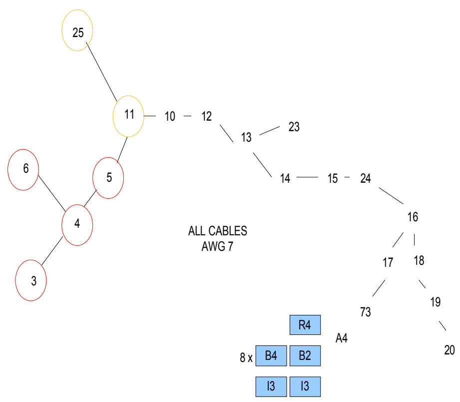


Because of this consideration, in step 5 cable 14-13 is replaced by an AWG 4 cable, while the remaining cables are the same considered in step 4: the voltage values for the loads placed in grid periphery are now acceptable, as shown below:

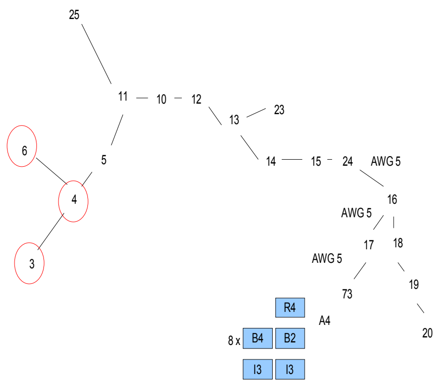
LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
17	227,55	230	2,45	1,07	---
16	225,93	230	4,07	1,77	---
18	225,46	230	4,54	1,97	---
19	225,38	230	4,62	2,01	---
20	225,15	230	4,85	2,11	---
24	224,49	230	5,51	2,40	---
15	224,40	230	5,60	2,43	---
14	222,23	230	7,77	3,38	---
13	220,50	230	9,50	4,13	---
23	220,20	230	9,80	4,26	---
12	219,71	230	10,29	4,47	---
10	218,66	230	11,34	4,93	---
11	217,85	230	12,15	5,28	---
25	217,22	230	12,78	5,56	---
5	215,34	230	14,66	6,37	---
4	212,81	230	17,19	7,47	---
6	211,73	230	18,27	7,94	---
3	211,69	230	18,31	7,96	---



Step 0:



Step 1:



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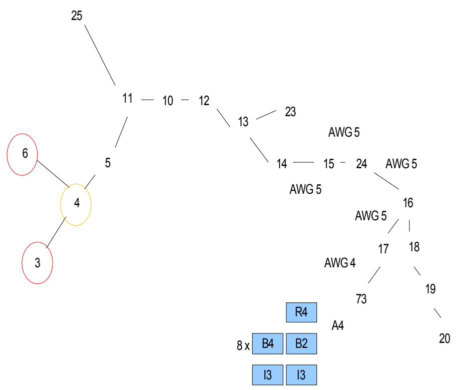
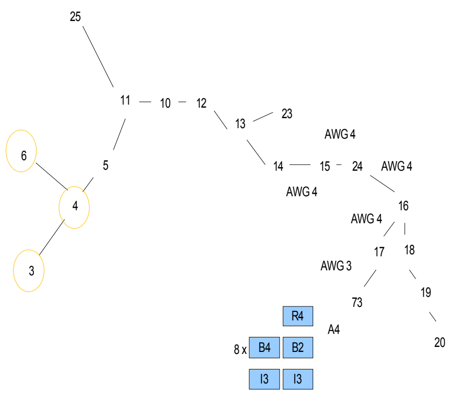
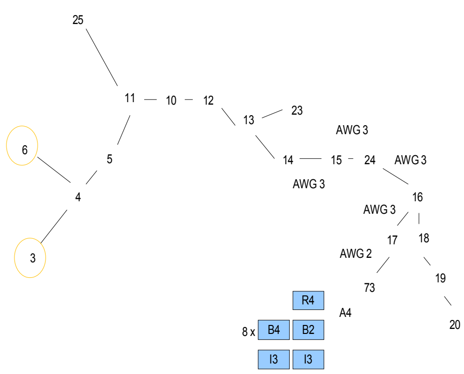


