POLITECNICO DI MILANO

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

Energy Engineering Master of Science

Thermal and Electric Modelling of a village-scale Multi-Energy System for the Sustainable Energization of Toconao

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Y si al final
lo que hay que vivir
lo que hay que soñar
hay que vivirlo

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Thanks to my family for supporting me for all these years, for believing in me and for having the opportunity to live this experience by supporting me and never obstructing me.

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Executive Summary

Introduction

Goal 7 of the Sustainable Development Goals adopted in September 2015 by the United Nations consists in achieving universal access to energy by 2030. The availability of energy is a necessary pre-requisite to enable development, and it should be regarded as a tool for people to improve their living condition. Energy access has to be considered not only as access to electricity but also access to thermal usages on energy. As stated by the IEA, heat consumption accounts for over 50% of the total final energy consumption worldwide but has not been given enough attention to the matter of switching from the fossil fuel technologies to the renewables ones for the thermal energy production. In accordance with that, the concept of energy access should be translated into the theme of energization. In fact, energization can be considered as the supply and planning of complete energy solutions to meet electrical and thermal demand, focusing on the improvement of rural communities living conditions.

Chile is one of the most developed countries of the South America continent. In terms of energy, the Total Primary Energy Supply (TPES) in 2015 amounts to 32.70 Mtoe, where the 70% of sources is given by crude oil and fossil fuels. The north of the country is occupied by the Atacama Desert with an extension of 105000 km^2, where the values of the solar irradiation reach almost 8500 MJ/m2 per year. This potential is currently scarcely exploited, in fact, the solar energy makes up only for the 0.3% of the TPES of the country. In the northern regions of Chile, there is a strong presence of communities that are extremely isolated, and most of them must produce energy for themselves, being disconnected from the national grid. Besides isolation from electricity, the long distance of the northern regions implies several constraints also to provide sources to satisfy the thermal demand. The main fuel for the domestic thermal usage is the LPG. Its distribution is performed regularly by trucks that deliver bottles of liquefied gas once per week. Due to the long distance to cover in the large extension of the desert territories the transportation results very expensive and consequently the price of the natural gas is higher than the national average.

The study area of this work consists in the rural village of Tocoano, in the Antofagasta region, inside the territory of Atacama Desert, near the border with Argentina and Bolivia, and represents a clear example of rural village of the Desert area.
From an electrical point of view, the village buys electricity from the near village of San Pedro de Atacama, where an Electrical Power Plant is installed and owned by the CESPA cooperative producing energy for the village of San Pedro and dispatching it to the village of Toconao. A diesel backup generator is present in Toconao due to the frequent blackouts caused by sand storms and the instability of the line.
In order to perform a sustainable energization in the study area, the present work has been organized following the guidelines defined by the Comprehensive Energy Solution Planning (CESP) methodology – developed by the UNESCO Chair in Energy for Sustainable Development at Politecnico di Milano – which consists in a practical sequence of steps to be followed from the conception of the idea until its completion.
The general objective of this study is to improve the reliability and sustainability of the energy supply of the study area based on the use of indigenous energy resources through the development of an energy optimization solution. To achieve the general objective, four specific objectives are formulated, namely:

I. To assess the current energy situation of the study area.
II. To assess the energy resources locally available with focus on solar, hydro and wind.
III. To develop an integrated thermal-electric energy system optimisation model, based on an open-source code.
IV. To propose, based on the developed model, rational scenarios for a more sustainable energy system for the area.

In order to assess the current energy situation of the study area, direct measurements are performed on field, consisting in administration of specifically redacted questionnaires to better understand energy needs and energy usage habits of the population, assessment of locally available energy resources potentials and load profiles of the village, to better size the proposed energy solution, finally a *Multi Energy System* model is proposed as an integration to *MicroGridPy* to meet thermal and electrical needs.

Methodology

Assessment of current energy situation.

As part of current energy situation assessment, the approach of Johnson is used to define a framework for the energy balance assessment of a rural area. In this framework, energy sources, energy drivers and final uses are defined. For each energy driver the primary sources of energy are identified, and the total primary energy supplied is estimated. Energy services demanded at each energy driver are then identified and for each of them are analysed the census data on the conversion technologies adopted to transform the total primary energy supplied into the total final energy consumed. The three drivers identified on the field by direct observation are:

- Domestic, including all the households.
- Artisans, including all the income generating activities like shops, restaurants and guesthouses.
- Public services, including the medical office, the police station and the school, along with other services and public street lighting.

The primary energy sources identified in the study area are: Electricity from the grid, LPG used to fire gas boilers and cooking purposes, Diesel to run a backup electric generator, solar energy collected by 150 solar thermal collectors present in the area and firewood, still used by a part of the population for traditional cooking purposes.

Grid. The total amount of electrical energy coming from the grid is calculated form the electrical bills of the village, as sum of the energy consumption measured from every single electric meter of the village rested the energy produced by the backup diesel generator. The energy from the grid, since no energy conversion happens inside the boundaries of the study area, is net of losses.

Diesel Generator. Inside the village a 400 kVA Diesel backup generator is present to make up for the electrical interruptions from the grid. The efficiency of the Diesel generator evaluated to have an estimation of the losses, is computed combining the experimental data collected on field and data form literature review.

LPG. The energy deriving from LPG in the village is calculated by means of the responses to the questionnaires and pieces of technical information about the gas gathered from the producer. On the one hand, from the questionnaires is possible to estimate the total amount of gas bottles, and with that, kilograms of gas consumed yearly in the village by each energy driver. On the other hand, from the literature the corresponding LHV is obtained. Finally, the efficiency of the final use is collected by direct observation in the case of gas boilers, and from literature in case of gas cookers.

Solar Collector. Inside the village 150 solar collectors are present. From the study carried out by the engineer that followed the project, the working parameters are extracted, such as efficiency, litres of water heated per collector, and working temperatures. In this way the primary energy entering the boundary of the study area and the total secondary energy produced daily from the collectors can be estimated.

Firewood is a source of thermal power for cooking that is not largely used but still present in the village. The amount of wood, in kilograms, used yearly from the population is extrapolated from the answers to the questionnaires, where a specific question is present for the purpose. In order to compute the thermal efficiency of a standard stove used in the village a Water Boiling Test (WBT) is carried out according to the protocol and following as much as possible the procedure.

Load Curves Modelling

To compute the Load Profiles of the different energy drivers a stochastic approach is adopted, by means of the LoadProGen software. LoadProGen, developed by Politecnico di Milano, allows to create a series of profiles of different categories of users inside a study area; for each of these classes it is possible to define which appliances are used, the nominal power of these, and their time of use and windows of usage. Through a random function all the nominal powers of the appliances of one class are summed up filling the time windows with the time of usage, creating a Load Profile of one class, that is then summed with the profiles of the other classes, creating the total Load Curve of the study area. In order to generate the electrical load profile of the village, two main sources of information are pulled together and used to generate an input for the LoadProGen software: the questionnaires administered to the population, where the kind of appliances and their pattern of use are investigated for each class, and the monthly and annual electrical consumption of each user.

The software has been rigorously designed to compute electrical Load Curves only. Nonetheless, in this work, it has been adapted by the authors in order to model also thermal loads. To adapt the working logic of LoadProGen to a thermal load, some precautions are taken. First of all, a thermal load curve of the entire study area is not computed, but several different profiles are calculated, given the impossibility of centralization of thermal energy production with solar collectors. In order to generate the thermal load profile of the village, the information gathered through the questionnaires are processed to compose an input file to fit the LoadProGen software and allow it to compute a Thermal Load Profile for the village. These pieces of information are then compared with the ASHRAE Handbook in order to confirm and better model the thermal demand profile. For this reason, the structures with a similar thermal behaviour are represented in a single class, considering only one "typical user", the total demand of the class is obtained multiplying the obtained values by the number of users.

Assessment of Local Energy Sources

Locally available energy sources potentials have been estimated by means of direct measurements during on field period.

Solar Potential is assessed measuring Global Horizontal Irradiation (GHI) in the area with a pyranometer and the collected data are compared and merged with the data obtained from a national study performed in the adjacent village of San Pedro de Atacama collecting meteorological data for three years.

Wind Potential is assessed through direct measurements during field work of wind velocity and direction, and the obtained result compared and merged with the data obtained from the online simulation tool *Explorador Eólico*, developed by the Universidad de Chile and considered to be the most suitable simulation tool for the purpose.

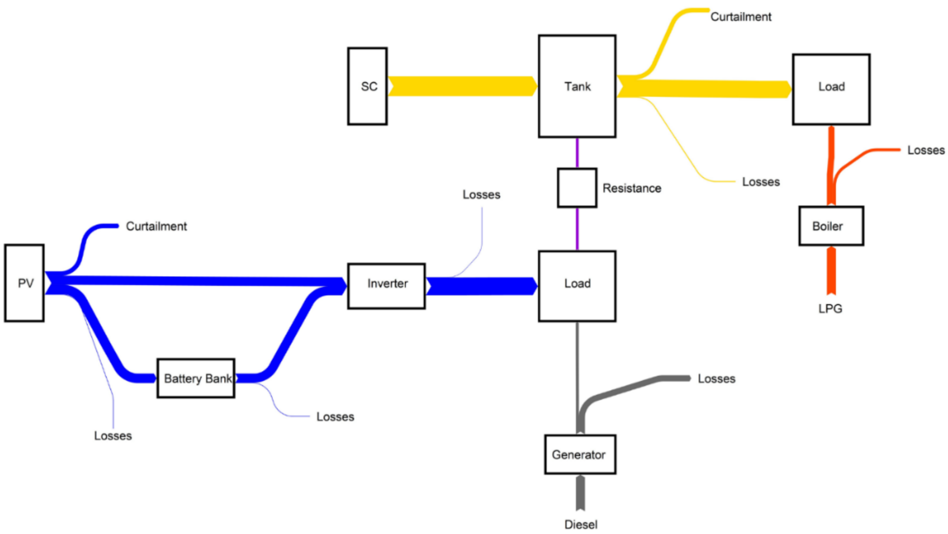
Hydropower Potential of the two rivers flowing in the area is assessed measuring two fundamental parameters, *Gross Head* and *Flow Rate*. Gross head is estimated by means of Google Earth online tool and the Flow rates through the application of the *Floating Object Method,* that allows to estimate the mean flow velocity of water streams with a non-invasive methodology, and through the mean bulk velocity and the directly measured cross section area the flow rate is calculated.

Thermal and Electrical Modelling Methodology

The methodology builds on an open source model of isolated hybrid micro grids, that models the behaviour of real components to perform a consistent sizing, ensuring the reliability of the energy supply and considering different scenarios for isolated rural villages. Based on such model, a new thermal model is implemented and aggregated to the original one in order to include thermal needs and favouring the transition towards renewable energy technologies for the heat production. Hence, the model proposes the following objectives:

I. combine the thermal and electrical energy access problem
II. satisfy the thermal load through the available local sources
III. find the optimal solution minimizing the net present cost (NPC) function as an objective function

The expanded model results thus in an integrated village-scale Multi-Energy System (MES) optimisation tool to generate a set of rational decision options for the implementation of a more sustainable and resilient energy system for the case study. Considering that the solar resource is by far the most abundant renewable resource in the area, the MES model is configured in order to synthetize, respectively, diesel generators, PV panels and batteries for the provision of electricity; and gas boilers, solar thermal collectors and hot water tanks for the provision of domestic hot water. Furthermore, an internal electric resistance element is included in the model of hot water tanks, thus allowing the electricity from the micro-grid to supply also thermal energy to charge the thermal storage. In the following figure the energy flow of the model configuration is presented.



On the one hand, the electrical optimization looks at the entire village, adopting a *centralized* logic approach to satisfy the load. The model receives the electrical load of the village and the photovoltaic energy as inputs and returns the sizing and the electric dispatch of the system based on the net present cost function optimization.

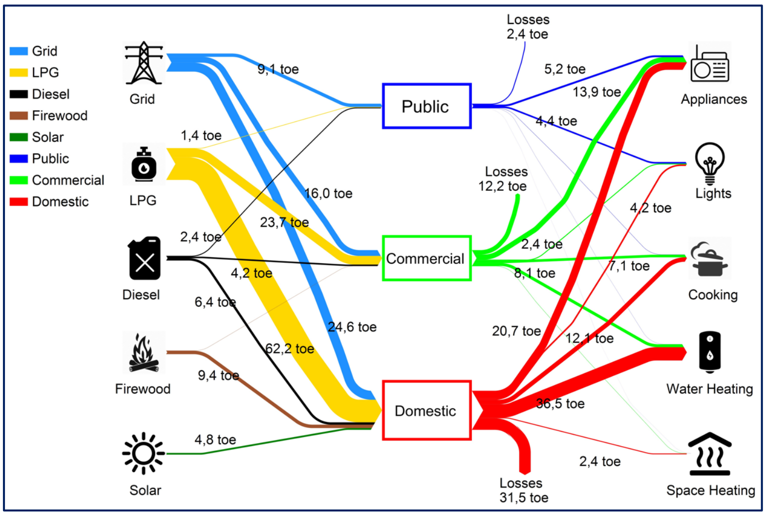
On the other hand, the thermal model is thought to take into account topographic constraints and to ensure that the solar collectors and thermal storage systems are optimised separately for each class. In fact, the thermal part has based on a *decentralized* logic approach that provide the optimal sizing configuration and thermal energy dispatch for each specific class with different thermal load.

The synergy between the two systems is represented by the electrical resistance. In fact, when it is used to supply thermal energy, it is seen by the electrical part as an additional demand. As each class is provided with its own resistance, in the electrical energy balance it will results as the sum of each electrical resistance per class. In this way a global optimization can be performed satisfying both thermal and electrical needs and optimizing the overall net present cost function.

Results

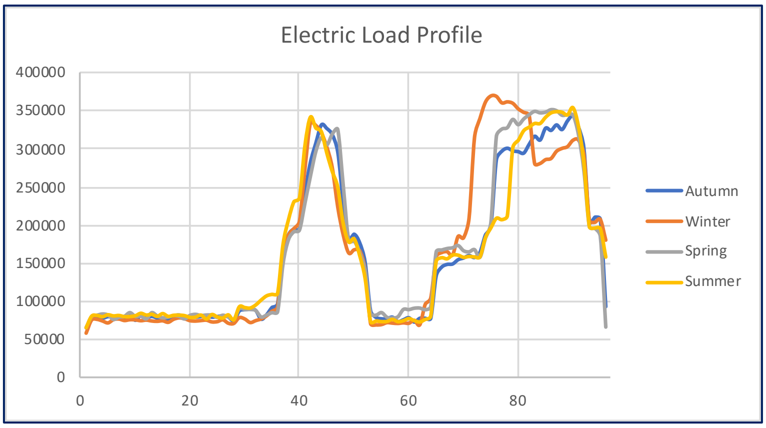
Assessment and Load Results

A good representation of the local energy assessment of the village is given by the energy flow diagram of the study area. Five energy sources, three main energy drivers and five energy services demanded are identified. Results regarding the current energy consumption are aggregated in the overall energy balance of the study area for a sample year and reported in the Sankey diagram in accordance with IEA criteria for energy balance representation.

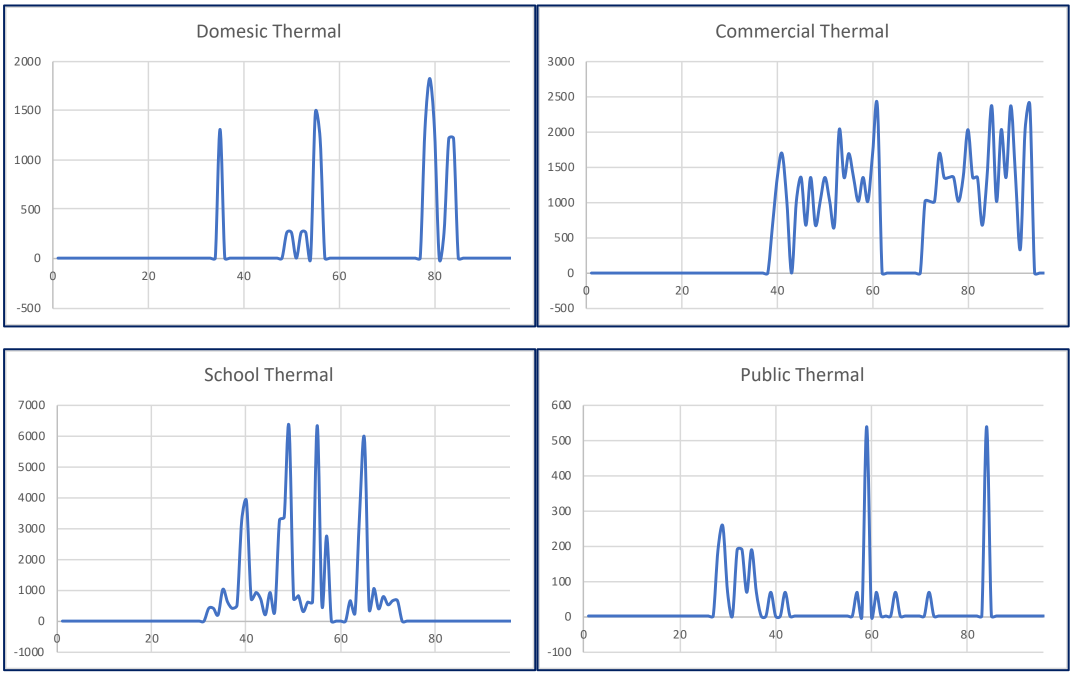


As is possible to observe the thermal demand of the village represents more than the half of the secondary energy use, with a share of 57%. Inside this thermal demand 66% of the energy is used for water heating purposes. This situation justifies the focus of this work on thermal solar thermal collector technologies. Is also possible to observe how the study area is strongly dependent of external sources of energy, since electricity form the grid, LPG and diesel are energy that have to be bought from outside the limits of the village, and strongly condition the usage of energy. The percentage of TPES deriving from sources outside the study are is 91% and increases to 95% when talking about secondary energy.

With respect to the load curves, the electrical demand is generated through the LoadProGen software and is performed with a time step of 15 minutes showing two intense loads: one during the midday and one during the evening hours. A seasonal variation is also introduced by the authors varying the functioning time of the light bulbs of the three energy drivers based on duration of night time, considering that the questionnaires were administered in June, during the winter season. A typical day is represented in the graph below, where it is possible to observe how the load varies in each season.



As mentioned above, the thermal demands are created adapting the working logic of LoadProGen to thermal load. Differently form the electrical demand where the load curve is unique for the entire village, the thermal needs have to be decentralized and in particular the domestic hot water consumption is divided in four classes: domestic, commercial, public and school. In the graphs below the thermal demands of a typical user of each class are reported.



The local renewable energy source assessment is focused principally on the solar potential, hydropower potential and wind potential.

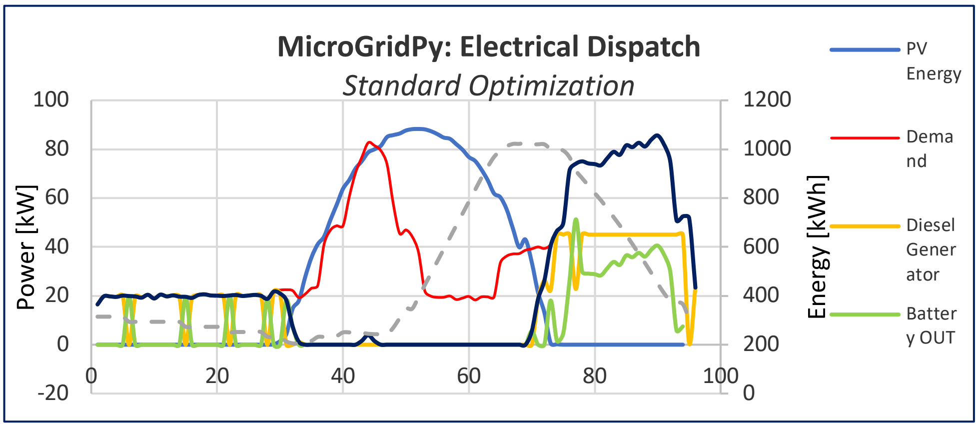
The *solar irradiation* represents the most abundant source in the study area with a total annual irradiation of 9280 MJ/m^2. After the solar irradiation, photovoltaic power output from a commercial panel available in the local area is performed. The photovoltaic panel selected is the model Yingli YL300P-35b Polycrystalline module with a nominal capacity of 300 W per module. The data of the solar irradiation are elaborated through the *Modelica* language.

To evaluate the *wind potential,* the wind speed is measured in the study area and the results are integrated with the reference data of the Explorador Eolico.

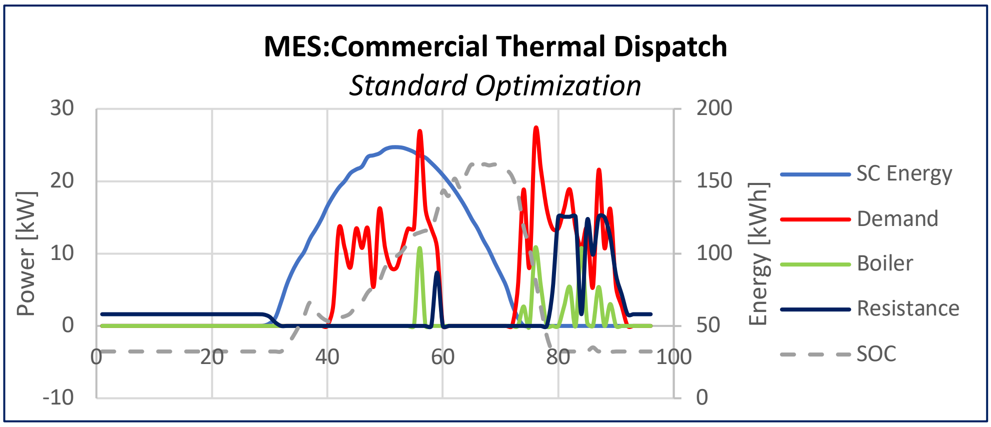
The *hydropower potential* is represented by two rivers: Rio Aguas Blancas with a flow rate of 0.013 m^3 /s and an estimated available power of 7.5 kW and Rio Toconao with a flow rate of 0.068 m^3 /s and an estimated available power of 12.7 kW.

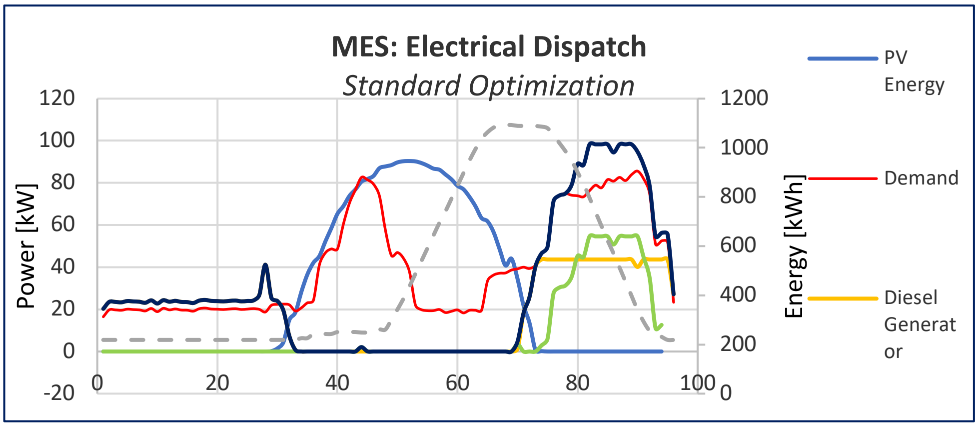
Multi Energy System Results

The *MicroGridPy* and the *Multi Energy System (MES)* model are performed through a robust Linear Programming optimization and it based on the local energy assessment and the local available energy resources. Three different scenarios, namely a standard case scenario, a scenario with increased fossil fuel prices and an *only-renewable* scenario, are run and compared with the baseline scenario (i.e. diesel and gas as the only primary energy sources) in terms of LCOE and system sizing. Below are reported the graph concerning the standard optimization that represents a possible configuration based on realistic parameters referred to the study area. Firstly, the electrical energy dispatch given by the *MicroGridPy* is presented where it is possible to observe that during noon the loads is provided by the photovoltaic power while during the evening hours the demand is exactly supplied by the diesel gen set and the battery flow out.



On the other hand, looking at the electrical despatch performed by *Multi Energy System,* the power provided by the diesel genset and the battery flow out overcome the load. This gap, in fact, correspond to the power required by the electrical resistance to satisfy the thermal demand when required.

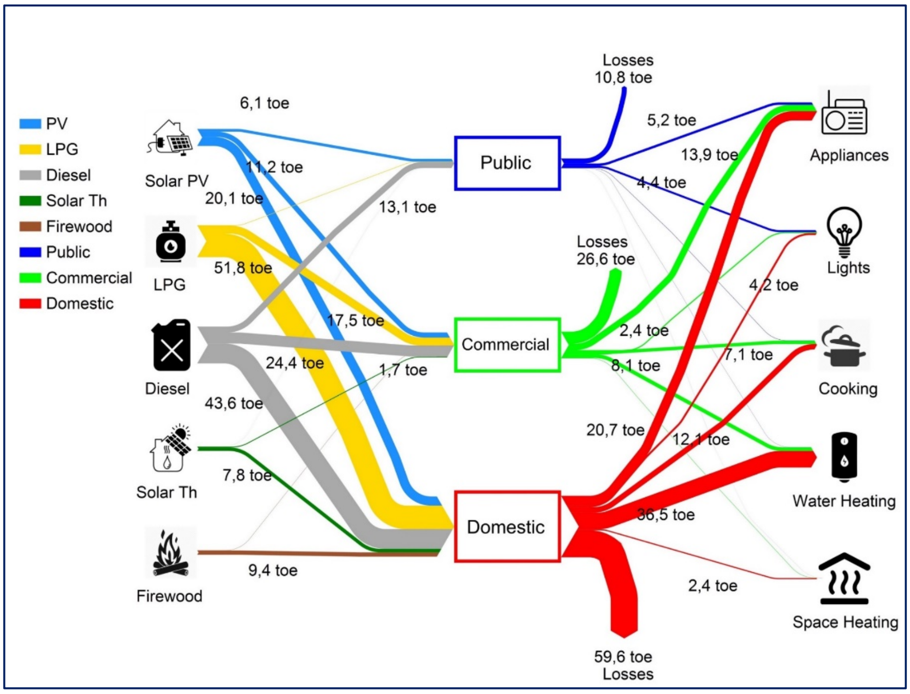




The sizing of the electrical and thermal system is reported in the following tables where the net present cost of the entire projects is reported as well as the Levelized Cost of Energy.

Standard Optimization								
Economical		**Electric**		**Thermal**				
					Com	Dom	Pub	Sch
NPC [M$]	8,18	N° PV	331	N° SC	15	17	1	1
LCOE [$/MWh]	0,264	Battery Cap[kWh]	1092,84	Tank Cap [kWh]	161,62	214,97	1,01	8,41
LCOE/LCOE$_{base}$	77%	Gen P Nom [kW]	174,68	Res [W]	15085	20732	111	452
Diesel Cost [$/l]	0,9			Boiler [kW]	24,24	318,55	1,03	2,14
LPG Cost [$/kg]	2,6							

To this regard, the results show that the cost-optimised MES can effectively reduce the LCOE as well as the NPC as compared to the baseline scenario. To have a global idea of the effects of the optimization on the study area, a Sankey Diagram based on the *Multi Energy System* optimization is presented:



After the implementation of the proposed energy system, the main benefits would be the decrease of reliance on fossil fuels and external sources of energy. In fact, the share of primary energy coming from outside the borders of the study area would become 73% and if referring to secondary energy 54%, compared to the 91% and 95% of actual situation showed above. In conclusion, the results show that the cost-optimised MES can effectively reduce the LCOE as well as the NPC as compared to the baseline scenario. What is more, the LCOE for the combined provision of electricity and heat is only slightly increased as compared to that of a scenario in which only the electricity supply is optimised (i.e. micro-grid only), even though the initial investment cost required is naturally higher due to the need to purchase a whole new set of technologies (viz. solar thermal collectors and hot water tanks). To this regard, the analysis shows how, in compensation for a higher investment cost as compared to the micro-grid alone, the integrated MES scenario offers a higher penetration of renewable sources in the primary energy mix and a lower dependency on external imports (i.e. an increased resilience of the village). The fully-renewable MES scenario implies a significantly larger LCOE and NPC than the baseline scenario, mostly since peak electric and thermal demands occur in times where solar radiation is absent, leading to a significant oversizing of the storage systems and of the energy conversion technologies as well. Other renewable technologies with a more controllable dispatch might be included in the energy system synthesis to investigate more fully-renewable MES scenarios.

Conclusions

This work represented a first step towards the development of a multi-energy system modelling framework and aims to draw attention to this matter. Moreover, energy policy research ostensibly lags behind other fields in promoting more open and reproducible science, hence, the open-source modelling is a key factor of the proposed work.

To this regard, the inclusion of thermal energy in the model imposes a change in the time step formulation, hence, the need to increase the time resolution of the model with sufficient resolution. The problems faced in the modelling of the thermal load profile of the study area with a software (LoadProGen) strictly meant to model electrical loads underline the need for the development of a proper tool, to be juxtaposed to already existing electrical models, in order to compute a whole picture of the energy consumption in rural contexts.

The optimization of the model is performed through a *Linear Programming(LP)* formulation. This choice is dictated by the excessive computational time that an *Integer* or *Mixed Integer Linear Programming* (MILP) would impose to the model. The *LP* is cause of some small computational errors but do not compromise the overall reliability of the results. Further development in the software structure could take into consideration those formulations.

Finally, another interesting possible future development direction of the proposed model could include other renewable energy sources besides solar energy and take into account other thermal needs such as cooking and space heating to reach a wider covering of the energy potentials and energy needs of study areas.

Table of Contents

Abstract

The goal of this work is to face the matter of insufficient attention that is being given to thermal energy consumption and production when treating sustainability in the energy field, in the purpose of achieving the 7th SDG and the necessity for open-source modelling in contrast to commercial software that lead the scene of energy modelling market.

The concept of Sustainable Energization, adopting the Comprehensive Energy Solution Planning (CESP) methodology, is applied within this work on a rural village in the North of Chile.

Energy solution planning is based on matching energy demand with local available Renewable Energy Sources, both assessed with field measurement and analysis. An open-source software is developed to meet with the needs faced in the identification of a strategy to improve energy efficiency and energy supply of the study area, taking into account not only the electrical needs but also the thermal need of energy. An already existing open-source software based on Python language that models the optimization of micro grids in rural environments is taken as basis to develop a similar tool, that takes into account not only electrical needs but sanitary water heating demand as well. The electrical energy balances of the original software are kept unchanged and valid in the new proposed model, while the new thermal balances, carefully explained throughout the work, are joined to consider a wider, not only electric, energy system in the optimization. The optimization is based on the minimization of the Net Present Cost function of the project and uses a Linear Programming logic.

In conclusion to the work, different scenarios are taken into account and energy optimization solutions for the study area are proposed to fulfil the needs in an off-grid configuration.

The limitations of the actual modelling tools, encountered during the development of the work, are explained and commented alongside with proposals for possible further developments in the field.

Keywords: Modelling, Energy Access, Energization, Sustainability, Open Source, Renewable Energy, Multi Energy System

Sommario

L'obiettivo di questo lavoro è affrontare la questione dell'insufficiente attenzione che viene data al consumo e la produzione di energia termica e nel trattare la sostenibilità nel campo energetico, allo scopo di raggiungere il 7 ° SDG, e la necessità di una modellazione open source in contrasto ai software commerciali che guidano la scena del mercato dei modelli energetici.

Il concetto di *Sustainable Energization*, adottando la metodologia CESP (Comprehensive Energy Planning), è applicato all'interno di questo lavoro in un villaggio rurale nel nord del Cile.

La pianificazione delle soluzioni energetiche si basa sulla corrispondenza tra la domanda di energia e le fonti di energia rinnovabile disponibili localmente, entrambe valutate con misurazioni e analisi sul campo. Un software open source è stato sviluppato per soddisfare le esigenze nell'individuazione di una strategia per migliorare l'efficienza energetica e l'approvvigionamento energetico dell'area di studio, tenendo conto non solo dei bisogni elettrici, ma anche del fabbisogno di energia termica. Un software open source già esistente basato su linguaggio Python che modella l'ottimizzazione delle micro reti negli ambienti rurali è preso come base per sviluppare uno strumento simile, che tenga conto non solo dei bisogni elettrici, ma anche della domanda di riscaldamento dell'acqua sanitaria. I bilanci di energia elettrica del software originale sono mantenuti invariati e validi nel nuovo modello proposto, mentre i nuovi bilanci termici, accuratamente spiegati durante il lavoro, sono uniti per considerare un sistema energetico più ampio, non solo elettrico, nell'ottimizzazione.

L'ottimizzazione si basa sulla minimizzazione della funzione obbiettivo Net Present Cost del progetto e utilizza una logica di programmazione e computazione lineare.

In conclusione al lavoro, vengono presi in considerazione diversi scenari e vengono proposte soluzioni di ottimizzazione energetica per l'area di studio per soddisfare le esigenze in una configurazione off-grid.

I limiti degli strumenti di modellazione reali, incontrati durante lo sviluppo del lavoro, sono spiegati e commentati insieme a proposte di possibili ulteriori sviluppi nel campo.

Parole Chiave: Modellazione, accesso all'energia, energizzazione, sostenibilità, open source, energia rinnovabile, sistema multi-energia

Introduction

This thesis work follows the CESP methodology, developed by UNESCO Chair at Politecnico di Milano – Department of Energy, to perform a sustainable energization on the case study of the rural village of Toconao, situated in the Atacama Desert, in the North of Chile. Performed following four main objectives, namely: (I) to assess the current energy situation of the study area; (II) to assess the renewable energy resources locally available; (III) to develop an integrated thermal-electric energy system optimisation model, based on an open-source code; (IV) to propose, based on the developed model, rational scenarios for a more sustainable energy system for the area.
Moreover, inside the frame of the development of an energy solution optimization model the attention is drawn to the matter that current off-grid energy systems optimisation models often tend to focus on the provision of electricity only, neglecting other energy needs. This is due to the increasing modelling efforts required by thermal energy systems in terms of: (i) higher temporal detail of load curves (e.g. for cooking, space heating and water heating activities); (ii) higher spatial detail and necessity to include topographic constraints for most energy conversion technologies, in the absence of centralised heat distribution networks. To this end, we expand the existing open-source MicroGridPy modelling framework – initially conceived for the optimisation of purely electric micro-grids –, by integrating it with a complementary thermal energy system model. The expanded model results thus in an integrated village-scale Multi-Energy System (MES) optimisation tool, which we apply to generate a set of rational decision options for the implementation of a more sustainable and resilient energy system for the case study.

Chapter 1 is dedicated to an overview of the issue to access to energy in Developing Countries and the necessity to draw attention to a wider point of view of energy access, switching form electrification to energization. Finally, the Chilean energy context is presented and the study area introduced.

Chapter 2 focuses on the methodology adapted for field data collection on actual energy situation, through specifically redacted questionnaires administered to the population to assess energy situation, and direct measurements of locally available renewable energy resources. Methodology for electrical and thermal load curves generation through the employment of a specific tool is also presented.

Chapter 3 illustrates the methodology adapted for the development of the Multi-Energy System optimization tool, merging the already existing MicroGridPy model, that considers diesel generators, PV panels and batteries for the provision of electricity; to new balances that represent gas boilers, solar thermal collectors and hot water tanks for the provision of domestic hot water. Furthermore, an internal electric resistance element is included in the model of hot water tanks, thus allowing the electricity from the micro-grid to supply also thermal energy to charge the thermal storage.

Chapter 4 consists in the presentation of the results obtained during the field assessment, in terms of current energy balance of the study area, synthetized by means of a Sankey Diagram, the potential of locally available energy sources, namely solar, wind and hydro power, and the results of the electrical and thermal demand modelling, resulting into daily load profiles of the village.

Chapter 5 is finally dedicated to the presentation of different energy solution scenarios run with the model, the analysis of the system configuration and energy dispatch of the results of the simulations and the energy balances of the village that would consequence the implementation of the proposed solutions by means of Sankey Diagrams. Finally, the Levelized Cost of Energy is used as parameter to compare each scenario with the present situation.

1. Sustainable access to energy in off-grid areas

1.1 From electrification to energization

It is widely recognized that energy is a key factor for the development, growth and progress of a country, region or population as motive power of all the activities of a community [1]. And it is thus of global concern that energy access should be provided for all those who lack it in the world: currently, an estimated in 1.1 billion people lack access to electricity, while 2.8 billion people lack access to clean cooking facilities [2]. A particular attention is placed onto off-grid areas of developing countries, which represent a large share of those numbers. In September 2000 all United Nations member states and many international organizations agreed on and adopted a 15-year development agenda including eight anti-poverty targets, known as the Millennium Development Goals (MDGs) [3]. Nonetheless, despite the progresses made, the MDGs were not sufficient to reach significant targets in terms of access to energy [4], leading to the adoption, in September 2015, of a new agenda consisting of 17 new targets: the Sustainable Development Goals (SDGs). The SDGs are broader and more ambitious than MDGs [5] and require that all three dimensions – economic, social and environmental – of sustainable development are taken into account. Only in SDGs a proper statement on energy has been inserted, as the seventh goal establishes to *"Ensure access to affordable, reliable, sustainable and modern energy for all"* [6] in order to achieve a universal access to energy by 2030. To this end, it is of critical importance to identify innovative solution for off-grid areas, for which grid extension is often not a feasible option both in technical and economic terms [7].