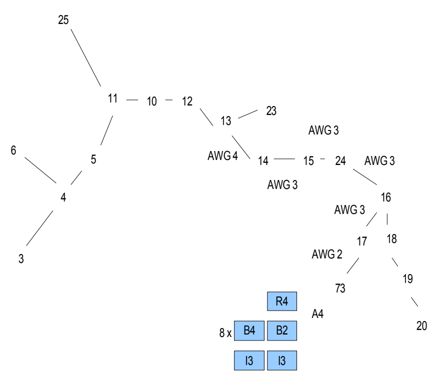
Step 3:



Step 4:



Step 5:



TOO HIGH

CLOSE TO LIMIT

The total extra cost required by step 5 is $ 364,42:

PROPOSED SOLUTION	CONNECTION POINTS	CABLE LENGTH [m]	CABLE TYPE [AWG]	CABLE SECTION [mm²]	EXTRA COST [$ / m]	CABLE EXTRA COST [$]	TOTAL EXTRA COST [$]
1st	73 – 17	66,60	AWG 5	16,80	0,45	29,97	
	17 – 16	43,22	AWG 5	16,80	0,45	19,45	
	16 – 24	48,27	AWG 5	16,80	0,45	21,72	*71,14*
2nd	73 – 17	66,60	AWG 4	21,10	0,76	50,43	
	17 – 16	43,22	AWG 5	16,80	0,45	19,45	
	16 – 24	48,27	AWG 5	16,80	0,45	21,72	
	24 – 15	4,12	AWG 5	16,80	0,45	1,86	
	15 – 14	82,23	AWG 5	16,80	0,45	37,00	*130,46*
3rd	73 – 17	66,60	AWG 3	26,70	1,16	77,07	
	17 – 16	43,22	AWG 4	21,10	0,76	32,72	
	16 – 24	48,27	AWG 4	21,10	0,76	36,55	
	24 – 15	4,12	AWG 4	21,10	0,76	3,12	
	15 – 14	82,23	AWG 4	21,10	0,76	62,26	*211,72*
4th	73 – 17	66,60	AWG 2	33,60	1,65	109,9	
	17 – 16	43,22	AWG 3	26,70	1,16	50,01	
	16 – 24	48,27	AWG 3	26,70	1,16	55,86	
	24 – 15	4,12	AWG 3	26,70	1,16	4,77	
	15 – 14	82,23	AWG 3	26,70	1,16	95,15	*315,69*
5th	**73 – 17**	**66,60**	**AWG 2**	**33,60**	**1,65**	**109,9**	
	17 – 16	**43,22**	**AWG 3**	**26,70**	**1,16**	**50,01**	
	16 – 24	**48,27**	**AWG 3**	**26,70**	**1,16**	**55,86**	
	24 – 15	**4,12**	**AWG 3**	**26,70**	**1,16**	**4,77**	
	15 – 14	**82,23**	**AWG 3**	**26,70**	**1,16**	**95,15**	
	14 – 13	**64,36**	**AWG 4**	**21,10**	**0,76**	**48,73**	***364,42***

Considering the seven analyzed grids, the total extra cost is $ 2003,97, about four times the cost calculated for the Positive Scenario, where the Reactive Power considered in the microgrids is lower and the voltage drops consequently higher.

NEGATIVE SCENARIO

	1st GRID	2nd GRID	3rd GRID	4th GRID	5th GRID	6th GRID	7th GRID	TOTAL EXTRA COST [$]
EXTRA COST [$]	82,36	222,34	502,30	502,30	317,36	12,89	364,42	**2003,97**

3.3 Proposed solutions by changing generator position

In this paragraph other solutions to improve microgrids performances by placing the generator(s) in a different point are described: first of all it is important to verify if the energy production a generator is supposed to produce in a given point is suitable to supply the total loads energy demand. The electrical devices efficiencies (inverters, batteries and connection cable) are considered: according to the preliminary analysis, these are the electrical devices efficiencies:

Batteries Efficiency	Inverter Efficiency	Cable Efficiency
0,85	0,85	0,91

For the load placed next to the generator, just batteries and inverter efficiencies are considered: so the total efficiency is:

0,85* 0,85 = 0,72

For the others loads also cable efficiency is considered:

0,85* 0,85 * 0,91 = 0,66

The proposed solutions concern the Negative scenario, where power factor is 0,75.