However, in many cases the focus of programs aiming at improving access to energy in off-grid areas is merely related to electricity access, even though a large share of final energy uses is typically associated with tasks that are satisfied by other energy carriers, such as heat that is used for cooking, space heating and water heating. Those energy uses are traditionally satisfied by means of non-renewable fuels and are more difficult to decarbonise, due to a combination of technical and non-technical barriers [8]. This reflects a general trend at the global level: indeed, as stated in a recent IEA communication [9], heat consumption accounts for over 50% of total global final consumption, but yet it has not been given enough attention in terms of decarbonisation potential as nowadays fossil fuels provide more than three quarters of heat production globally.

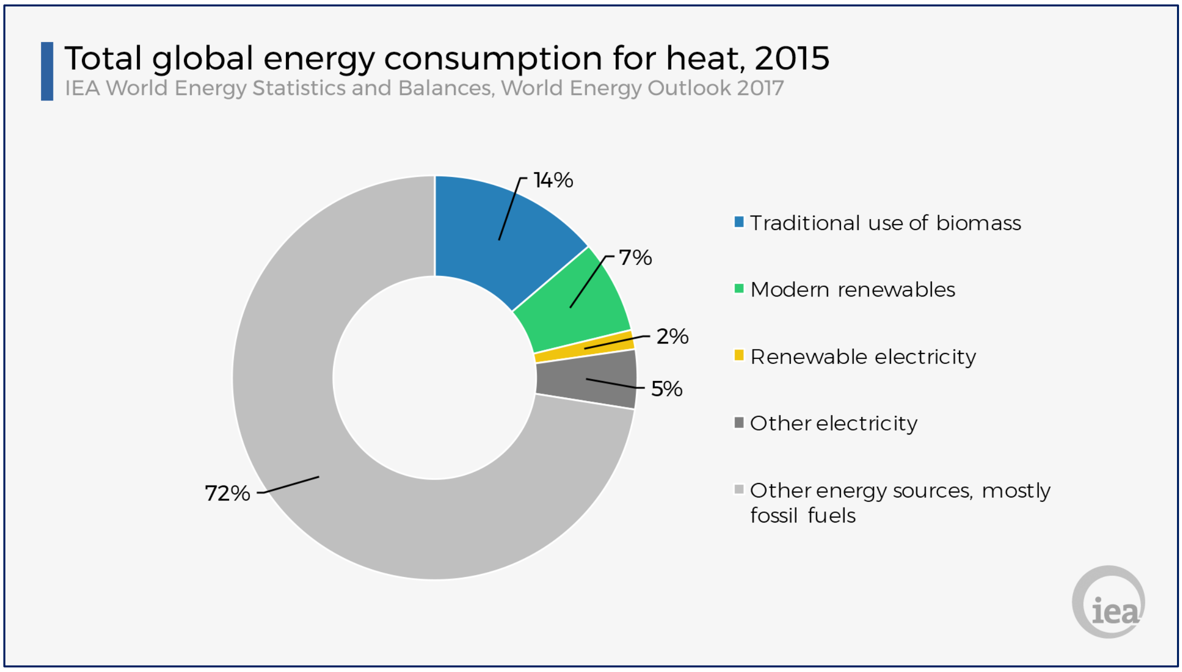


Chart 1: Total global energy consumption for heat, 2015. Source: IEA

The relevance of non-electric energy uses is possibly even higher for off-grid areas of developing countries, where energy-intensive tasks such as cooking and water heating typically dominate the total final consumption, as compared to the relatively smaller amounts of energy required by powering small electric appliances.

In this framework, the issue of access to energy is better captured by the concept of *energization*, which includes: matching of energy needs and energy resources, improving of the energy supply, promoting cleaner and more efficient fuels, covering household needs, providing public services, promoting economic development, emphasizing cultural and social aspects and local empowerment as well as promoting renewable energy systems [10]. To this regard, and with a special reference to small-scale off-grid systems, the widely adopted concept of "Micro-grid" – referring to decentralised energy systems for the provision of electricity – should be enlarged to that of "Multi Energy System" (MES), formalised by Mancarella et al. [8], and comprising all final energy uses and carriers.

1.2 The Chilean context and the village of Toconao

As already stated, the IEA's projections show current efforts towards ensuring access to energy for all are struggling to keep pace with population growth and failing to address multiple energy needs in a comprehensive way.

Nonetheless, access to electricity in Central and South America has seen a remarkable increase in the last period switching from 56 million people - 13% of the population - without access in 2000 to 17 million - 3% of the population – in 2016 [2].

Figure 1: Geographical location of Chile, country of the study area. Source: mapsland.com

Chile is located on the pacific coast of the South American continent, and is one of the most developed countries of the region, with a human development index (a composite indicator used to rank countries based on life expectancy, education and income pro capita) of 0.847 [11].

The mix of sources for Total Primary Energy Supply in Chile is shown in Chart 2.

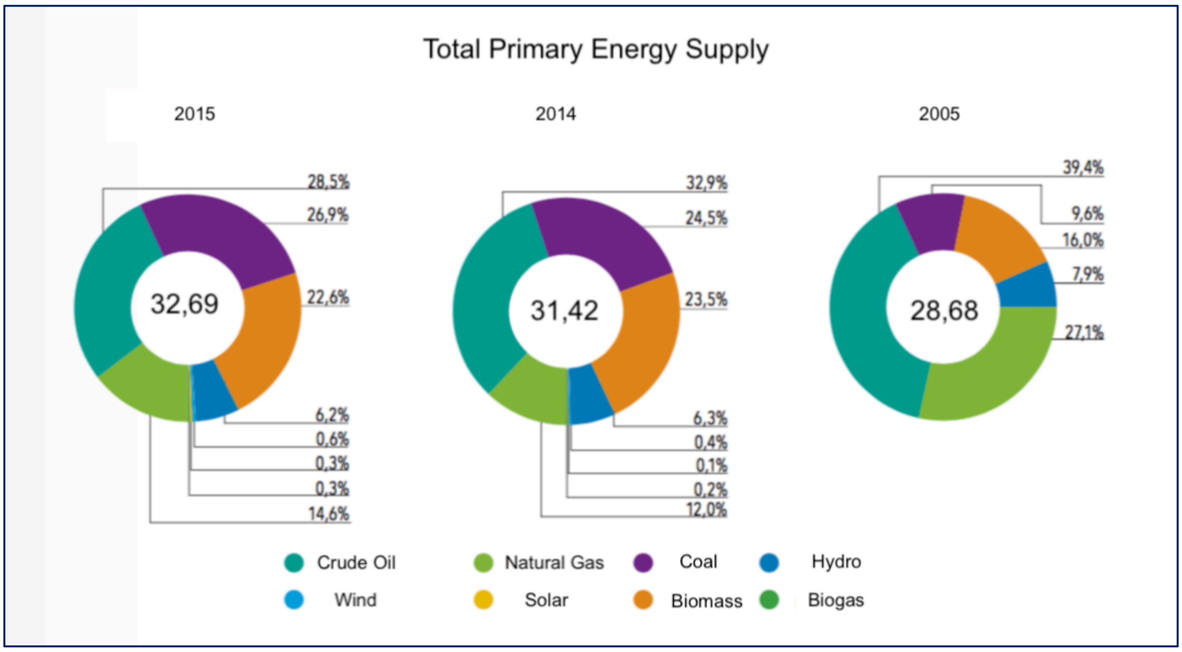


Chart 2: TPES of Chile. Source: CNE

Total primary energy supply in 2015 amounts to 32.69 Mtoe, the largest share of source is Crude Oil and fossil fuels represent 70% of the energy matrix of the country. The north of the country is occupied by the Atacama Desert, a desert with an extension of 105000 km^2, that has been pointed out as one of the places on earth where the highest surface solar irradiance may occur [12], reaching values of 8500 MJ/m^2 per year in some regions [13].

The national electrical grid of Chile is composed of mainly two systems that are not connected one to the other, the SIC (Sistema Interconectado Central) that serves the central part of the country, generating 76,4% of the electricity, and the SING (Sistema Interconectado del Norte Grande) that serves the north of the country and generates 22,8% of the electricity [14].

Chile has a population of around 17 million people [15], and half of it live in the capital, Santiago de Chile, this leads to a strong presence of rural areas in the north of the country, where the 8,4% of the national population occupy the 35% of national territories, namely the Region XV, Region I, Region II and Region III. The percentage of rural population of these regions is around 5%, this implies that the communities that live outside of the cities in the North are extremely isolated, and often have to produce energy for themselves, being disconnected from the national grid.

The villages that are disconnected from the national grid have to rely on small private companies that produce electricity with diesel generators and sell the energy at higher prices than the national average [16], being outside the regulation of the government. In addition, often the price of gas bottles, the only way to distribute natural gas in isolated areas, is higher because of the long journey that is necessary to deliver the product with trucks.

The study area of this work is represented by the rural village of Toconao, in the north of the country, in the Antofagasta region, in the territory of the Atacama Desert, near the border with Argentina and Bolivia, representing a clear example of rural village in the Desert area.

Figure 2: Geographical location of the study area. Source: Google maps.

The village has a population of around 800 inhabitants, 332 households, a Public School that served communities not only of the village but also from villages in the thereabouts, with a number of 180 enrolled students, 32 commercial structures, mainly restaurants and small grocery stores and 9 public structures among which a medical office, a police station and other public offices and services. The village has also a public light service.

The entire list of the structures of the village with relative monthly electrical consumptions of year 2016 is presented in Appendix C.

The village buys electricity from the near village of San Pedro de Atacama, where the CESPA cooperative owns an Electric Power Plant consisting of 2 gas fired generation units of 650 kW each and 3 diesel fired generation units of 300 kW producing energy for the village of San Pedro and dispatching it to the village of Toconao through a 23 kV line of about 32 km [16]. The company sells the energy at prices that are more than the double of the national average [16], as shown (with prices in Chilean Pesos) in Table 1.

Table 1: Electricity prices in Toconao. Source: Authors.

kWh	CLP/kWh
0 - 50	170
51 - 100	180
101 - 200	190
201 +	225

Because of the sand storms and instability of the line, the electric supply suffers of frequent blackouts due to the damage of the line between the two villages and can take days to be restored. For this reason, the village is equipped with a 320 kW diesel backup generator.
The distribution of natural gas in the village is regular, with trucks that deliver bottles once a week, but the price is consistently higher than the national average, because of the isolated position of the study area. 150 thermal solar collectors are already present in the village thanks to a rural development project implemented from the national government with funds from the ALMA observatory, settled in the area and committed to social projects to help the sustainable growth of indigenous communities [17].

The overall energy situation of the village is thus characterised by several limitations, due the heavy reliance on non-renewable, expensive and unreliable primary energy sources. Nonetheless, there is a great potential to further exploit the renewable and abundant solar resource by means of innovative and optimized energy solutions.

1.3 Comprehensive Energy Solution Planning (CESP)

In order to propose potential improved energy solutions, the present work has been organized following the guidelines defined by the Comprehensive Energy Solution Planning (CESP) methodology – developed by the UNESCO Chair in Energy for Sustainable Development at Politecnico di Milano – which consists in a practical sequence of steps to be followed from the conception of the idea until its completion.

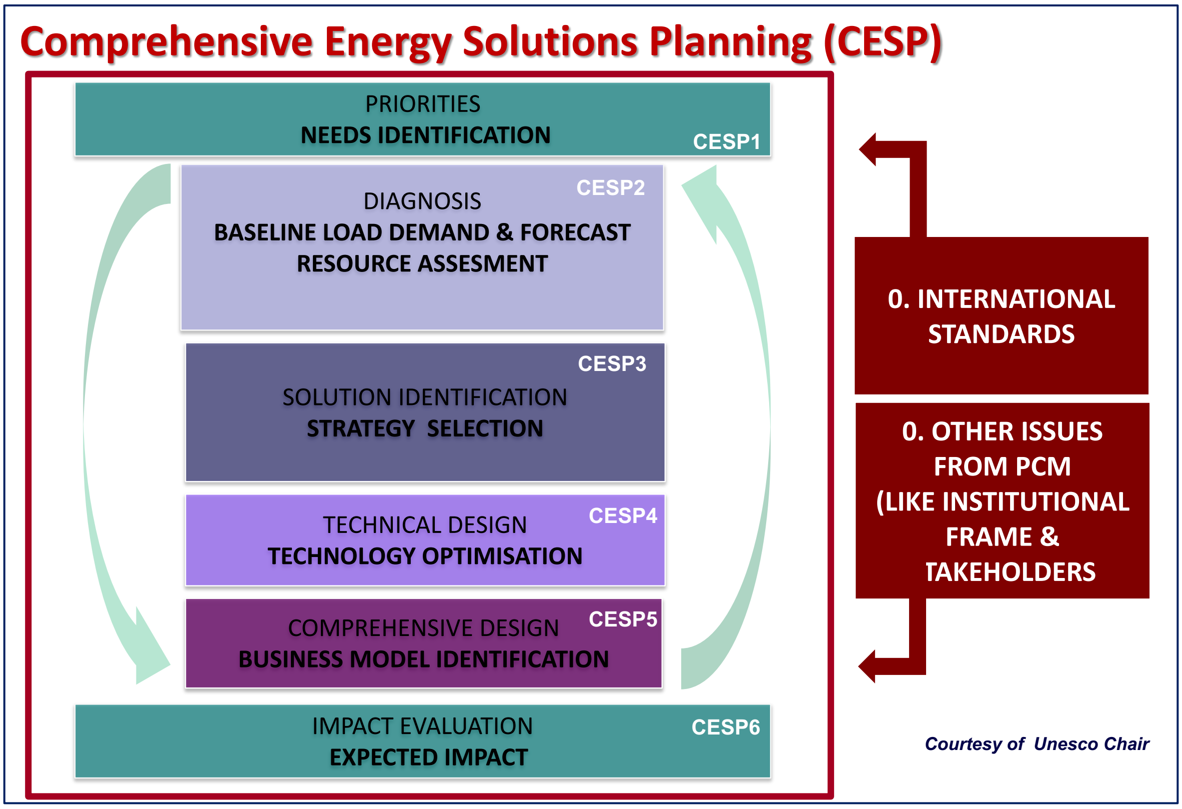


Figure 3: CESP flow diagram. Source: UNESCO Chair Politecnico di Milano.

The general objective of this study is to improve the reliability and sustainability of the energy supply of the study area based on the use of indigenous energy resources through the development of an energy optimization solution.

In order to achieve the general objective, four specific objectives are formulated, namely:

I. To assess the current energy situation of the study area.

II. To assess the energy resources locally available with focus on solar, hydro and wind.

III. To develop an integrated thermal-electric energy system optimisation model, based on an open-source code.

IV. To propose, based on the developed model, rational scenarios for a more sustainable energy system for the area.

The need for a new and open-source model emerges due to the lack, in the framework of off-grid energy systems modelling, of software that: on the one hand, allow to take into account not only the electrification aspect but the whole MES concept; on the other hand, allow for transparency, adaptability to users' needs and knowledge transfer. Such a model would represent a first step towards a multi-energy system modelling approach as well as an alternative to commercial closed-source software available for everyone.

The energisation scenarios proposed in this thesis work are aimed towards an increase of reliability of electrical supply, disconnecting the study area from the village of San Pedro – cause of the frequent shortages – and increasing the quality of the service. Considering that the population is aware of the great solar potential of the area they live in, they are incline to a "green" switch of the energetic matrix of the village, moving towards the seventh goal of the SDGs with a strong example for the other rural communities of the area that could adopt the same strategy and give a push to the decarbonisation of the energy production in the country.

2. Methodology for assessment and load modelling

The field work consisted of both preparatory desk work and data collection in the village of Toconao. Preparatory desk work included preliminary literature review, collection of information about the study area, drafting of the reference energy system and of questionnaires for the population, identification of possible energy drivers and selection and testing of needed instruments. The preparatory work started approximately two months before the on-field work in Toconao. The field work included tests, direct observations, direct measurements, surveys and interviews based on questionnaires to obtain primary data. The field work lasted for ten days and was carried out with the full cooperation of the local community.

The chapter below is subdivided into three paragraphs: assessment of current energy situation, energy resource assessment and electrical and thermal load curves calculation. For each paragraph, the specific adopted methodology to drive the analysis and the activities to reach the results are explained, by reviewing the literature and gathering examples to adapt and apply to the desert rural context of Toconao.

2.1 Assessment of current energy situation

In this thesis the approach of Johnson [18] is used to define a framework for the energy balance assessment of a rural area. In this framework, energy sources, energy drivers and final uses are allocated as the diagram below.

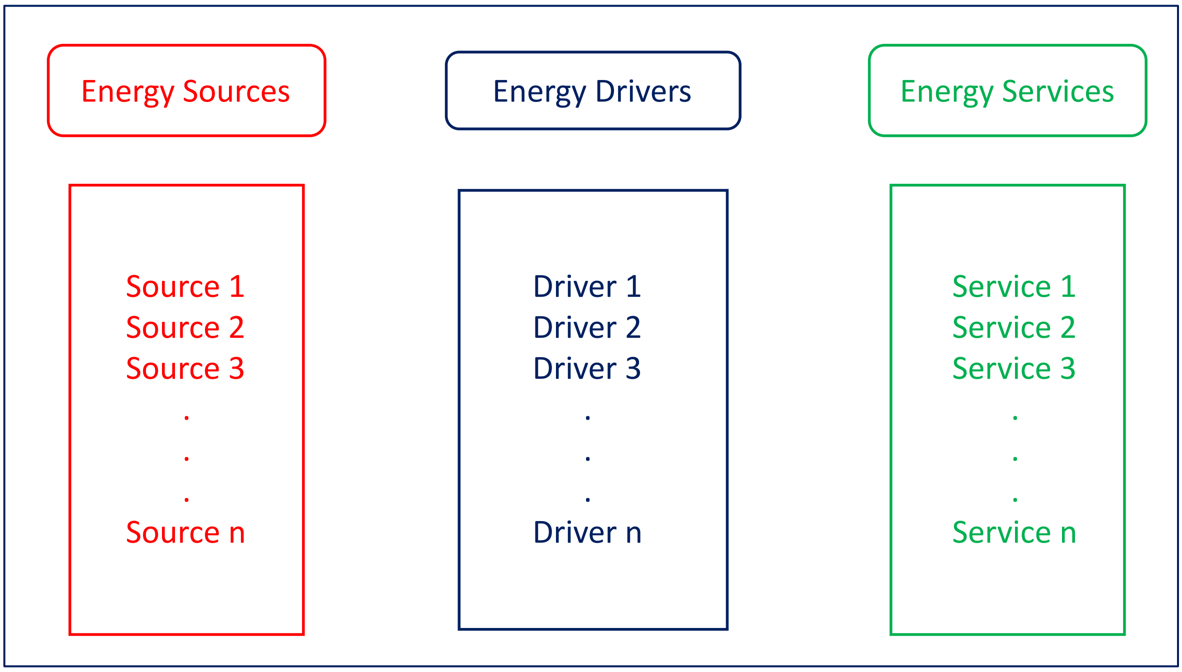


Figure 4: General scheme of an energy system. Source: Authors.