Change 1 – Second grid, Wind Energy System, High Demand – El Alumbre

The optimization software used in the preliminary analysis gives a solution in which the 2000 W wind Generator is placed close to load 12; that point has the highest wind resource value: a 2000 W generator is supposed, in fact, to produce an average of 13216 Wh / day. The same wind Generator, placed in point 23, can produce an average of 12153 Wh / day, considered a high energy value. it is important to verify if that amount of energy is equal or higher than the required energy demand, in order to supply the 8 loads connected to the grid: there are 7 houses that require 560 Wh / day, and the health center, that requires 1950 Wh / day.

Six houses and the health center are connected one to another, so the total required energy is:

$$[(6*560 \text{ Wh/day}) + 1950 \text{ Wh/day}] / 0,66 = 8084,43 \text{ Wh / day}$$

For load 23, the required energy is:

$$560 / 0,72 = 775,09 \text{ Wh / day}$$

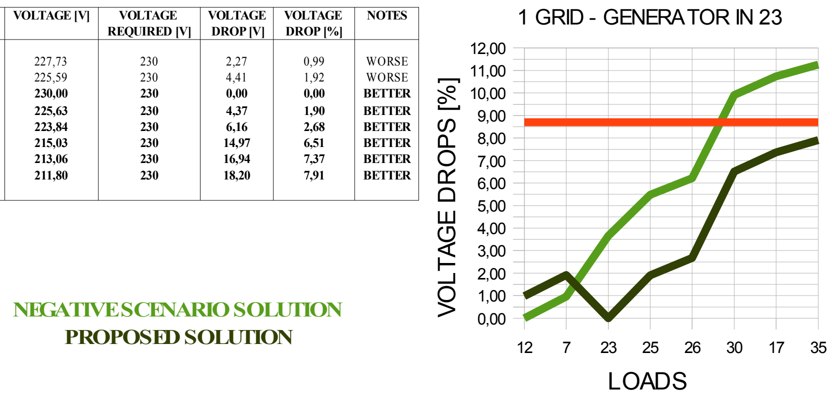
The total energy required by the grid is:

$$8084,43 + 775,09 = 8859,52 \text{ Wh / day}$$

The 2000 W wind generator can generate in point 23 an average of 12153 Wh / day, so it is possible to simulate grid behavior in this configuration.

Here are the voltage drop values measured in Simulink – Matlab Environment: all the voltage drops are acceptable, and this solution is better than the preliminary analysis.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
12	227,73	230	2,27	0,99	WORSE
7	225,59	230	4,41	1,92	WORSE
23	**230,00**	**230**	**0,00**	**0,00**	**BETTER**
25	**225,63**	**230**	**4,37**	**1,90**	**BETTER**
26	**223,84**	**230**	**6,16**	**2,68**	**BETTER**
30	**215,03**	**230**	**14,97**	**6,51**	**BETTER**
17	**213,06**	**230**	**16,94**	**7,37**	**BETTER**
35	**211,80**	**230**	**18,20**	**7,91**	**BETTER**



Furthermore, the average voltage drops now is 3,66%, while in the preliminary case was 6,06%.

Notice that the preliminary analysis has several voltage drop problems, and so it would require bigger cables, as exposed in paragraph 3.2, and consequently an extra cost ($ 502,30) that it is not necessary if generator was placed in point 23, as AWG 7 cables are suitable to guarantee required voltage for each load.

Change 2 – Fourth grid, Wind Energy System, High Demand – El Alumbre

Although this grid doesn't have any voltage drop problem in the preliminary analysis, it is interesting to analyze how it performs if the 1000 W wind generator is placed next to load 9, and not to load 2. Point 2 has a high wind resource value, as the 1000 W generator is supposed to produce 6211 Wh / day: point 9, however, is supposed to produce 6132 Wh / day. Let's see if this amount of energy is enough to supply loads demand, considering electrical device efficiencies:

There are 4 houses connected with cables:

(4 * 560) / 0,66 = 3410,38 Wh / day

Also load 9, where the generator is placed, requires 560 Wh/ day:

560 / 0,72 = 775,09 Wh / day

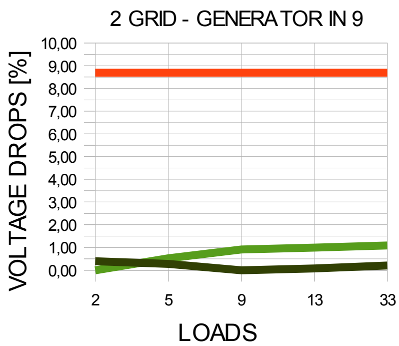
The total energy demand to consider is:

3410,38 + 775,09 = 4185,47 Wh / day

Once verified the generator can supply the loads even in the new position, it is possible to simulate grid's behavior and analyze the voltage drops:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
2	229,08	230	0,92	0,40	WORSE
5	**229,37**	**230**	**0,63**	**0,27**	**BETTER**
9	**230,00**	**230**	**0,00**	**0,00**	**BETTER**
13	**229,83**	**230**	**0,17**	**0,07**	**BETTER**
33	**229,54**	**230**	**0,46**	**0,20**	**BETTER**

NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION



The average voltage drop is just 0,19%, respect 0,70% measured in the preliminary analysis.

Change 3 – Main grid, Hybrid Energy System, Low Demand – Alto Peru

This grid connects 15 houses, and in the preliminary analysis the 2000 W wind generator is placed in point 20, that has a good wind resource (the generator can produce 9890 Wh/day). The proposed solution places the generator in point 19, in which the same generator is supposed to produce 9846 Wh/day.

The 14 connected loads demand is, totally:

(14*280)/0,66 = 5968,17 Wh / day

while load 19 requires:

280/0,72 = 387,54 Wh / day

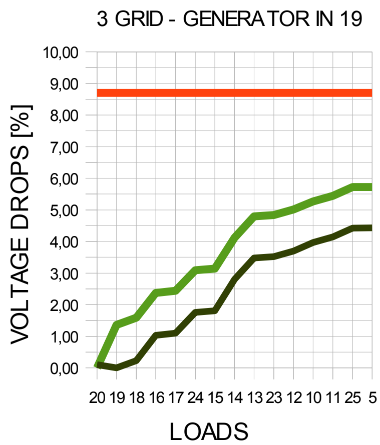
So the total energy demand is:

5968,17 + 387,54 = 6355,71 Wh / day

As commented before, the generator is supposed to produce more than 9800 Wh / day, so it is possible analyze this configuration:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	NOTES
20	229,77	230	0,23	0,10	WORSE
19	230,00	230	0,00	0,00	BETTER
18	229,47	230	0,53	0,23	BETTER
16	227,63	230	2,37	1,03	BETTER
17	227,47	230	2,53	1,10	BETTER
24	225,96	230	4,04	1,76	BETTER
15	225,85	230	4,15	1,80	BETTER
14	223,55	230	6,45	2,80	BETTER
13	222,00	230	8,00	3,48	BETTER
23	221,90	230	8,10	3,52	BETTER
12	221,49	230	8,51	3,70	BETTER
10	220,88	230	9,12	3,97	BETTER
11	220,46	230	9,54	4,15	BETTER
25	219,82	230	10,18	4,43	BETTER
5	219,81	230	10,19	4,43	BETTER

NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION



As shown in the figure above, this grid performs better, as the voltage drops are lower than those in the preliminary analysis: the average voltage drop is 2,43%, while it is 3,66% in the previous case.

Change 4 – Third grid, Wind Energy System, High Demand – Alto Peru

This grid has two generators placed in point 20, that has a high wind resource (9890,41 kWh/day for 2000 W wind generator); it is possible to place a generator in point 19 and the other in point 17, because it would surely increase the voltage values in the loads that are connected to the grid. The energy required by the 13 loads (each load requires 560 kWh/day) connected to the grid through cables is:

(13*560)/0,66 = 11083,74 Wh / day

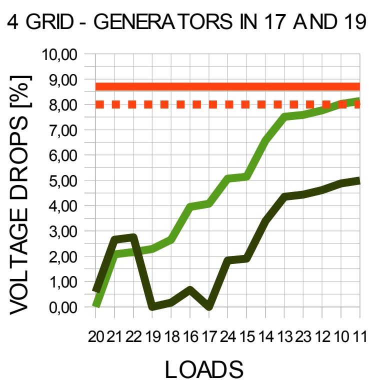
while loads 19 and 17, as they are connected directly to the generators, require:

(2*560)/0,72 = 1550,17 Wh / day

The total energy required by the microgrid is **12633,91 Wh / day.**

According to the wind resource database, a 2000 W wind generator can produce in loads 17 and 19 10441,10 Wh/day and 9846,58 Wh/day: the total amount of energy the generators are supposed to produce is 20287,68 Wh/day, largely higher than the energy required (161% of energy demand). Here are the simulation results with the new configuration:

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	VOLT. DROP DIFFER [%]
20	228,64	230	1,36	0,59	0,59
21	223,91	230	6,09	2,65	0,58
22	223,69	230	6,31	2,74	0,58
19	**230,00**	**230**	**0,00**	**0,00**	**-2,28**
18	**229,61**	**230**	**0,39**	**0,17**	**-2,49**
16	**228,45**	**230**	**1,55**	**0,67**	**-3,28**
17	**230,00**	**230**	**0,00**	**0,00**	**-4,08**
24	**225,80**	**230**	**4,20**	**1,83**	**-3,24**
15	**225,62**	**230**	**4,38**	**1,90**	**-3,24**
14	**222,20**	**230**	**7,80**	**3,39**	**-3,19**
13	**219,99**	**230**	**10,01**	**4,35**	**-3,16**
23	**219,80**	**230**	**10,20**	**4,43**	**-3,16**
12	**219,39**	**230**	**10,61**	**4,61**	**-3,15**
10	**218,78**	**230**	**11,22**	**4,88**	**-3,14**
11	**218,51**	**230**	**11,49**	**5,00**	**-3,13**



NEGATIVE SCENARIO SOLUTION
PROPOSED SOLUTION

The simulation results shows 12 of the 15 loads connected to the grid have a lower voltage drop; the average voltage drop in the preliminary analysis is 4,87%, while in this proposed solution it is just 2,48%, that is -49%.

Change 5 – First grid, Hybrid Energy System, High Demand – Alto Peru:

This grid have two 2000 W generators placed in point 30, that has a high wind resource value, as happened in the previous cases: 7619,54 Wh / day.

There are two points in which it would be possible to place one of the two 2000 W generator, point 15 and 18; they are supposed to produce 8794,52 Wh/day and 9772,60 Wh/day. Both of them are acceptable because they have wind resource values higher than point 30. it is significant to make a simulation for each solution and comment the results: the Positive scenario results are taken as reference.

Solution A: Generators in 30 and 15

The average voltage drop is 1,86% in this simulation (it was 14,50% in the preliminary analysis).

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	VOLTAGE DROP DIFFER. [%]
25	228,30	230	1,70	0,74	-2,27
11	225,18	230	4,82	2,10	-7,96
5	222,99	230	7,01	3,05	-7,88
10	225,21	230	4,79	2,08	-9,23
4	221,52	230	8,48	3,69	-7,83
12	225,51	230	4,49	1,95	-10,63
13	225,89	230	4,11	1,79	-11,58
23	225,71	230	4,29	1,87	-11,57
14	227,47	230	2,53	1,10	-13,67
15	230,00	230	0,00	0,00	-16,38
24	229,81	230	0,19	0,08	-16,37
16	227,82	230	2,18	0,95	-16,23
17	227,56	230	2,44	1,06	-16,21
18	226,51	230	3,49	1,52	-16,13
19	226,23	230	3,77	1,64	-16,12
20	225,09	230	4,91	2,13	-16,03
22	221,03	230	8,97	3,90	-15,75
21	221,21	230	8,79	3,82	-15,76

5 GRID - SOLUTION A

POSITIVE SCENARIO SOLUTION
PROPOSED SOLUTION

Solution B: Generators in 30 and 18

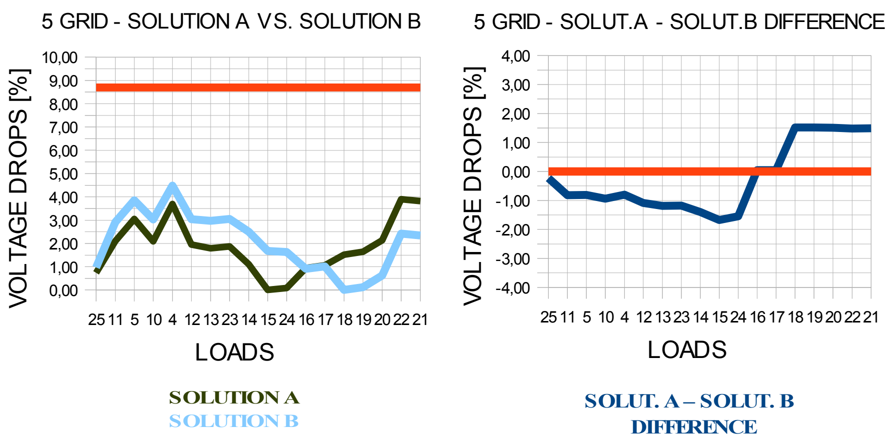
The average voltage drop is now 2,09%, a little higher than solution A.

LOAD	VOLTAGE [V]	VOLTAGE REQUIRED [V]	VOLTAGE DROP [V]	VOLTAGE DROP [%]	VOLTAGE DROP DIFFER. [%]
25	227,77	230	2,23	0,97	-2,04
11	223,30	230	6,70	2,91	-7,14
5	221,13	230	8,87	3,86	-7,07
10	223,04	230	6,96	3,03	-8,28
4	219,68	230	10,32	4,49	-7,03
12	223,00	230	7,00	3,04	-9,54
13	223,16	230	6,84	2,97	-10,39
23	222,99	230	7,01	3,05	-10,38
14	224,25	230	5,75	2,50	-12,27
15	226,14	230	3,86	1,68	-14,70
24	226,25	230	3,75	1,63	-14,82
16	227,92	230	2,08	0,90	-16,27
17	227,67	230	2,33	1,01	-16,26
18	230,00	230	0,00	0,00	-17,65
19	229,72	230	0,28	0,12	-17,63
20	228,56	230	1,44	0,63	-17,54
22	224,44	230	5,56	2,42	-17,23
21	224,63	230	5,37	2,33	-17,24

5 GRID - SOLUTION B

POSITIVE SCENARIO SOLUTION
PROPOSED SOLUTION

It is evident solution A performs better than the second one, so to improve grid stability it would be necessary to place a generator in point 30, and connecting the other to load 15.



All the five analyzed grids perform better than in the preliminary analysis; it is important to notice that they don't require any extra cost, as the generator has to be placed in a different point of the grid, and the used cables are always AWG 7.

4. Conclusions

The simulations run in a Simulink-Matlab environment can be used to analyze microgrids' performances and to evaluate grids' stability by measuring voltage values at each load; this is surely important and it represents a useful instrument to evaluate the microgrid’s stability and moreover to understand if solutions calculated by the optimization model are the best for a given real case. Moreover, considering three different scenarios regarding the reactive powers in the loads allows the GRECDH Team to better understand the different scenarios that they could face during the next phases of the electrification project.

Twenty grids are analyzed: for each one, three simulations are run with different reactive power values, so totally there are 60 analysis: the simulation results are however pretty satisfactory, since 46 microgrids out of 60 have acceptable voltage values (77%): concerning the Low Demand Scenario, just 3 microgrids out of 21 have unsatisfactory voltage values (14%), while in the High Demand Scenario the percentage is double (28%), since 11 microgrids out of 39 do not perform suitably.

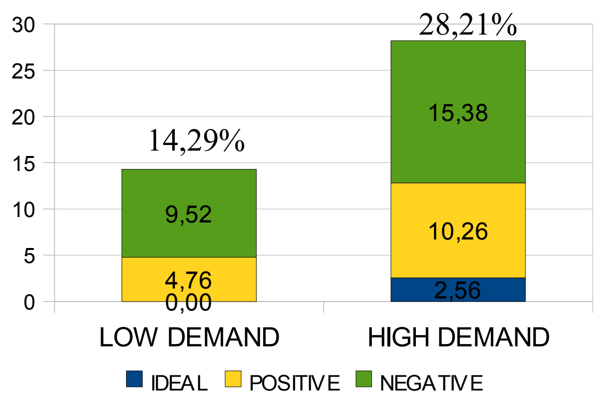


Figure 4.1: Unacceptable microgrids for low and high demand scenarios (values expressed in %)

Regarding the grids studied by GRECDH Team, called the Ideal Scenario in this paper, just 1 microgrid simulation creates serious problems: however, it does worth stating 95% of these grids have acceptable values. Regarding Positive Scenario results, this percentage decreases to 75%, since 5 microgrids have unacceptable voltage values when the load power factor is 0,90; finally, for the Negative Scenario (in which loads power factor is 0,75) 8 simulations are unsatisfactory (60% of microgrids are considered acceptable).