For each energy driver the primary sources of energy are identified and the total primary energy supplied is estimated. Energy services demanded at each energy driver are then identified and for each of them are analysed the census data on the conversion technologies adopted to transform the total primary energy supplied into the total final energy consumed.

2.1.1 Energy Drivers

According to Johnson et al [18] the energy consumption for a rural community can be organized in the following energy drivers: *domestic, artisan or productive activities, public services* and *transport.*

Three of these four categories were identified on the field by direct observation:

- Domestic, including all the households.
- Artisans, including all the income generating activities like shops, restaurants and guesthouses.
- Public services, including the medical office, the police station and the school, along with other services and public street lighting.

A complete list of all the components of the drivers is obtained in form of an excel spreadsheet (Appendix C) as courtesy of the electric committee of the village, that manages all the bills of the village to be paid to the company that provides the electrical energy.

Domestic Energy Driver

For the domestic energy driver, the households of the study area are identified through direct observation. The data regarding energy consumption of this energy driver are collected by means of a questionnaire administered to a static sample of households. The questionnaire was administered in the form of peer-to-peer interviews during the field period: this strategy allowed mutual understanding and gave the possibility to clarify the questions and ensure cooperation of the interviewee. The questionnaire fully reported in Appendix A consists of eight parts meant to assess energy sources, uses and supply.

The first part, *General Information,* aimed to gather few personal information regarding profession and family status of the interviewee. The second part, *Electricity Use and Supply,* is meant to investigate the means and security of electricity supply and questions related to the single electric devices (type, peak power, and hours of use) are asked to collect data such as equipment characteristics, operation and usage patterns, as suggested by A. C. Menezes et al. [19]. The third part, *Cooking*, is intended to understand which fuels are used to cook meals in the households and the level of security in their use. The forth part, *Space Heating,* aims to investigate the fuels used for space heating, and the quality of thermal comfort inside the house according to The World Bank's Tiers [20]. The fifth part, *Sanitary Water Heating,* is meant to investigate the means of heating sanitary water in the households. Part six, *Fuel Supply,* asks in which way and at which cost the fuels are collected from the families, mainly LPG and firewood. Part seven, *Other Energy Sources,* investigates if other fuels from LPG and firewood are used and in which way. Part eight, *Domestic Residuals Production,* is meant to assess the amount of biogas that can be potentially produced by animal dung and agricultural waste. The model is based on other sample questionnaires used for energy assessment in rural areas [21].

Commercial Energy Driver

For the commercial energy driver, the same pattern as the domestic driver is adopted, the same questionnaire was administrated to the owners of a selected statistical sample of commercial activities of the study area, in order to assess the energy consumption habits of the category.

Public Energy Driver

For the public energy driver, the same questionnaire was administrated in the same way of the other two drivers. In addition to that, in order to better estimate the Electrical Load Curve of the school, the major unit of the village, a real time energy consumption assessment was completed. The school is just a part of the Public Energy Driver, for this reason the data is used just as a mean of verification. A programmable camera was placed (as shown in figure 5) to take pictures of the electricity counter every minute for 24 hours.

Figure 5: Camera installed to monitor energy consumption of the local Public School. Source: Authors.

For the public street lighting, only the data from the electric committee and sunrise and sunset times throughout the year are used to compute the electric load curve.

2.1.2 Primary Energy Sources

Parallel to the questionnaires an assessment of the current primary energy sources is conducted by means of direct observation and data analysis.

Grid:

The total amount of electrical energy coming from the grid is calculated form the electrical bills of the village, as sum of the energy consumption measured from every single electric meter of the village rested the energy produced by the backup diesel generator.

$$E_{grid} = \sum E_{user,i} - E_{genset} \tag{1}$$

The energy from the grid, since no energy conversion happens inside the boundaries of the study area, is considered to be net of losses.

Diesel Generator:

Inside the village a 400 kVA Diesel backup generator is present to make up for the electrical interruptions from the grid. To estimate the electrical efficiency of the generator the following methodology is adopted. From the literature [22] the LHV (Lower Heating Value) [MJ/kg] and the energy density [MJ/l] for the diesel are extracted. On the generator is present a LCD Display that shows information about the working conditions, in particular the instant consumption [l/h] and the total energy produced [kWh]. Combining these pieces of information is possible to compute the efficiency. In detail, the working of the generator is monitored for three hours in peak load period, and the energy produced calculated differentially as:

$$E_{i \to i+1}\,[kWh] = E_{i+1} - E_i \tag{2}$$

The fuel consumed in the same period is computed through the mean of the instant fuel consumptions measured:

$$\dot{C}_{diesel}\left[\frac{l}{h}\right] = \frac{\left(\sum \dot{C}_{diesel,i}\right)}{n_i} \tag{3}$$

Where n_i is the number of observations.

And the total diesel consumed in the three hours observed calculated with the inverse formula:

$$C_{diesel}[l] = \dot{C}_{diesel} * 3\ [hours] \tag{4}$$

And the electrical efficiency as the ratio between total energy produced and diesel chemical energy consumed:

$$\eta_{GenSet} = \frac{E_{i\rightarrow i+1}}{C_{diesel} * Energy\ Density} \tag{5}$$

The energy produced in one year by the Diesel Generator is computed through the knowledge of the time elapsed [years] since the installation of the Diesel Generator and the total energy [kWh] produced since.

$$E_{one\_year}[kWh] = \frac{E_{tot}}{y_{tot}} \tag{6}$$

In this way is also possible to estimate the percentage of energy that the electric meters measured but is not injected by the grid, since the meter does not differentiate whether the electricity comes from the grid or form the generator and keeps measuring unaffected.

$$E_{grid} + E_{genset} = E_{measured} \tag{7}$$

LPG:

The energy deriving from LPG in the village is calculated by means of the responses to the questionnaires and pieces of technical information about the gas gathered from the producer [23].

From the questionnaires is possible to estimate the total amount of gas bottles, and with that, kilograms of gas, consumed yearly in the village by each energy driver.

From the literature the corresponding LHV is obtained [24].

The total energy is then computed as product of total mass of gas consumed times the LHV.

$$E_{LPG} = m_{LPG} * LHV_{LPG} \tag{8}$$

While the efficiency of the final use is collected by direct observation in the case of gas boilers, and from literature [2] in case of gas cookers.

Solar Collectors:

Inside the village 150 solar collectors are present, installed for the Joint Social Development Program of the Chilean Government and the ALMA observatory [17], on selected households.

From the study carried out by the engineer that followed the project the working parameters are extracted, such as efficiency, litres of water heated per collector, and working temperatures.

In this way the total secondary energy produced daily from the collectors can be estimated.

$$E_{SC}[kWh] = \dot{m}_{water} * cp_{water} * \Delta T \tag{9}$$

And through the efficiency of the system, the primary energy entering the boundary of the study area:

$$E_{solar}[kWh] = \frac{E_{SC}}{\eta_{SC}} \tag{10}$$

Firewood:

Firewood is a source of thermal power for cooking that is not largely used but still present in the village. The amount of wood, in kilograms, used yearly from the population is extrapolated from the answers to the questionnaires, where a specific question is present for the purpose.

The wood most used for burning purposes is Carob (Ceratonia Siliqua L.) which LHV is found in literature [25]. In order to compute the thermal efficiency of a standard stove used in the village a Water Boiling Test (WBT) is carried out according to the protocol [26] and following as much as possible the procedure. The WBT is conducted for an improved firewood stove.

Figure 6: Advanced cook stove present in the study area. Source: Authors.

The WBT is conducted including all three consecutive phases shown in the figure below:

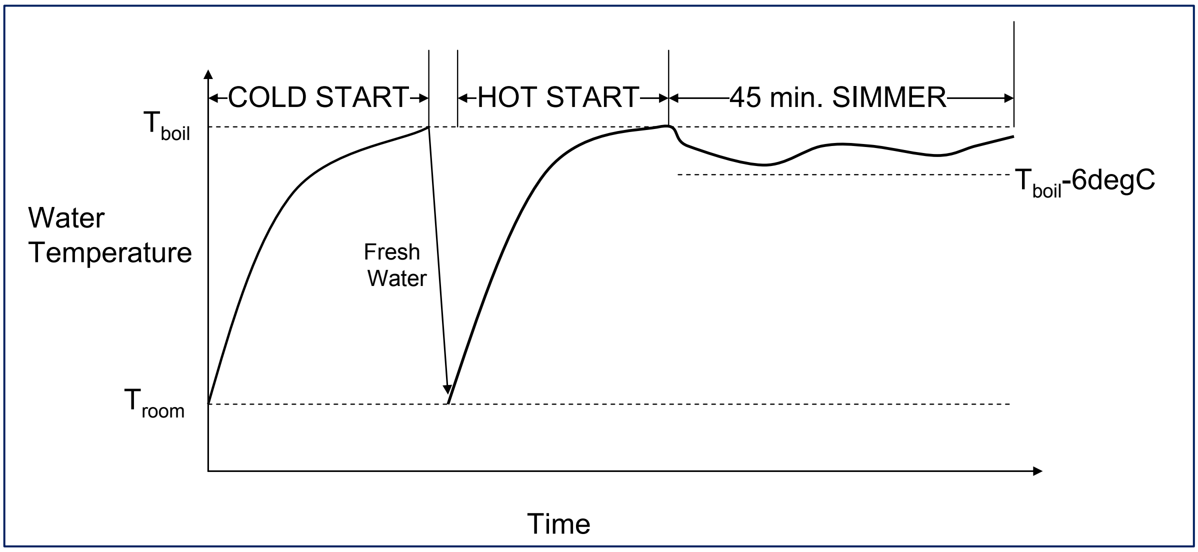


Figure 7: Phases of Water Boiling Test. Source: [26]

1) *Cold-Start high-power phase,* starting with stove at room temperature firewood is used to boil a known quantity (2,5 litres) of water in a standard pot.
2) *Hot-Start high-power phase,* the water is replaced with water at ambient-temperature on the still hot stove and it is brought to local boiling temperature equal to 90 °C, adding fuel to the fire.
3) *Simmer phase,* without changing the water, a temperature between 3 and 6 °C below boiling temperature is kept for 45 minutes

Inputting the measured values, along with ambient parameters in the WBT excel spreadsheet the thermal efficiency of the stove is given as result.

2.2 Load Curves Modelling

In order to compute the Load Profiles of the different energy drivers a stochastic approach is adopted, by means of the LoadProGen software [27]. LoadProGen, developed by Politecnico di Milano, allows to create a series of profiles of different categories of users inside a study area; for each of these classes it is possible to define which appliances are used, the nominal power of these, and their time of use and windows of usage. Through a random function all the nominal powers of the appliances of one class are summed up filling the time windows with the time of usage, creating a Load Profile of one class, that is then summed with the profiles of the other classes, creating the total Load Curve of the study area. The software has been rigorously designed to compute electrical Load Curves only. Nonetheless, in this work, it has been adapted by the authors in order to model also thermal loads.

2.2.1 Electric Load Curves

The software works through a random estimation of load profiles based on the following inputs:

- Number of user classes, containing all the users with a similar electric usage behaviour
- Number of users per class
- Kind and number of appliances per each class
- Nominal power of appliances
- Functioning time and minimum functioning cycle of each appliance
- Functioning windows of each appliance

In order to generate the electrical load profile of the village, two main sources of information are pulled together and used to generate an input for the LoadProGen software.

First of all, the questionnaires administered to the population, where the kind of appliances and their pattern of use are investigated for each class in section two. On the other hand, the monthly and annual electrical consumption of each user, helped classify the users into different classes, more specifics than the energy drivers, based on total annual consumption. The six identified classes are:

- High Households, the 130 households that consumed more than the average per year;
- Low Households, the 202 households that consumed less than the average per year;
- School, that is treated as a single class because of its strong differences in energy consumption from the other public services due to the high number of daily users;
- Public, the 6 public services that consumed electrical energy apart from the school in the village;
- Commercial, the 32 commercial activities, for which is possible to identify a common pattern in the electrical energy usage;

- Street Lighting, computed solely through the electrical bill, estimating the time of usage from dawn and sunset times and the nominal power dividing the monthly energy consumed by the functioning time.

A seasonal variation is introduced by the authors varying the functioning time of the light bulbs of the three energy drivers based on duration of night time, considering that the questionnaires were administered in June, during the winter season.

The LoadProGen software includes the feature of creating different load profiles scenarios for a single input, based on small variations of the random function that generates the load curve. The creation of a scenario for each day of the four seasons configurations would have represented a more realistic way to create a one-year electrical load profile of the entire village, necessary for the creation of the village Electrical Demand, as will be discussed in Chapter 3. But this option resulted impossible to realize due to computational limits of the LoadProGen software. As an alternative the same profile is repeated equal to itself for every day of the season, and the four seasons obtained, concatenated obtaining the load profile of the entire year.

2.2.2 Thermal Load Curves

In order to adapt the working logic of LoadProGen to a thermal load, some precautions are taken. First of all, a thermal load curve of the entire study area is not computed, but several different profiles are calculated, given the impossibility of centralization of thermal energy production with solar collectors. In order to generate the thermal load profile of the village, the information gathered through the questionnaires are processed to compose an input file to fit the LoadProGen software and allow it to compute a Thermal Load Profile for the village. These pieces of information are then compared with the ASHRAE Handbook [28] in order to confirm and better model the thermal demand profile. For this reason, the structures with a similar thermal behaviour are represented in a single class, considering only one "typical user", the total demand of the class is obtained multiplying the obtained values by the number of users. The classes created are:

- Households, all together in a class because of the similar pattern of hot water consumption that is identified from the questionnaires.
- Commercial, considering that all the restaurants have a similar pattern of water consumption based on the number of meals served per day as suggested in [28].

- School, based on the questionnaire administrated to the Dean, in order to have most precise answer as possible.
- Public, as the Police Station and the Medical Office, only other public services with a hot water consumption.

Since the LoadProGen software works with electrical appliances, a set of fictitious thermal appliances with the same logical structure of an electrical one has to be created. Given the peculiarity of the operation, every appliance is modelled in a different way depending on the class of usage.

From the questionnaires the daily consumption of energy for heating water is estimated, from the two sources, LPG and solar collectors; then the energy is divided following ASHRAE indications [28] as guidelines to confirm the field data, into different tasks, depending on the class; finally an average time is estimated for each task based on direct observations. The nominal power of each appliance created is thus calculated as the ratio between energy consumed by the task and its functioning time.

$$P_{nom} = \frac{E_{task}}{t_{task}} \tag{11}$$

Households:

For the households' class, three appliances are created, *Dish Washing* - two per day -, *Shower* – one per person per day - and *Face and Hand Washing* - one per person per day -.

Commercial:

As already stated for the commercial class a fictitious appliance called *Normal Use* is created, based on the number of meals served by the restaurant per day, and repeated during the duty hours as many times as the meals served. The nominal power is calculated with the total energy – time ratio and compared with the ASHRAE guidelines.

School:

The input for the school is created combining the logic used for the restaurants, because of the school canteen, and a *Face and Hand Washing* appliance is created to consider the normal use of the toilets from the students and the staff.

Public:

For the public class, the same logic as for the households' class is applied, with the information from the questionnaires three appliances are created, *Shower, Hand Washing* and *Food Use*, and the nominal power calculated as the ratio between daily thermal energy consumed and the total functioning time of each fictitious appliance.

For every class defined, 365 different scenarios are simulated with the software and then concatenated in a single column in order to obtain a more realistic year of operation of the system.

In this case no seasonal variation has been considered due to the steady hot water consumption during the entire year assessed through direct observation.

2.3 Assessment of Local Energy Sources

Toconao is situated in the geographic zone of the Atacama Desert, where seasonal variability of the weather is almost inexistent, and is characterized by extremely dry climate.

In some areas no rainfall has ever been recorded, making it the driest desert on Earth, although rain does fall in San Pedro de Atacama when, in the summer months, the thermal air currents above the Bolivian side of the Andes form large rain clouds that then drift down back into Chile and deposit heavy, but short, rain showers over the area, often accompanied by loud thunder and lighting. This phenomenon is called the *Bolivian Winter*, resulting in snow fall at higher elevations [29]. This phenomenon affects the river flows but not the intensity and constancy of solar radiation.

The assessment of the energy resources locally available is divided by energy source focusing on renewables: solar, wind hydro energy and biomass.

2.3.1 Solar Potential

Installation of the instruments and data collection:

The collection of data of solar global irradiation and humidity and temperature parameters is to be carried out directly on site with real-time measurements with a system of:

- SP Lite 2 Kipp and Zonen silicon pyranometer,
- TinyTag Plus Millivolt Imput Data Logger connected to the pyranometer,

- TinyTag Plus Temperature Data Logger,
- TinyTag Plus Relative Humidity Data Logger,

assembled by the authors and mounted on the roof of the Public School of Toconao. The station remains on location for a month collecting data.

Figure 8: Measuring station installed on site. Source: Authors.

Before leaving for Toconao the used pyranometer is calibrated with a CMP10 Kipp and Zonen Pyranometer, ISO 9060 Secondary Standard, based at the *Renewable Energy Laboratory* of Universidad Tecnica Federico Santa Maria, comparing the measures of the two instruments in different conditions and proving the reliability of the used tool.

Data Elaboration:

The data directly acquired on site include: Solar Global Horizontal Irradiation (GHI), Ambient Temperature (T) and Ambient Relative Humidity (ϕ), all computed every 10 minutes.

The measurements taken on field started right after the installation on the 12^{th} of June 2017 allowing to collect data till the 4^{th} of July 2017 for a total of almost a month. However, this sample of data is not enough to determine the effective solar radiation regime in the study area since data for at least one year are required to consider seasonal fluctuation.

In the case of this research a longer measurement period was not feasible, therefore a comparison with a reliable database is required. The reference dataset is chosen to be the three-years measurement performed by the Chilean Government in cooperation with the German Technical Cooperation, in the town of San Pedro de Atacama, 37 km away from the study area, from May 2009 to May 2012 [30].

The dataset consists of direct measurements of GHI and Direct Normal Irradiation (DNI) every 10 minutes in the described operation period.

In order to compare the two datasets an average of the measurements for every time step same period, 12th June to 4th July, of the three years is computed, and then each one compared with the same values in the field collected dataset by means of ratio between them. The average ratio between the two datasets resulted to be 1,02, enough to consider the average values of the three years a suitable Typical Meteorological Year for the aims of the study.

The ambient temperatures of the same dataset are assumed to be valid for the case study considered the distance from the study area and the similarity of weather conditions and geographical characteristics.

In order to compute the Global Irradiation on a tilted surface the isotropic model is adopted [31]. In particular for a tilted surface with an inclination assumed to be equal to the latitude of the study area and facing North in the southern hemisphere, the equation is:

$$I_i = I_{bh}\, R_b + I_{dh}\left(\frac{1 + cos\beta}{2}\right) + \rho_r (I_{bh} + I_{dh})\left(\frac{1 - cos\beta}{2}\right) \quad (12)$$

2.3.2 Wind Power Potential

Installation of the instruments and data collection:

The collection of data of wind speed and direction is carried out directly on site with real-time measurements with a Weather Station PCE-FWS 20, consisting of:

- Cup anemometer for measurement of wind speed
- Wind direction sensor for measurement of wind direction
- Rainfall sensor
- Ambient temperature sensor

- Relative humidity sensor
- Display unit to monitor data in real-time and store data.

The weather station is placed at a height of 6,7 meters outside the Public School on the flagpole.

Figure 9: Wind measuring station installed on site. Source: Authors.

The station remained installed on location for a month collecting data.

Data Elaboration:

The data directly acquired on site included: wind speed (Sw) and wind direction, both computed every 5 minutes.

The measurements taken on field started right after the installation on the 12^{th} of June 2017 and was supposed to collect data till the 4^{th} of July 2017 for a total of almost a month. But for malfunctioning of the instrument data from only few days was finally available. For this reason, this sample of data was completely useless to define the effective wind speed regime in the study area since data for at least one year are required to consider seasonal fluctuation, a reliable dataset is then necessary. The reference dataset is chosen to be the data available in the *Explorador Eólico,* a tool developed by the University of Chile that that delivers results from a numerical simulation of wind conditions and air density on the national territory, considered well-known, reliable and having data available for a long observation period for free [32].

The exact geographical coordinates can be inserted in the web page, and selecting an altitude a detailed report of wind data for a Typical Meteorological Year is produced. For the scope of the work, 5,5 meters data are considered as the most similar to the directly measured ones and most indicate for micro-wind turbine solutions.

The annual average wind speed obtained from the *Explorador Eolico* data is used to determine the available power per unit of swept area according to Betz's law [33] (Equation 13).

$$P_{wind}\left[\frac{W}{m^2}\right] = \frac{1}{2}c_{Betz} * \rho_{air} * v_{air}^3 \tag{13}$$

2.3.3 Hydropower Potential

Through the survey of the environment two water streams are identified, one that flows through the village itself, Rio Toconao, and one 10 kilometres away from the village, Rio Aguas Blancas.

In order to compute the micro hydropower potential of the flows two main parameters have to be measured, flow rate and gross head since the gross power potential is basically given by the product of the two, as shown in Eq. 14.

$$P_{gross} = g * H * \rho_{water} * \dot{Q} \tag{14}$$

Where P_{gross} is the gross power, g the gravitational acceleration, H the head, ρ_{water} the water density and $\dot{Q}$ the volumetric flow rate of the river. Thus, flow rate and head between catchment and location have to be measured. The gross potential is the energy contained in a given quantity of water with a certain head. Instead, the net power P_{net} accounts for the losses along the conversion chain (penstock, turbine, generator, drive system) in the efficiency term η:

$$P_{net} = P_{gross} * \eta_{hydro} \tag{15}$$

The activities to assess water flow and head are explained in detail in the following parts:

Water Flow

The average volumetric flow rate of the water is the quantity of water flowing past one point in a given time. Flow rate measurements are realized using the *floating object* method as described in [34].

The materials used for the *floating object* method r a measuring tape, a stopwatch, an object of small size that can float and if lost will not pollute the environment (an orange) and a stick. A suitable part of the river, as straight as possible for a length of approximately 8 meters and uniform in depth and width is selected for the first river. While for the second, the water flows in a pipe for a length of about 7 meters, and the inlet and outlet are easily accessible, making it an extremely suitable situation for flow rate measurements.

Figure 10: Measurement of local river flows. Source: Authors

The floating object is let free to move in the river at the starting point and the time necessary to reach the ending point is registered. This operation is repeated ten times for each stream to estimate the average travel time (Δt) [34].

The average velocity is obtained as ratio between the constant length, x, and the average time, according to Equation 16.

$$v_{water}\left[\frac{m}{s}\right] = \frac{x}{\Delta t} \tag{16}$$

In the case of the open stream of Rio Toconao the river is divided along the width (W) at specific intervals of 0,6 meters and the depths (D_i) at each point are measured with the help of the stick and the measuring tape.

The cross-sectional area of the section considered is obtained applying the trapezoidal rule.

In the case of the piped stream of Rio Aguas Blancas, the cross-section area of the flow is computed with the circular segment formula.

The average volumetric flow rate $\dot{Q}$ is computed using Equation 17.

$$\dot{Q}\left[\frac{m^3}{s}\right] = A * v * c \tag{17}$$

Where $A\ [m^2]$ is the mean cross-section area of the stream, $v\ \left[\frac{m}{s}\right]$ is the average stream velocity and c a correction factor, which accounts for the type of stream bed [13].

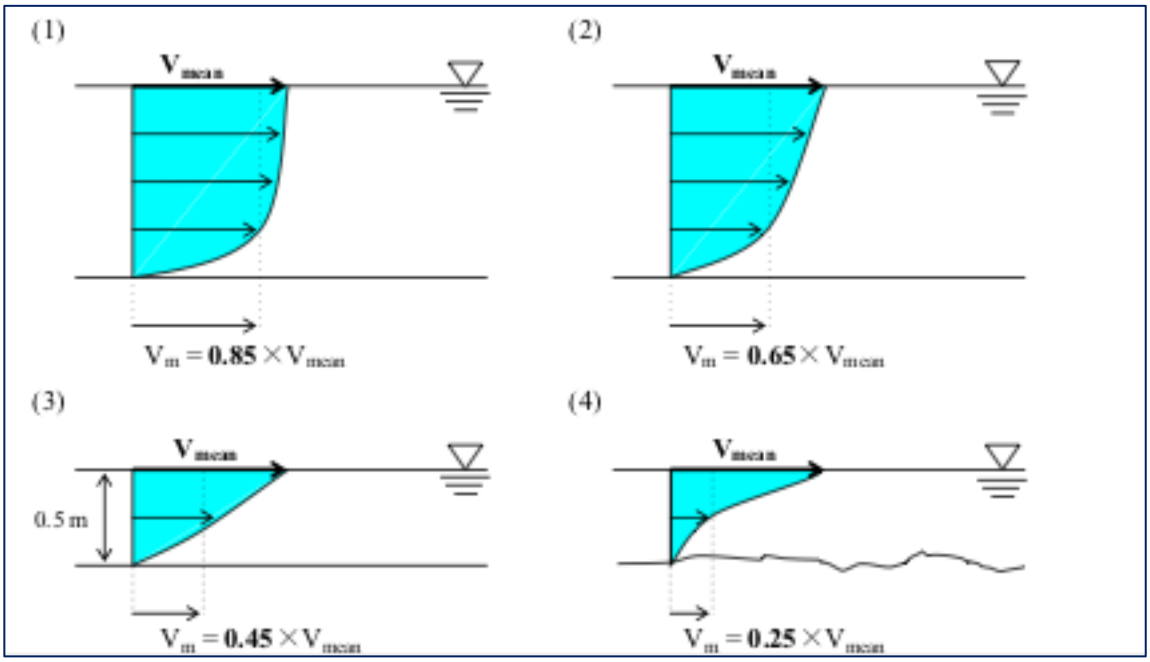


Figure 11: Riverbed profiles and correction factors. Source: [21]

Due to the observed morphology the streambeds of both rivers are characterized as *Shallow Flow*, therefore a value equal to 0.45 is chosen for the correction factor in both cases.
The measurements of the river flows are performed in winter, as to say the driest time of the year, due the *Bolivian Winter* phenomenon that happens in summer. For this reason, the computed flows are assumed to be the minimum value of the year.

Gross Head

The hydraulic head between the rivers catchment and the village is assessed in the first case, and the head between the rivers catchment and the position of an old powerhouse, where a hydraulic turbine was once installed, is assessed in the case of the second river analysed.
Due to the absence of more suitable instruments the measurements are performed via Google Earth, identifying the positions under investigation with the help of local people, and considering the data obtained accurate enough for the scope of this work.

3. Thermal and Electrical Modelling Methodology

The concept of energy access could be translated into the theme of *energization.* Energization can be considered as the supply and planning of the complete energy solution to meet electrical and thermal demand, focusing on the short-term improvement of rural communities [10]. The aim of this study is the development of an optimization tool that considers not only the electrical aspects but also the thermal ones.

Nowadays, several commercial software are able to solve energy balances for the rural electrification, however, in most of cases they are not able to perform the optimization of a thermal and electrical solution planning at the same time. Therefore, this analysis proposes a new open source model that is able to satisfy both the electrical and the thermal demand considering the local energy requirements and the locally available renewable resources.

The methodology builds on an open source model of isolated hybrid micro grids [35] , that models the behaviour of real components to perform a consistent sizing, ensuring the reliability of the energy supply and considering different scenarios for isolated rural villages. Based on such model, a new thermal model is implemented and aggregated to the original one, in order to:

1. combine the thermal and electrical energy access problem
2. satisfy the thermal load through the available local sources
3. find the optimal solution minimizing the net present cost (NPC) function as an objective function

The code is implemented in the Python language [36] using the Pyomo Library [37]. The input files are the electrical and the thermal demand, the photovoltaic energy (PV Energy), the solar collector energy (SC Energy) and a data file where all parameters are defined. Then the optimization is performed by the IBM CPLEX [38] solver through the simplex algorithm that optimizes and minimizes the net present cost function. Finally, the program returns the electrical and thermal energy dispatch as well as the optimal configuration of both systems.

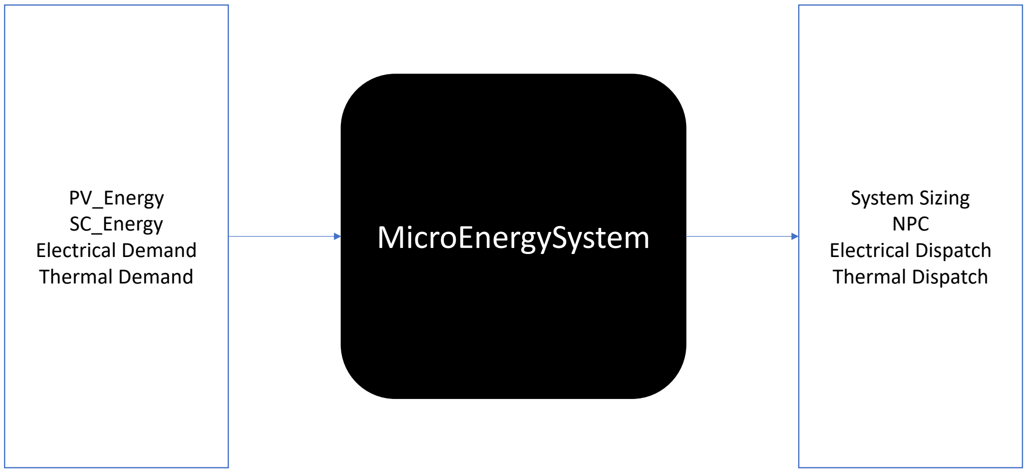


Figure 12: Black Box scheme of the proposed model. Source: Authors.

In Chapter 5 a case study is analysed, and all the results are presented with respect to the rural village of Toconao, Chile.

3.1 Model Characteristics

3.1.1 Electrical System

The model aims to satisfy the electrical energy requirement of an isolated village through the following configuration as shown in the figure:

- *PV array* connected to an inverter that generates electricity from the solar irradiation
- *Battery bank* that stores the excess energy
- *Backup diesel* generator.
- *Load* that represents the electrical demand of the local community.

A centralized PV generation system, a unique battery bank system for the entire village as well as a single unit of diesel gen-set are considered for the electrical configuration [39].

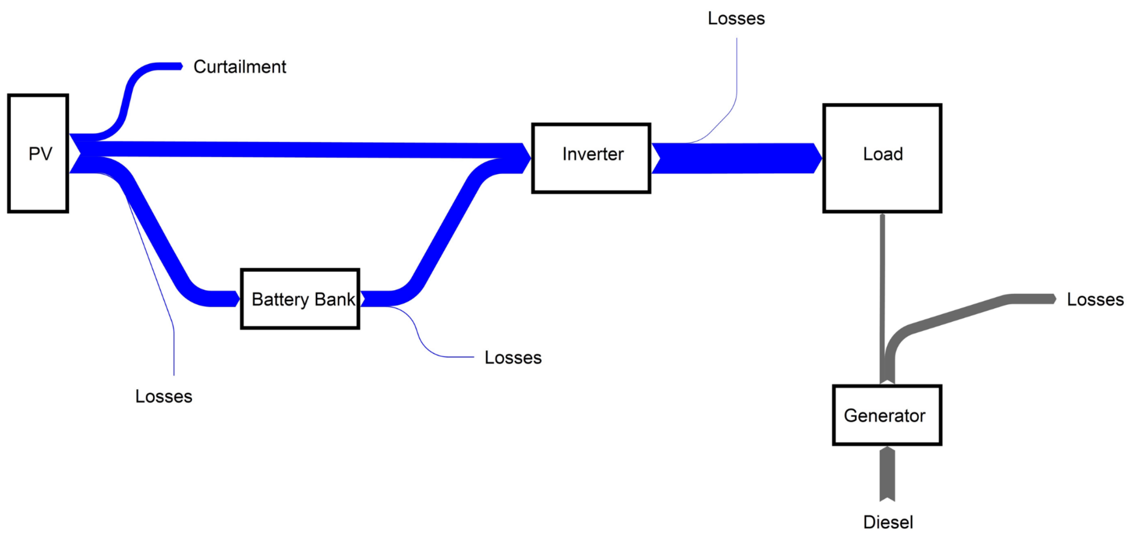


Figure 13: Considered micro-grid typology. Source: Authors

PV Energy

To calculate the energy coming from a photovoltaic panel, the local temperature, the solar radiation, and the techno-economic information collected in the study area are used in the analysis. The inclination of the module is assumed to be equal to the latitude of the study area. The simulation of the PV module is an exogenous parameter, which has been provided by the University of Liège based on a five parameters model [40] implemented in the *Modelica* language [41] and calibrated with real data from commercial PV array available on site. The energy yield of one PV module is evaluated considering an equivalent circuit.

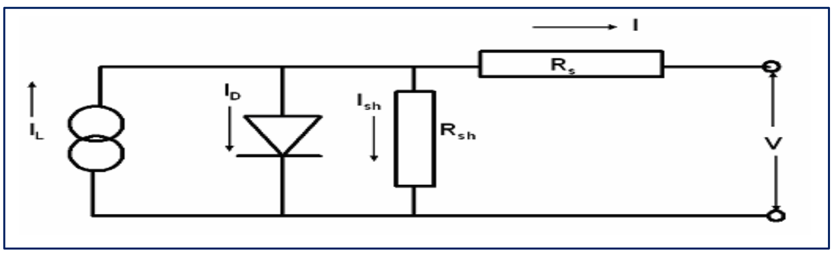


Figure 14: Equivalent circuit of a PV. I_L is the light current, I_D is the current in the diode, I_{sh} is the current in the shunt resistance, R_s is the series resistance, R_{sh} is the shunt resistance, I is the current and V is the voltage. Source: [35].

In this methodology the perfect maximum power point tracking (MPPT) controller is considered, which maximized the generated power. The final parameters of the model are the short circuit current, the open circuit voltage, the current at the maximum power point, the voltage at the maximum power point, the slope of the I-V curve at the short circuit point and the nominal operation cell temperature. The values of these parameters for more than 10,000 different commercial PVs are available in the SAM PV library [42]. The production of the whole array $E_{PV}(s,t)$ in the *i^th^* scenario and period *t,* is given by the following equation that takes into account the number of the PV installed (N_{PV}) and the efficiency of the inverter η_{inv}.

$$E_{PV}(i,t) = \eta_{inv} * E_{PV,m}(i,t) * N_{PV} \quad \forall i, \forall t \tag{17}$$

Battery Bank

The battery bank is modelled trough an energy balance on the State of Charge (SOC_{bat}) of the battery. The energy flow into and out of the battery are defined by $E_{bat,ch}$ and $E_{bat,dis}$ respectively. Finally, the charge and discharge efficiencies are given by as η_{ch} and η_{dis}.

$$SOC_{bat}(i,t) = SOC_{bat}(i,t-1) + E_{bat,ch}(i,t) * \eta_{ch} - E_{bat,dis}(i,t)/\eta_{dis} \quad \forall i, \forall t \tag{18}$$

To ensure the optimal operation and life time of the battery bank several constraint are considered as suggested by S. Balderrama et al in [35].

Diesel Generator

The diesel gen-set represent a backup system and it is activated when the energy provided by the PV array is not available and when the state of charge of the battery bank is lower than its minimum value or when it is convenient the use of the gen-set due to the lower price of the diesel. The behaviour of the diesel generator is modelled through the robust *Linear Programming* formulation that assume a constant efficiency with respect to the power output and reduce the computational time of the entire model. The slope of the cost curve for the generator system α_{LP} is calculated by the following equation, where LHV_{di} is the low heating value of the diesel, P_{di} is the cost of the diesel and η_{Gen} is the generator efficiency [35].

$$\alpha_{LP} = \frac{P_{di}}{(LHV_{di} * \eta_{Gen})} \tag{19}$$

The total operation cost C_{diesel} of the diesel generator system in each period and scenario is evaluated as the expression ():

$$C_{diesel}(i,t) = E_{Gen}(i,t) * \alpha_{LP} \tag{20}$$

Finally, the constraint on the energy outputs that has not to exceed the generator nominal capacity has to be added:

$$E_{Gen}(i,t) \leq C_{gen}\Delta t \tag{21}$$

Where the E_{Gen} is the energy coming from the diesel generator and the C_{gen} is the nominal capacity.

Electrical Load

The electrical demand is evaluated through the *Load Pro Gen* program [27]. To create the total electrical load, several class are considered in order to distinguish the appliances and the different manners to use them. The methodology to create the electrical load curve is better explained in the Chapter 2. It is importing to observe that the *LoadProGen* program returns an electrical load of the entire village, hence, the model designs the optimal configuration considering a *centralized* system for the electrical energy despatch.

3.1.2 Solar Water Heating System

The thermal energy access for domestic usage regards principally activities as cooking, space heating and water heating [28]. The scope of this work is to analyse exclusively the water heating system that represent a relevant percentage of the thermal energy usage in the study area as stated in Chapter 4.

A solar system represents one of the most popular application for the domestic water heating. The peculiarity of these systems is the fact that relatively simple systems are involved, and they are generally viable. The solar water heating system is a combination of a solar collector array, an energy transfer system and a storage tank. The solar collectors absorb the solar irradiation and converts it to heat. This heat is transferred to a fluid that passes through the collectors. Then, the hot fluid is stored in a storage tank [40].