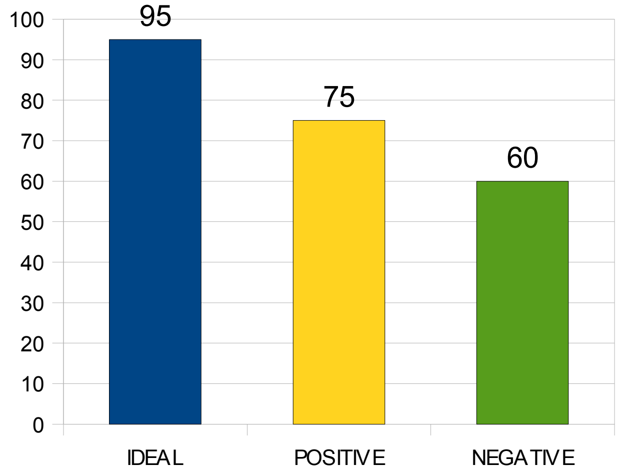


Figure 4.2: Acceptable microgrids concerning ideal, Positive and Negative scenarios (values expressed in %)

It is interesting to closely examine the results obtained for the communities involved in the project:

<u>Alto Peru</u>

In the first community, Alto Peru, there are a total of 11 microgrids: 8 of them do not show any voltage problems for the loads connected to the microgrids, while one grid in the low demand scenario has unacceptable voltage values both in Positive and Negative scenario. Furthermore, one grid is unsuitable for the Negative scenario for high demand, and finally a grid discovered by GRECDH Team is not acceptable not even in the Ideal Scenario (in the figure below "OK" means no voltage problems in the three scenarios). Bigger cables are required to solve these problems, as shown in chapter 3, or, as an alternative, it is also possible to change the generator position(s) to decrease voltage drops.

	Low Demand		**High Demand**	
	Wind System	Hybrid System	Wind System	Hybrid System
Main Grid	---	OK	OK	**ID – POSIT – NEGAT**
1st Grid	OK	---	OK	OK
2nd Grid	**POSIT – NEGAT**	---	**NEGATIVE**	---
3rd Grid	OK	---	OK	---
4th Grid	OK	---	---	---

Figure 4.3: Microgrids analysis results for Alto Peru

El Alumbre

Concerning the second community, just 4 grids out of 9 are acceptable considering the three reactive power scenarios: two grids show problems in a Negative scenario, and three grids in both Negative and Positive ones.

	Low Demand		**High Demand**	
	Wind System	Hybrid System	Wind System	Hybrid System
Main Grid	OK	**NEGATIVE**	---	---
1st Grid	---	---	**NEGATIVE**	**POSIT – NEGAT**
2nd Grid	---	---	**POSIT – NEGAT**	**POSIT – NEGAT**
3rd Grid	---	---	OK	OK
4th Grid	---	---	OK	---

Figure 4.4: Microgrids analysis results for El Alumbre

As mentioned above, bigger cables are required to solve the problems connected to excessive voltage drops; this of course implies extra costs for each grid.

4.1 Extra cost considerations

It is interesting comment on the effects of the extra costs calculated in chapter 3 on the total budget the GRECDH Team supposed in the preliminary study: this regards of course both the Positive and the Negative scenario.

Alto Peru

Concerning the Positive scenario, there is one solution that must be mentioned: the extra cost is just $ 59,07, and considering the total budget for the Wind Generation System, Low Demand Scenario, the incidence is not significant (0,15%).

POSITIVE SCENARIO

	LOW DEMAND WIND GENERATION
TOTAL COST [$]	39567
EXTRA COST [$]	59,07
EXTRA COST / TOTAL COST [%]	0,15

Regarding the Negative scenario, there are two cases: the first regards the Low Demand Case and the remainder the High Demand one. The extra cost incidence in the first case is significant (0,92%), since the extra cost is $ 364,42 and the total cost is $ 39567. For the other case, the extra cost is very low (just $ 12,89).

NEGATIVE SCENARIO

	LOW DEMAND	HIGH DEMAND
	WIND GENERATION	WIND GENERATION
TOTAL COST [$]	39567	59272
EXTRA COST [$]	364,42	12,89
EXTRA COST / TOTAL COST [%]	0,92	0,02

For Alto Peru the maximum extra cost incidence ? is not even 1% of the total budget the GRECDH Team calculated to build the microgrids; this shows how convenient the proposed solutions are, considering that they allow increased voltage values at each load and better microgrid performances by spending very little money.