The model proposes a direct and active system, in which the potable water is heated directly in the collector, stored in the tank and then sent to the domestic use (direct system). The water is moved through the system by a pump, hence, the system has a forced circulation (active system). The power absorbed by the pump can be assumed to be negligible. In the tank an electrical resistance is installed to ensure thermal energy when the energy coming from the sun is not enough. In addition, a natural gas boiler is used as a back-up system to satisfy the demand when it is necessary. Finally, the solar water heating system (Figure 15) is composed of:

- *Solar Collectors* connected directly to the water storage tank
- *Water Storage Tank* that receive the hot water from the collectors and send the flow the domestic use.
- *Electrical Resistance* that maintain the temperature of the hot water above a certain value.
- *Natural Gas Boiler* used as a back system.
- *Thermal Load* that correspond to the thermal energy demand.

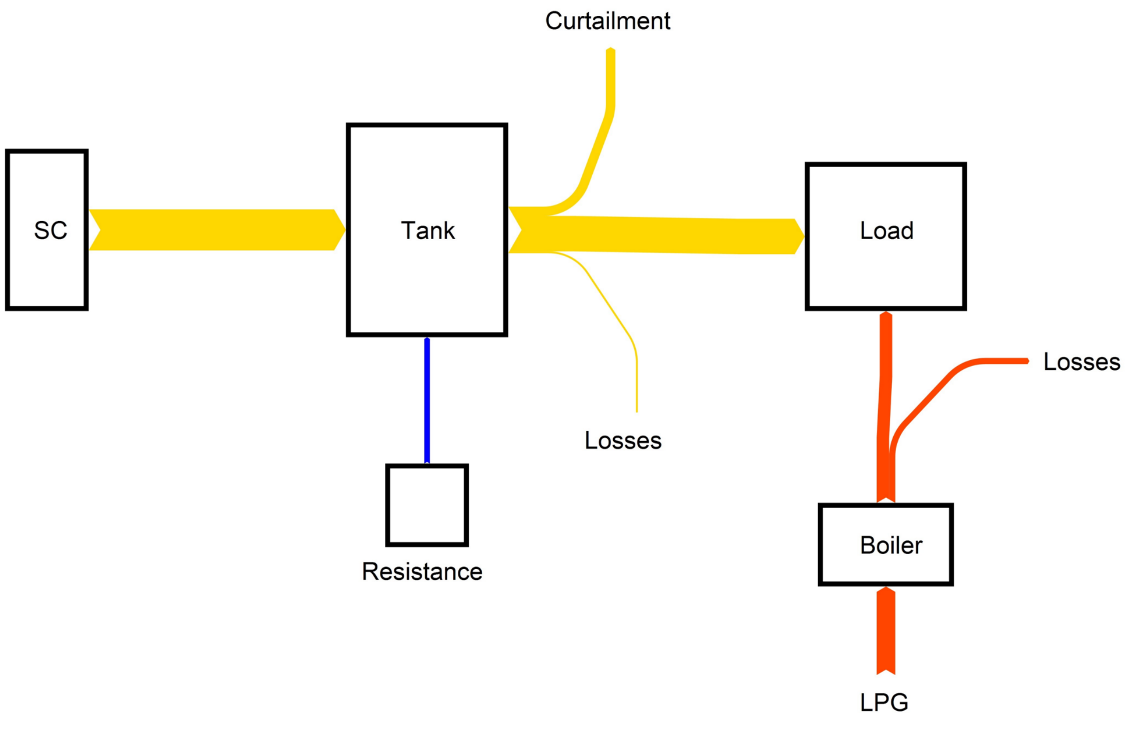


Figure 15: Considered thermal system typology. Source: Authors.

In the electrical part, the design of the system looks at the village as a whole with a global electric energy demand as inputs and a global power station as output. Otherwise, in the thermal part the issue of topographic constrains (i.e. the need to consider buildings separately) arises. As a matter of fact, a centralized system could be extremely expensive and not appropriately to satisfy the hot water demand of an entire village. For these reasons, the model considers the design of the solar water heating system separately for several classes in the same scenarios. Each class represents a typical usage of sanitary hot water such as the domestic use, the public use or the commercial ones. Therefore, the model designs a solar water heating system for each class and for several scenarios. In other words, each class is seen as a whole system with a solar collector array, a water storage tank with own electrical resistance and a natural gas boiler as backup system.

Solar Collectors

The thermal energy provided by the solar collectors is given by the solar irradiation that heats the potable water through the solar collector and ends in the storage tank. The solar collector energy output E_{SC} is computed as the product of the solar irradiation on the inclined surface evaluated through the isotropic model as explained in Chapter 2 and the nominal efficiency of the selected solar collector times the area. The solar collector selected for the study is the model that is already installed in the local area namely First Solares Co., Ltd. FP-GV2.15.00.

The total thermal energy provided by the solar collectors $E_{SC_{tot}}$ for each class *c* and for each scenario *i* has been evaluated as the solar collector energy E_{SC} multiplied by the number of solar collector in that class N_{SC}:

$$E_{SC_{tot}}(i,c,t) = E_{SC}(i,c,t) * N_{SC} \quad \forall i, \forall c, \forall t \tag{22}$$

In this way, the model returns the optimized number of solar collectors for each class in each scenario. The energy coming from a solar collector unit E_{SC} is given as an input data.

Electrical Resistance

To maintain the minimum level of thermal energy in the storage tank and to satisfy the thermal demand when it is required, an electrical resistance is considered to be installed in the storage water tank (as it is the case for the pilot tanks installed in the village). The use of the electrical resistance to heat the water in the tank and to satisfy the demand is a result of the objective function of the net present cost. The solver decides when it is convenient provide thermal energy by the electrical resistance or by the natural gas boiler taking into account the energy constraints and the cost of the electrical energy. The resistance is assumed to have a unitary efficiency and its thermal energy $E_{Resistance}$ has not to exceed it nominal capacity $C_{Resistance}$ as expressed in the Equation 23:

$$E_{Resistance}(i, c, t) \leq C_{Resistance}(c) * \Delta t \quad \forall i, \forall c, \forall t \tag{23}$$

The thermal energy coming from the electrical resistance is calculated for each period *t,* each class *c* and each scenario *i* as well as the nominal capacity is designed for each class due to the different thermal demand that they have. Once the design is optimized, the energy required by the electrical resistances of each class has to be summed and included in the electrical energy balance. In fact, the energy required by the resistances has seen by the electrical part as an additional load. Therefore, the total energy resistance is evaluated for each period and each scenario as in the following expression:

$$E_{TOT_{Resistance}}(i, t) = \sum_{c=1}^{n} E_{Resistance}(i, c, t) \quad \forall i, \forall c, \forall t \tag{24}$$

Where *n* is the number of classes in each scenario.

Water Storage Tank

The energy balance on the water tank represent the energy balance of the thermal storage system. In fact, for each time-step *t*, for each class *c* and in each scenario *i,* the thermal energy stored in the water tank $E_{SOC_{Tank}}(i, c, t)$ is evaluated as a balance on the tank as the energy stored in the period before $E_{SOC_{Tank}}(i, c, t-1)$, the incoming energy flow from the solar collectors $E_{SC_{tot}}$ and the electrical resistance $E_{Resistance}$ assuming its efficiency $\eta_{Resistance}$ equal to one, and the outcoming energy flow $E_{Tank_{out}}$ sent to the thermal load. The losses are considered through the efficiency of the tank η_{tank} through the definition given by [40]. Hence, the thermal energy balance is defined by the equation () and it is expressed in Wh.

$$E_{SOC_{Tank}}(i,c,t) = \\ = E_{SOC_{Tank}}(i,c,t-1) * \eta_{tank} + E_{SC_{tot}}(i,c,t) \\ + E_{Resistance}(i,c,t) * \eta_{Resistance} - E_{Tank_{out}}(i,c,t) \;\; \forall i, \forall c, \forall t \tag{25}$$

Finally, several constraints have to be defined to complete the storage water tank model:

- The energy stored in the tank has not to exceed the maximum capacity $C_{soc_{tank}}$ of the water tank for each class *c:*

$$E_{SOC_{Tank}}(i,c,t) \leq C_{soc_{tank}}(c) \quad \forall i, \forall c, \forall t \tag{26}$$

- The energy stored in the tank has to be maintained above a minimum value defined, hence, deep of discharge D_{soc} corresponding to a percentage of the nominal tank capacity:

$$E_{SOC_{tank}}(i,c,t) \geq C_{soc_{tank}}(c) * D_{soc} \;\; \forall i, \forall c, \forall t \tag{27}$$

- The energy tank flow out coming from the water tank $E_{out}(i,c,t)$ must be lower than the tank maximum power discharge $P_{out_{Max}}$ multiplied by the delta time Δt :

$$E_{Tank_{out}}(i,c,t) \leq P_{out_{Max}} * \Delta t \;\; \forall i, \forall c, \forall t \tag{28}$$

Natural Gas Boiler

The natural gas boiler is a back-up system connected directly to the load. The thermal energy coming from the boiler is provided when results convenient compared to the electrical resistance. The boiler thermal energy E_{Boiler} has to be remain under its nominal value C_{Boiler}. For this reason, a nominal boiler capacity is defined as $C_{Boiler}(c)$ and the following constraint have to be respected:

$$E_{Boiler}(i,c,t) \leq C_{Boiler}(c) * \Delta t \quad \forall i, \forall c, \forall t \tag{29}$$

As for the other equipment, the thermal energy provided by the natural gas boiler is defined for each periods, classes and scenarios, while the size that correspond to the nominal capacity is designed for each class. Additionally, the Natural Gas consume $NG_{consume}$ is given by the boiler energy E_{boiler} divided the efficiency η_{boiler} and the Low Heating Value LHV:

$$NG_{consume} = \frac{E_{boiler}}{\eta_{boiler} * LHV} \tag{30}$$

Thermal Load

The thermal demand regards exclusively the sanitary hot water consumption of different classes of users. Differently from the electrical load, the hot water demand has to be considered for each class separately; in this way the model designs an optimal thermal configuration for each class, while all the electrical requirement will be summed and integrated in the electrical energy balance. Therefore, for the thermal part a *decentralized* logic is adopted. As deeply explained in the Chapter 2, for the thermal load the same tool of the electrical part, *Load Pro Gen,* has been used to characterize the demand of each class separately.

3.2 Connection of the two systems

The layout of the entire system configuration is presented in Figure 16, where it is possible to observe that the electrical resistance is connected to the electrical part. In fact, the electrical energy required by the resistance to satisfy the thermal demand is provided by the electric energy part.

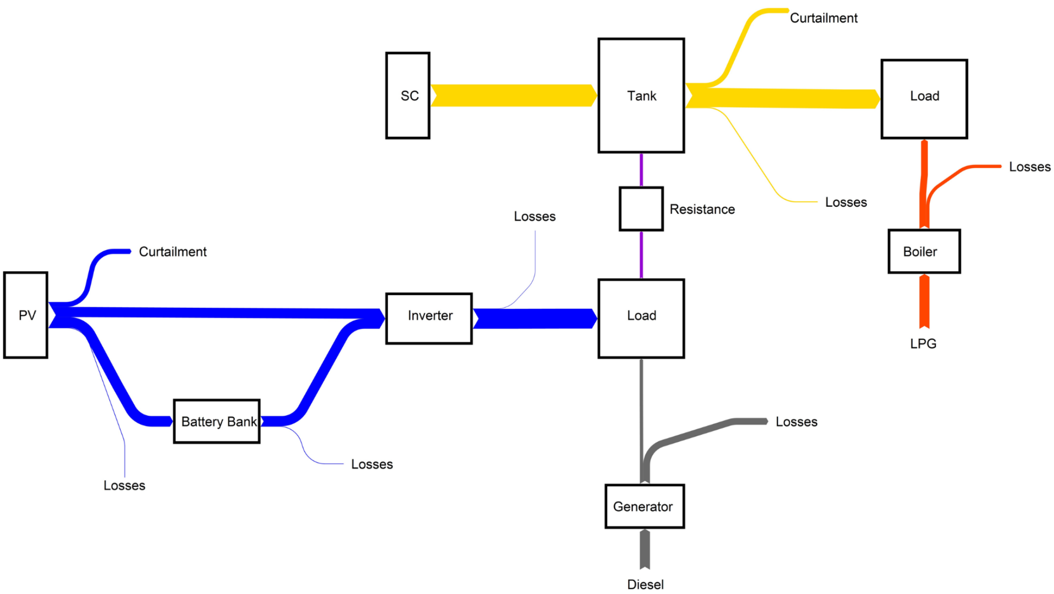


Figure 16: Considered energy system configuration. Source: Authors.

3.2.1 Energy Balances

Thermal Balance

The thermal energy balance aims to satisfy the hot water consumption of each class independently. In fact, the optimization is performed for a single class *c,* in each scenario *i,* and for each period. As explained in the section 2.2.2, the profile of thermal demand is evaluated on a user's sample, for this reason the thermal demand of each class has to be multiplied by the number of users in that class as in the Expression 31:

$$E_{TOT_{Thermal_{Demand}}}(i,c,t) = E_{Thermal_{Demand}}(i,c,t) * N_{Users}(c) \quad \forall i, \forall c, \forall t \tag{31}$$

Once the total thermal demand is defined, the thermal balance can be expressed as in the Equation 32, where on one side there is the total thermal load that has to be satisfied for each class, and on the other side there is the summation of the boiler energy E_{boiler}, the energy tank flow out and the curtailment energy.

$$E_{TOT_{Thermal_{Demand}}}(i,c,t) = E_{boiler}(i,c,t) + E_{Tank_{out}}(i,c,t) - E_{Curt}(i,c,t) \quad \forall i, \forall c, \forall t \tag{32}$$

The energy tank flow out $E_{Tank_{out}}$ represents the thermal energy that comes from the water storage tank, where the energy is accumulated thanks to the solar collector energy and the resistance energy and flows directly to the load. The energy curtailment E_{Curt} is the energy coming from the solar collectors that cannot be used to satisfy the thermal demand. Therefore, the model returns as output the design of thermal configuration for each class including the number solar collectors installed, the size of the water storage tank and the use of electrical resistance.

Electrical Balances

The electrical energy balance regards the energy dispatch to satisfy the electrical load considering the energy required by the thermal part. The balance sees on the left side the electrical load $E_{El_{Demand}}$ and on the right side the energy flows that satisfy as the total PV energy E_{PV}, the energy coming from the diesel generator E_{Gen} and the energy flow out of the battery $E_{bat,dis}$. In addition, the energy curtailment E_{Curt}, the energy that will be accumulated in the storage battery bank $E_{bat,ch}$ and the total resistance energy $E_{Tot_{Res}}$ required provide thermal energy, are considered as negative terms. Hence, the balance is expressed in Equation 33:

$$E_{El_{Demand}}(i,t) = E_{PV}(i,t) + E_{Gen}(i,t) - E_{bat,ch}(i,t) + E_{bat,dis}(i,t) - E_{Curt}(i,t) - E_{Tot_{Res}}(i,t) \quad \forall i, \forall t \tag{33}$$

The electrical energy dispatch will be a result of the net present cost optimization for the entire village. In fact, as mentioned above, the load is related to the entire village while the thermal demand is divided in different class.

3.2.2 Economical Analysis

Objective Function

The economic analysis is performed starting from the *MicroGridPy* model and considering the investment and operation costs of each new technologies to satisfy the thermal demand. The technologies that compose the water heating system are: solar collectors, water storage tank, the electric resistance and the natural gas boiler.

The scope of the model is minimizing the weighted sum of the net present cost (NPC) relative to each scenario and for each class of the thermal part through the objective function. The weighting factors are the probabilities of occurrence (Po) and each scenario is given an equal weight, where *S* is the number of scenario.

$$ObjectiveFuntion = \sum_{i=1}^{S} Po(i) * NPC(i) \tag{34}$$

$$\sum_{s=1}^{S} Po(i) = 1 \tag{35}$$

The NPC of each scenario is given by the following expression, where, YCC is the yearly constant cost of the project, n is the year of the project, Inv is the total investment cost, e is the discount rate factor and $Cost_{rep}$ is the cost of replacing the batteries.

$$NPC(i) = Inv + \sum_{n=1}^{N} \frac{YCC(i)}{(1+e)^n} + Cost_{rep} \quad \forall i \tag{36}$$

$Cost_{rep}$ is the reposition cost of the battery and it is calculated using following equation, where, y is the year when the battery bank is replaced and Uni_{bat} is the unitary cost of the battery.

$$Cost_{rep} = \frac{Cap_{bat} * Uni_{bat}}{(1+e)^{y}} \quad (37)$$

To create the financial cost and the investment cost functions for the thermal technologies, it is necessary to take into account the design of each class defined that are considered in the optimization. For this reason, the cost of function of the water heating solar system components will be evaluated as:

- *Solar Collector Financial Cost* $C_{SC_{finan}}$ is the sum of the solar collector investment cost U_{SC} multiplied by the nominal capacity C_{SC}, that correspond to the maximum value that could be out from a solar collector, and number for units $N_{SC}(c)$ of each class *c*:

$$C_{SC_{finan}} = \sum_{c=1}^{n} N_{SC}(c) * U_{SC} * C_{SC} \quad (38)$$

- *Tank Financial Cost* $C_{Tank_{finan}}$ that define the summation of the tank investment cost multiplied U_{Tank} by the tank nominal capacity $C_{soc_{tank}}(c)$ referred to the maximum storable thermal energy in the water tank for each class *c* :

$$C_{Tank_{finan}} = \sum_{c=1}^{n} U_{Tank} * C_{soc_{tank}}(c) \quad (39)$$

- *Boiler Financial Cost* $C_{Boiler_{finan}}$ is the sum of the boiler investment cost multiplied by the nominal capacity of the boiler $C_{Boiler}(c)$ for each class *c:*

$$C_{Boiler_{finan}} = \sum_{c=1}^{n} U_{Boiler} * C_{Boiler}(c) \quad (40)$$

- *Electrical Resistance Financial Cost* $C_{Res_{finan}}$ is the sum of the electrical resistance investment cost U_{Res} multiplied by the nominal capacity $C_{Resistance}$ of the resistance for each class *c:*

$$C_{Res_{finan}} = \sum_{c=1}^{n} U_{Res} * C_{Resistance}(c) \tag{41}$$

Therefore, Inv is evaluated considering all costs of the different technologies where, the unitary cost of the PV, genset and the battery bank are given by U_{PV}, U_{gen} and Uni_{bat} the respectively. The thermal technologies are defined through their financial costs. The percentage of Inv that is financed by a bank (or any another entity), is given by fun and C_{PV} is the nominal capacity of one PV module. During the LP optimization N_{Gen} is set equal to 1.

$$Inv = \Big(N_{PV} * U_{PV} * C_{PV} + Cap_{bat} * Uni_{bat} + C_{gen} * N_{gen} * U_{gen} + C_{SC_{finan}} + C_{Tank_{finan}} + C_{Boiler_{finan}} + C_{Res_{finan}}\Big) * (1 - fun) \tag{42}$$

YCC is calculated in the Expression 43, where, $Cost_{om}$ is the cost of operation and maintenance of the system, $Cost_{finan}$ (USD) is the constant payment for the loan to pay for the Inv.

$$YCC(i) = Cost_{om} + Cost_{finan} + \sum_{t=1}^{T} Cost_{Gen\,Set}(i,t) + \sum_{t=1}^{T} Cost_{\mathrm{gas}}(i,t) \quad \forall s \tag{43}$$

The $Cost_{om}$ is given, where OyM (%) is a percentage of Inv.

$$Cost_{om} = \Big(N_{PV} * U_{PV} * C_{PV} + Cap_{bat} * Uni_{bat} + C_{gen} * N_{gen} * U_{gen} + C_{SC_{finan}} + C_{Tank_{finan}} + C_{Boiler_{finan}} + C_{Res_{finan}}\Big) * OyM \tag{44}$$

The equation below is used to calculate $Cost_{finan}$, where *i* is the number of years in which the loan has to be paid back and the interest rate is r.

$$Cost_{finan} = \frac{Inv \times fun \times r}{1 - (1 + r)^{-i}} \tag{45}$$

The levelized cost of energy (LCOE) of the project is evaluated with the help of with D_a as the annual demand of energy [43].

$$LCOE = \sum_{i=1}^{S} \frac{NPC(i) * Po(i)}{\sum_{n=1}^{N} \frac{D_a(i)}{(1 + e)^n}} \tag{46}$$

Finally, this equation is used to calculate D_a, where the demand of electrical energy in each period t of the system is represented by D_p, while the thermal demand is represented by $D_{thermal}$ for each periods, class and scenario.

$$D_a(i) = \sum_{t=1}^{T} D_p(i,t) + \sum_{t=1}^{T} D_{thermal}(i,c,t)\ \forall i\ \ \forall c \tag{47}$$

$$D_{thermal}(i) = \sum_{t=1}^{T} D_{thermal}(i,c,t)\ \forall i\ \ \forall c \tag{48}$$

4. Assessment and Loads Results

In this chapter the results of the energy balance, load curves and local resource assessment are presented. Firstly, the analysis is focused on aspects of current electricity and fuel consumption in domestic, commercial and public drivers, to achieve the first specific objective of this work. The results are summarized in an energy flow diagram including all energy drivers, energy sources and final uses. Secondly, the computed Load Curves for every energy driver are presented in a graphical form. Lastly, results of the main characteristics of RES potential are reported to evaluate the sources available in the study area.

4.1 Current energy situation

4.1.1 Energy Drivers

The study area is represented by the entire village of Toconao, where domestic, commercial and public energy drivers are identified through the analysis of the village's electric bills.
The domestic driver is composed of 332 households, each one with its own electric meter.
The commercial driver is composed by the activities that produced an income in the village, basically restaurants, artisan laboratories and guesthouses. In the commercial driver are considered two telephone company antennas as well, that consume energy and have an electric meter regularly registered at the local electrical committee. In total 32 structures are considered.
The public driver is composed by the public school, the police station, the medical office, the community reunion office and some other public services like two football fields with night lights.
In total 13 elements are considered, including street lights as one user.
The reference energy system investigated in the study area is presented in Figure 17., in which are reported energy sources, energy drivers and energy services demanded corresponding to the community energy needs: lighting, power of appliances, cooking, space and water heating.

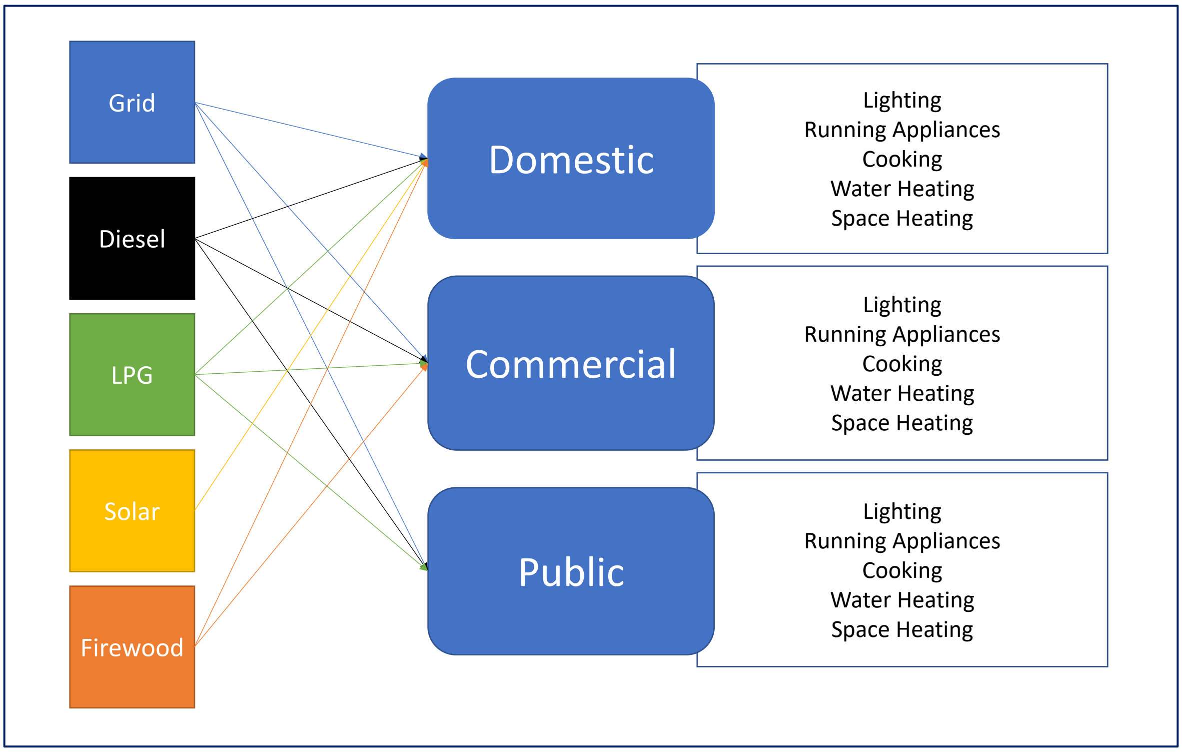


Figure 17: Reference energy system of the study area. Source: Authors.

4.1.2 Current Energy Balance

The energy sources identified in the study area are:

- Electricity from the grid, produced by the private contractor CESPA, external the study area
- Diesel, fuel used to power the backup generator inside the village
- LPG, fuel used to power the boilers and fire gas cookers
- Firewood, used to cook in some households and restaurants
- Solar, in form of 150 solar collectors installed on selected households

All the sources are treated as "Primary Energy Sources".

Energy supply from the Grid amounts to 49.68 toe/year, from Diesel amounts to 12.96 toe/year, form LPG amounts to 87.35 toe/year, form Firewood amounts to 9.78 toe/year and from Solar to 7.00 toe/year.

The total primary energy supply (TPES) amounts to 166.78 toe/year, 65.74% in the domestic driver, 26.56 % in the commercial driver and 7.70 % in the public driver. The total final energy consumption (TFC) amounts to 118.40 toe/year to satisfy the energy need within the study area namely lighting, running of appliances, cooking, water and space heating. The difference between TPES and TFC express the electrical and thermal energy losses, 48.37 toe/year in total, corresponding to about 30%. Results from the energy consumption assessment of each energy driver are presented in the following paragraphs.

Domestic

The 332 households make up the domestic energy driver.

Diesel is used to run the backup generator that substitutes the electricity from the grid, to which every house is connected, and the consume measured by an electric meter.

LPG, bought in bottles of 5 or 15 kg, is used to cook and fire boilers to heat sanitary water.

Firewood is still used in some households to cook or bake bread in the traditional way, and 150 households are equipped with solar collectors to heat water, that reduces significantly the consume of gas in the house.

In Chart 3 are presented the shares in energy consumption by source.

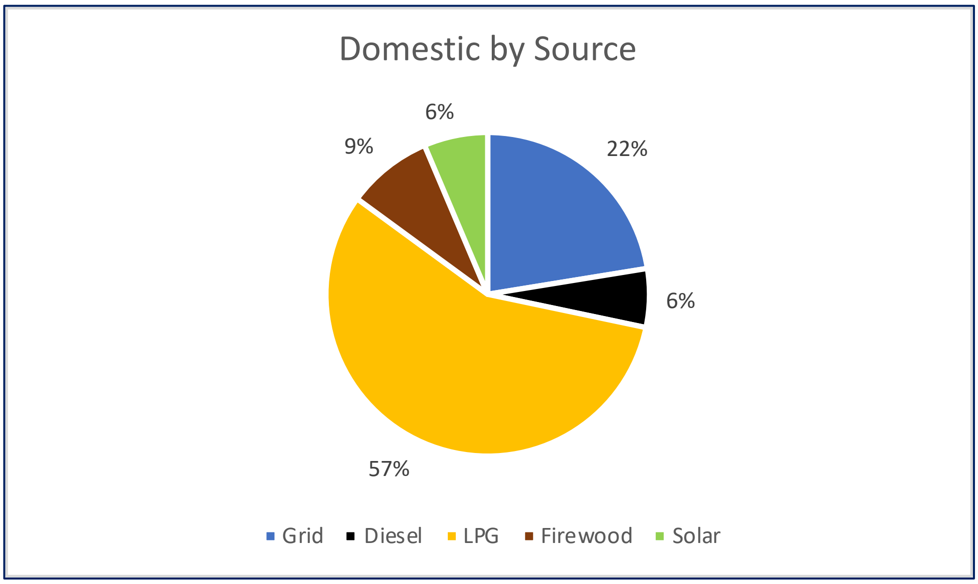


Chart 3: Energy mix present in the domestic driver.

More than the half of energy supply is from LPG with 62.23 toe/year, followed by the electric energy from the grid with an amount of 24.61 toe/year, firewood accounts for 9 % of the share with 9.38 toe/year and finally solar energy with 7.00 toe/year and diesel that amounts to 6.42 toe/year.

The energy services identified in the domestic energy driver and their relative share of final consumption are presented in Chart 4.

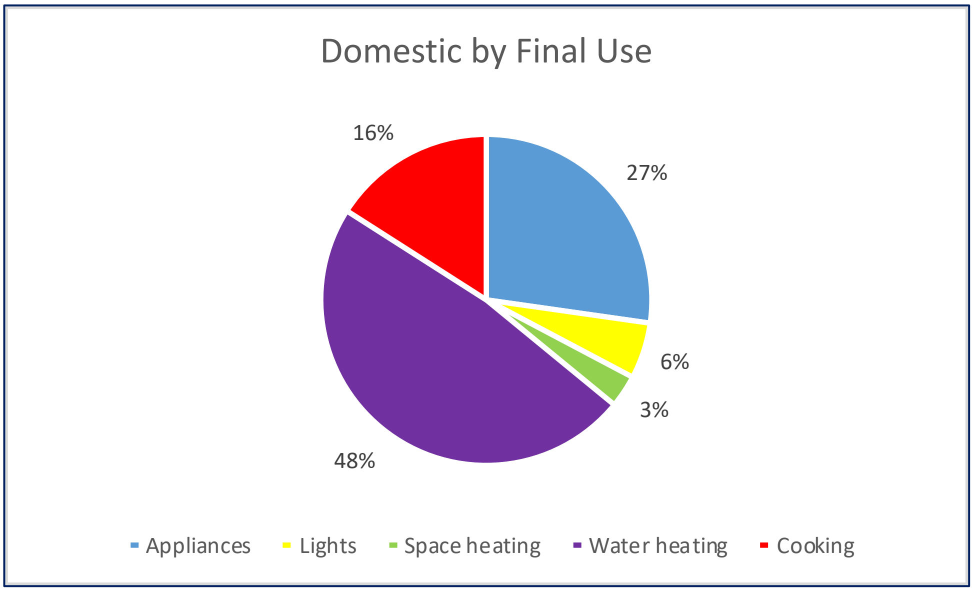


Chart 4: Share of final energy consumption in the domestic driver

The major share of final energy consumption goes for water heating, equal to 48% and corresponding to 36.50 toe/year. For running appliances goes 27% of the final energy supplied, corresponding to 20.67 toe/year, 16% goes to cooking, with 12.10 toe/year, 4.17 toe/year are spent for lighting and 2.42 toe/year for space heating.
Demand for water heating is satisfied with LPG and solar collectors, cooking with LPG and firewood, while the electricity needed for lights and running the appliances is satisfied from the grid and with diesel to run the backup generator.
Is possible to see how space heating represents such a reduced share of energy use, because despite the low temperatures that are reached in the desert at night, is still a technology considered only for few, the majority of the population do not possess any kind of space heating device.

Commercial

The commercial energy driver uses the same energy sources as the domestic one, with the exception for solar energy since solar collectors are installed only on households.
The contribution of each category is shown in Chart 5.

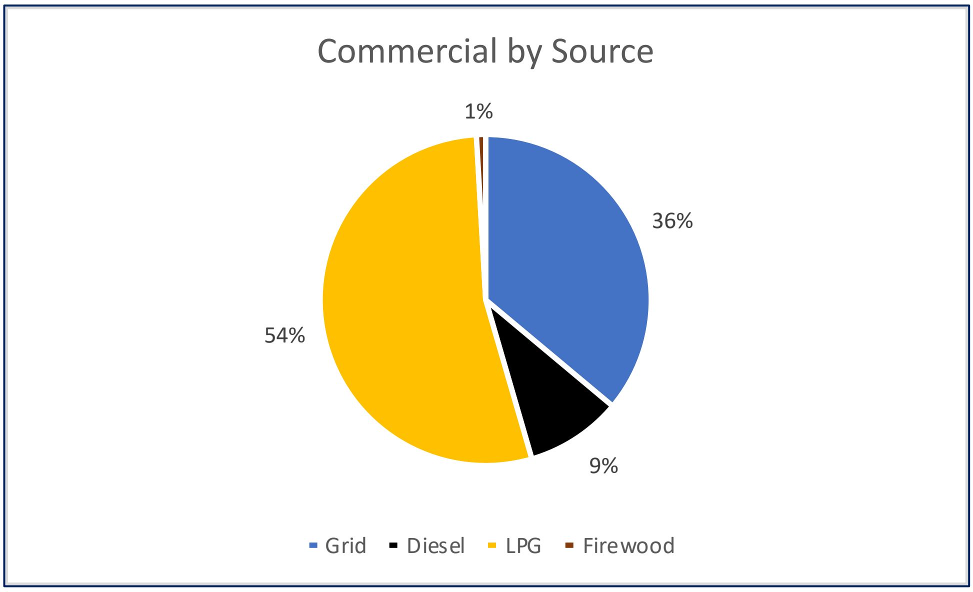


Chart 5: Energy mix present in the commercial driver.

The 54% of primary energy consumption in the commercial driver is attributed to LPG, corresponding to 23.74 toe/year. Primary energy from the grid accounts for 36% of the share, for an amount of 15.98 toe/year. Finally, 4.17 toe of diesel and 0.39 toe of firewood make up the rest of the share.

Energy services demanded in the commercial driver have no difference from the services of the domestic driver, there is however a difference in the share of their use, cooking and water heating are significantly lower, and electricity for using appliances represents almost half of the usage of energy. This is due to the fact that only the restaurants make large use of sanitary water and cook, and they represent only a part of the commercial facilities.

The shops and artisan workshops make use of almost only electricity.

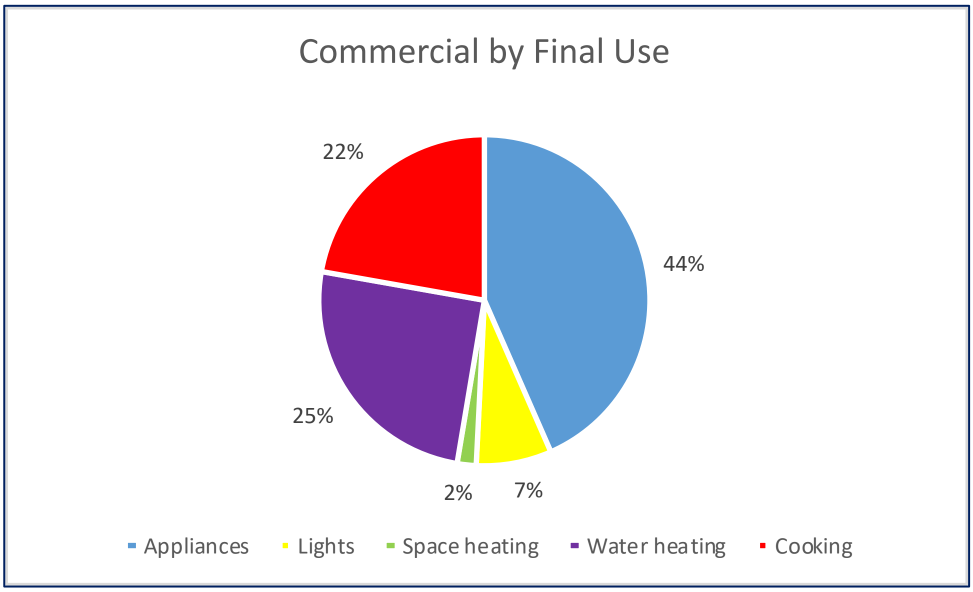


Chart 6: Share of final energy consumption in the commercial driver

The energy required for running appliances represent the 44% of the total final energy, with an amount of 13.94 toe/year. The energy for water heating represents 25% of total share (8.07 toe/year), energy for cooking is 22% (7.13 toe/year) and for lighting 7% (2.36 toe/year). Only 2% is spent for space heating (0.59 toe/year).

Public

In the public energy driver, the primary energy sources reduce to three since no firewood is used neither. The contribution of each source is presented in Chart 7.