El Alumbre

Eight of the eleven proposed solutions concerns El Alumbre: concerning the Positive Scenario, the incidence on the Wind Generation System total cost is just 0,19%; considering both wind generation and photovoltaic panels, the incidence sightly increases (0,27%).

POSITIVE SCENARIO

	HIGH DEMAND	
	WIND GENERATION	HYBRID GENERATION
TOTAL COST [$]	89056	87027
EXTRA COST [$]	169,54	236,77
EXTRA COST / TOTAL COST [%]	0,19	0,27

Concerning the Negative Scenario, these incidences increase to 0,81% and to 0,94%; in the Low Demand Scenario, the extra cost is just $ 82,36, and the incidence on the total cost is very low, just 0,16%.

NEGATIVE SCENARIO

	LOW DEMAND	HIGH DEMAND	
	HYBRID GENERATION	WIND GENERATION	HYBRID GENERATION
TOTAL COST [$]	52912	89056	87027
EXTRA COST [$]	82,36	724,64	819,66
EXTRA COST / TOTAL COST [%]	0,16	0,81	0,94

These considerations focus on the extreme economic convenience of the proposed solutions described in this paper: even if considering a High Energy Demand and a Negative Scenario, that is low electronic devices efficiency and a large amount of reactive power in the microgrids, the extra cost ($ 819,66) needed to solve the problems concerning voltage drops in El Alumbre doesn't even reach the 1% of the total budget ($ 87027) for the entire solution (that includes the cost of Generators, Regulators, Inverters, Batteries, the cost of work and other overall costs).

These eleven proposed solutions do not change the microgrids' layout the GRECDH Team designed, since they do not change generators' position; they can be considered as a useful instrument for the team to evaluate the convenience of changing cables type to increase grids' performances, and furthermore the greatest advantage is that they do not require any layout change. In Chapter 3 other solutions that involve changing generator positions are exposed: of course they change the original layout designed by GRECDH Team, even if there are no extra costs to be considered, since AWG 7 cables are suitable to guarantee acceptable voltage values.

4.2 Project impact on population

Finally, it is interesting to evaluate the impact the project might have on the population of the communities, since an electrification project like this has of course a great impact on people and it certainly changes their daily life.

Thanks to an evaluation survey carried out by GRECDH Team in Peru in the first phase of an electrification project in El Alumbre, it is possible to obtain an approximate evaluation of the project impact on population. This survey was carried out in the last two months of 2008, after the first phase of the electrification project, in which several wind generators were connected to the houses, the school and the health center, without building a microgrid.

The survey points out that wind turbines installed in each home cover the domestic use of electricity for 5 hours/day. It found furthermore that 100% of households use the system for lighting, 93% are charging cell phones, 64% are using the lighting for studying, 57% can weaving or knitting in the evenings, and finally 43% can turn on radios.

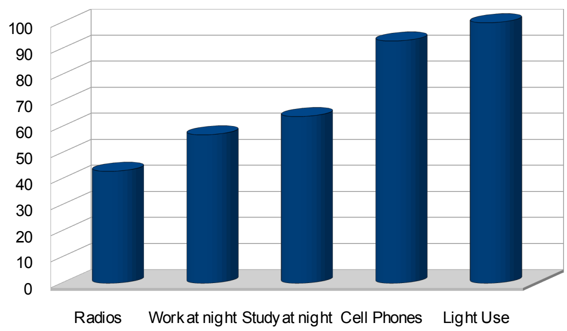


Figure 4.5: Evaluation survey results regarding the first phase of the electrification project in El Alumbre

Moreover, 70% of the families claimed a reduction in expenditures in other energy sources such as kerosene or candles; families had been using energy in a direct or indirect way in the implementation of small business such as a radio station and weaving.

There is also a significant impact regarding the 80 students who attend the school and the health center, which attends people from four communities:

- Energy in the school powers four computers (with electronic encyclopedias) and a DVD reader for educational videos
- The health center has electricity for lights, a sterilizer and a vaccine refrigerator

Neighbouring communities have also benefited by being able to charge cell phone batteries, while El Alumbre residents have benefited from the small fee paid for cell phone charging. A few micro-enterprises for rural electrical services were created, and some people were taught to practice the simplest maintenance operations directly on the electrical equipments, also thanks to the use of small visual manuals and the participation of authorities and the local technician in the community training sessions.

Finally, the introduction of concepts of customer service in the structure of a single person micro-enterprise seemed to be an innovative way of promoting sustainability.

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