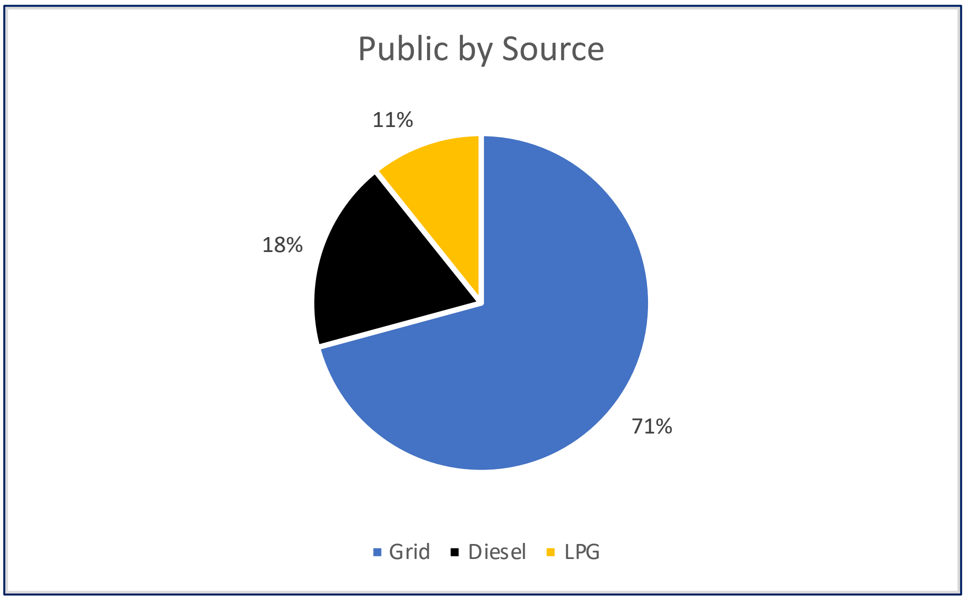


Chart 7: Energy mix present in the public driver.

The great majority of the energy sources is represented by the electric energy from the grid, 71% and 9.09 toe/year. Diesel represents 18% of the share with 2.37 toe and the remaining 11% is taken by the 1.38 toe of LPG.

As its possible to see in Chart 8, thermal uses are almost negligible in this driver, since only the school make use of cooking services, and only the police station has a space heating system, the rest of the energy is used to run appliances in offices and for public lights, that justifies the great share of lighting final use.

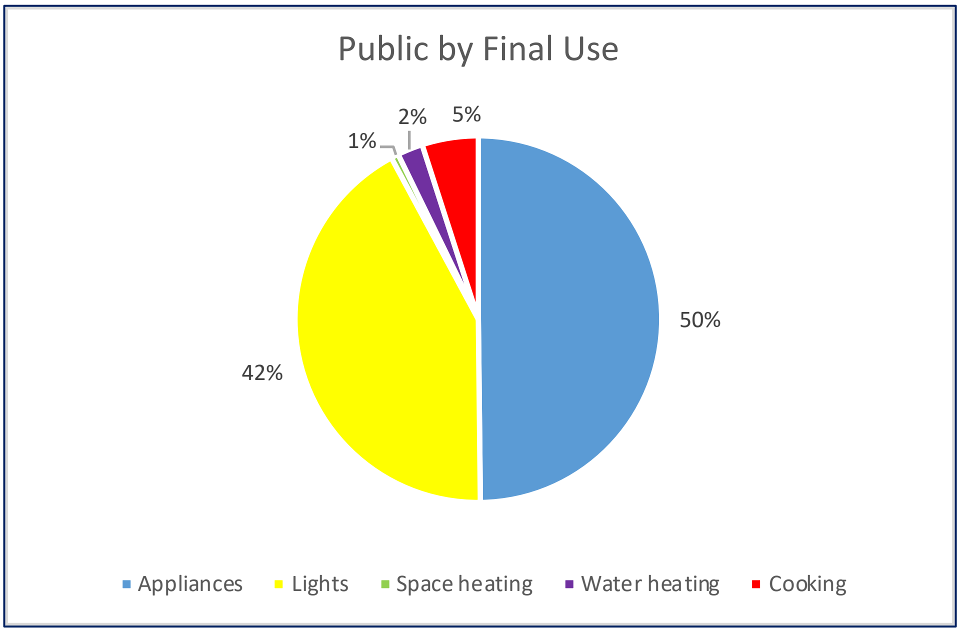


Chart 8: Share of final energy consumption in the public driver

The half of the energy is used for running appliances, with an amount of 5.20 toe/year, the energy for lighting services is 42% (4.41 toe/year). Cooking 5% (0.52 toe/year), water heating 2% (0.23 toe/year) and space heating 1% (0.07 toe/year).

Energy Flow diagram of the study area

In the reference energy system five energy sources, three main energy drivers and five energy services demanded are identified. Results regarding the current energy consumption are aggregated in the overall energy balance of the study area for a sample year and reported in the Sankey diagram present in figure 18 in accordance with IEA criteria for energy balance representation [44], the Sankey diagram, created using the software e!Sankey®, includes the energy flows of the study area represented in the figure with arrows and expressed in toe.

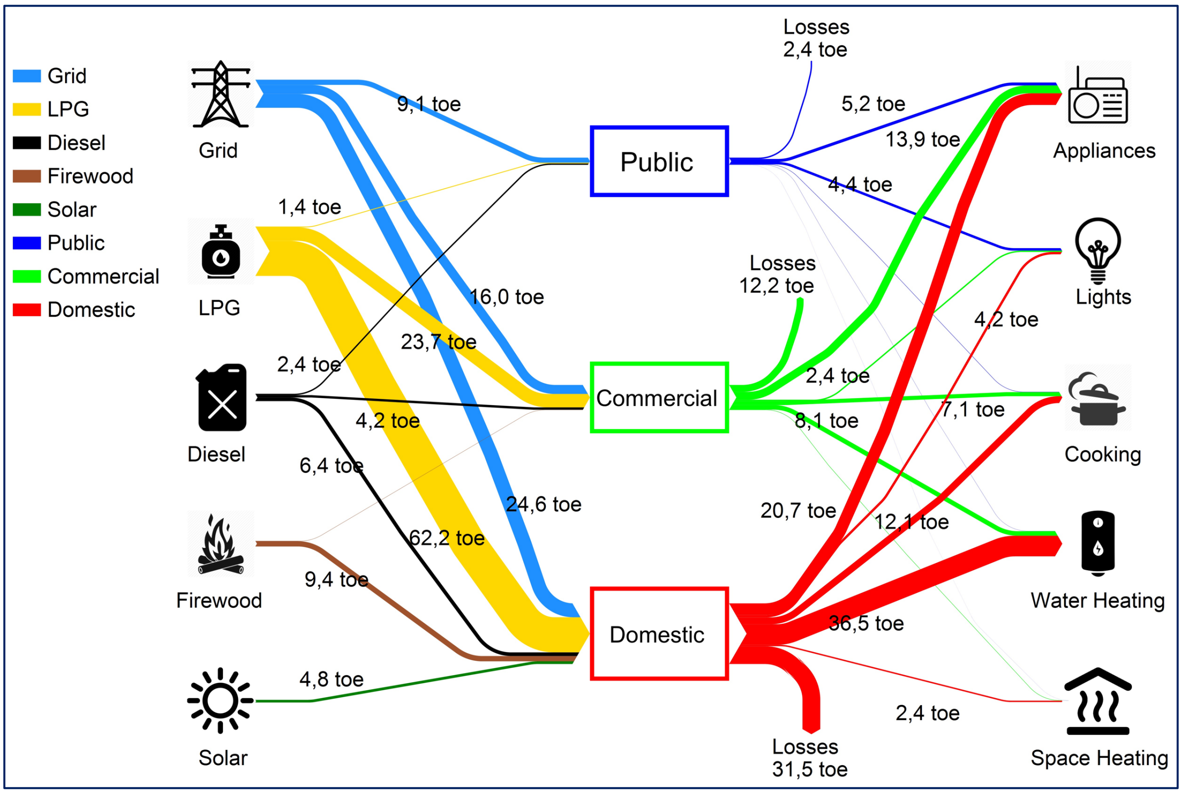


Figure 18: Sankey Diagram of the actual situation in the study area.

As is possible to observe the thermal demand of the village represents more than the half of the secondary energy use, with a share of 57%. Inside this thermal demand 66% of the energy is used for water heating purposes. This situation justifies the focus of this work on thermal solar thermal collector technologies.

Is also possible to observe how the study area is strongly dependent of external sources of energy, since electricity form the grid, LPG and diesel are energy that have to be bought from outside the limits of the village, and strongly condition the usage of energy. The percentage of TPES deriving from sources outside the study are is 91% and increases to 95% when talking about secondary energy.

4.1.3 Shortages and Diesel Consumption

Being the power supply rather unreliable in developing area, the rural villages of Atacama Desert are included this context. The quality of the power supply is assessed through specific questions in the questionnaires and direct observations on the power line.

In the questionnaires the number and duration of power shortages per month is assessed, and the voltage fluctuations investigating the number of damaged appliances due to electricity supply problems.

The number of shortages in the winter season is around two per month, and the duration could vary from few hours to an entire day depending on the cause of the shortage. Usually the cause is a voluntary interruption of the energy supply from the distributor due to an extreme peak load in the village of San Pedro de Atacama, main customer of the CESPA cooperative, that decides to cut off the power line to Toconao in order to fulfil the demand of the main village. These shortages are communicated in advance to the community's responsible for electricity in the study area and the diesel generator is powered right after the interruption of the line in order to avoid discomfort to the population.

If the shortage is due to a failure in the line, such as the fall of an electric trellis, situation that occurs more frequently in the summer season, during the storms typical of the climatic region, the shortages are of longer period, and can last up to a week depending on the intervention time.

This changes in power source from grid to generator cause voltage fluctuations that lead to frequent damage of electrical appliances. From the questionnaires resulted that almost every user experienced damage of two or more domestic or office appliances since the electrification of the village.

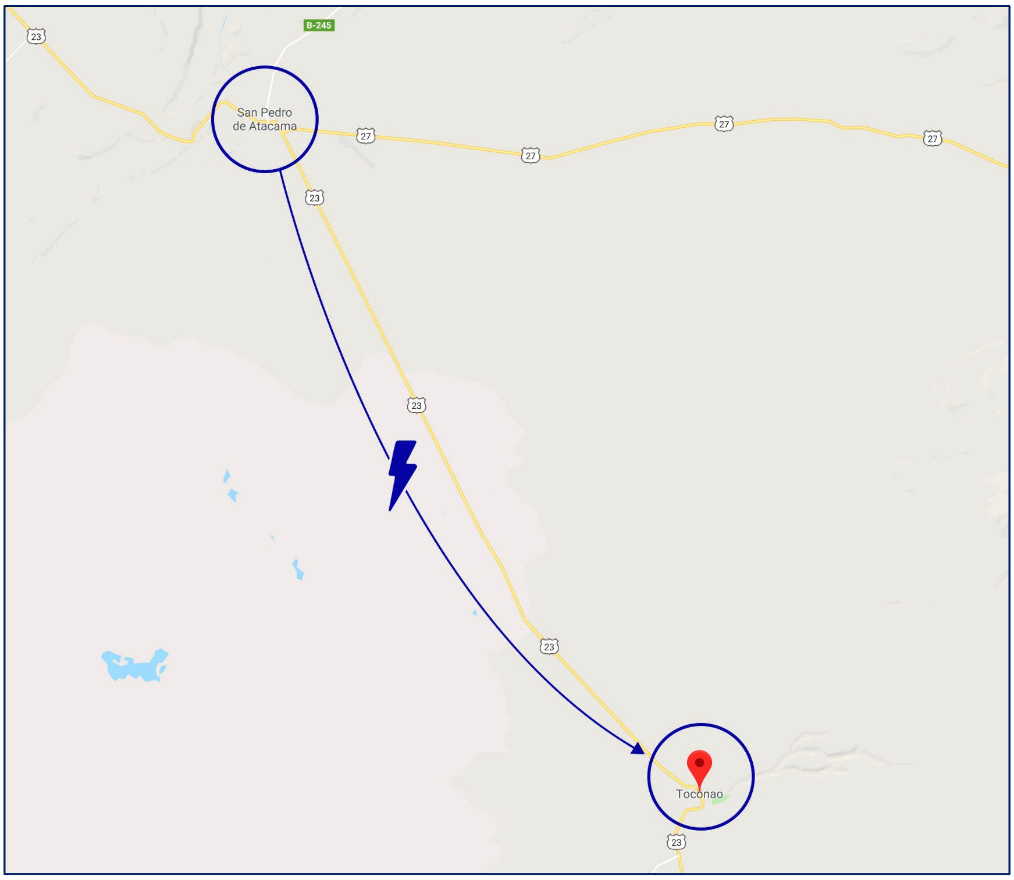


Figure 19: Geographical relatve positions of San Pedro the Atacama and Toconao. Source: Authors' adaptation from Google Maps

In order to assess the working parameters of the diesel generator, a Westac model KPP400, direct observations on the monitoring display of the generator were performed and measurements were carried out during a monitored working period of three hours.

From the monitoring display the total functioning hours and total energy produced since the day of start-up were obtained. The generator was installed in 2010 and at the investigation moment 7 years of activity were supposed. The parameters observed are:

- 3501 hours,
- 955 starts,
- 232203.5 kWh produced.

Supposing a similar behaviour for each year, the following parameters can be estimated:

- Hours of activity per year: 500 h,
- Start-ups per year: 136,
- Energy produced per year: 33172 kWh.

To calculate the efficiency of the generator with the methodology illustrated in Chapter 2, a trial and monitored working period of three hours was performed and the efficiency estimated to be 22%.

In order to put into operation the diesel generator, the supply from the main grid was interrupted, and a manual switch had to be activated in order to change the source of energy to the village.

During this test an unexpected problem emerged, when the energy was supplied from the grid the entire village was served by electricity, but when the generator was in action a part of the study area, highlighted in red in Image 20, was left without electricity without anybody being aware of the situation before that moment.

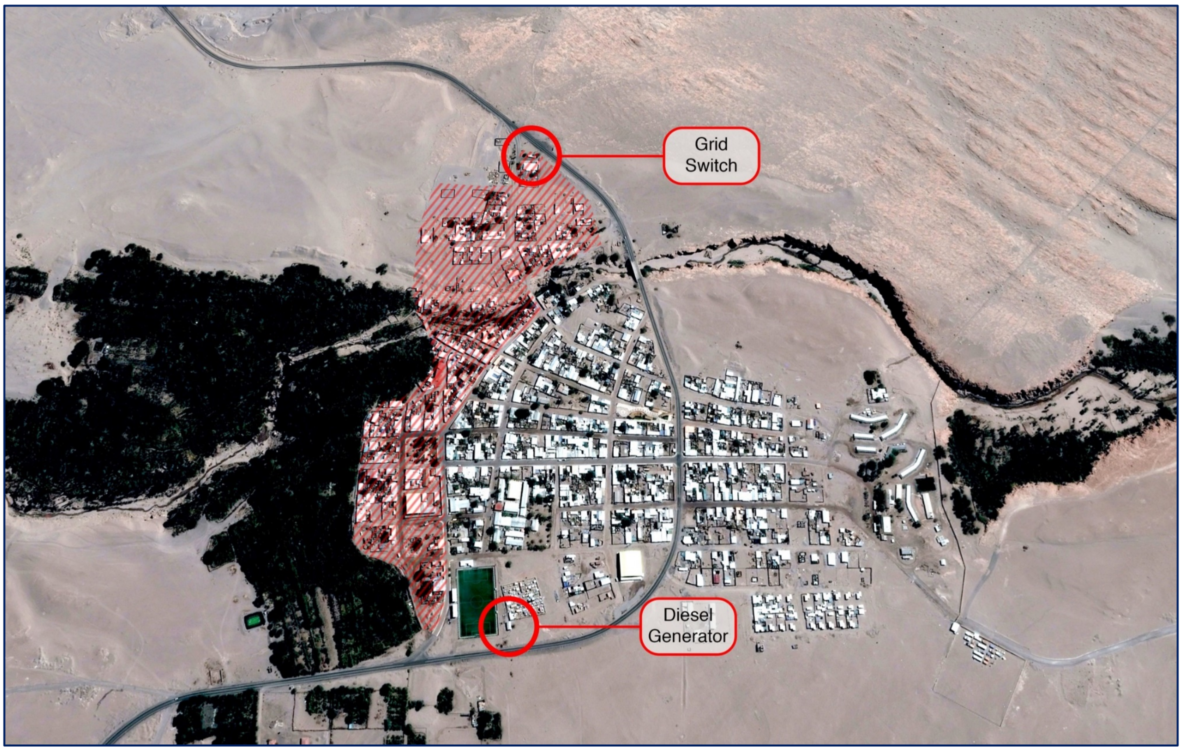


Figure 20: Area of the village excluded form generator's energy supply. Source: Authors' adaptation from Google Earth.

In order to understand the possible cause of the problem various hypothesis were taken in consideration, and after an investigation was found out that two weeks before the arrival in the study area a renovation work of the power line had been implemented, and the switch to change from grid to generator was moved to the wrong position, and a part of the village was not included inside the area under the control of the switch. No shortages had occurred before that moment and for that reason the problem had not been found out until that moment. A redesign of the line is necessary in order to re-include the excluded area.

4.2 Local Energy Sources Assessment Results

In this section, the potential of the studied renewable energy sources is quantified through the application of the different methods and procedures presented in chapter 2.

4.2.1 Solar

The average insolation measured in the study area for the data collection period is presented in chart 9.

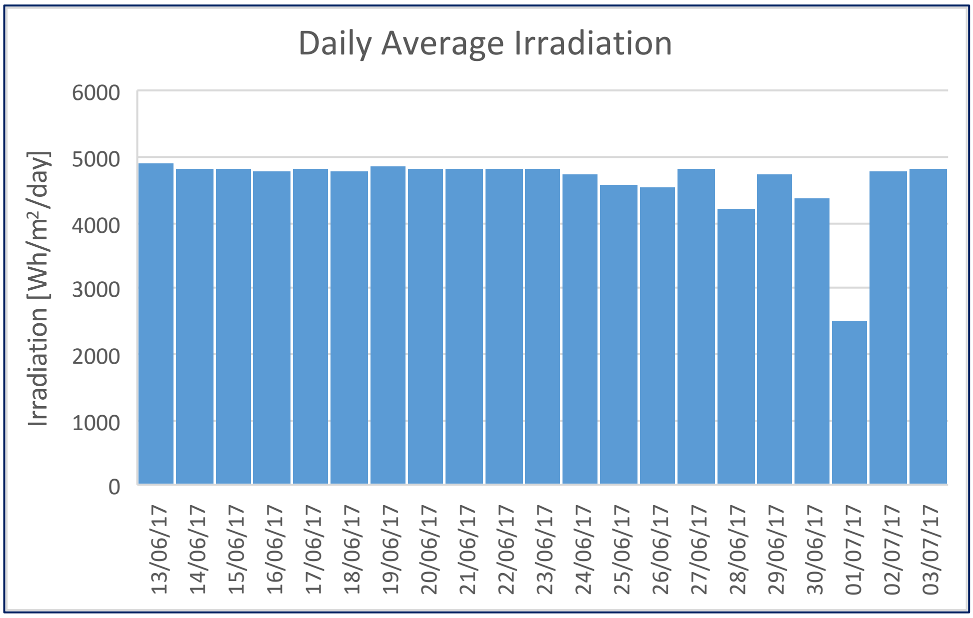


Chart 9: Daily measured average irradiation in the study area.

The monthly average solar irradiation obtained from the data of the three years from the weather station in San Pedro de Atacama [30] is presented in chart 10.

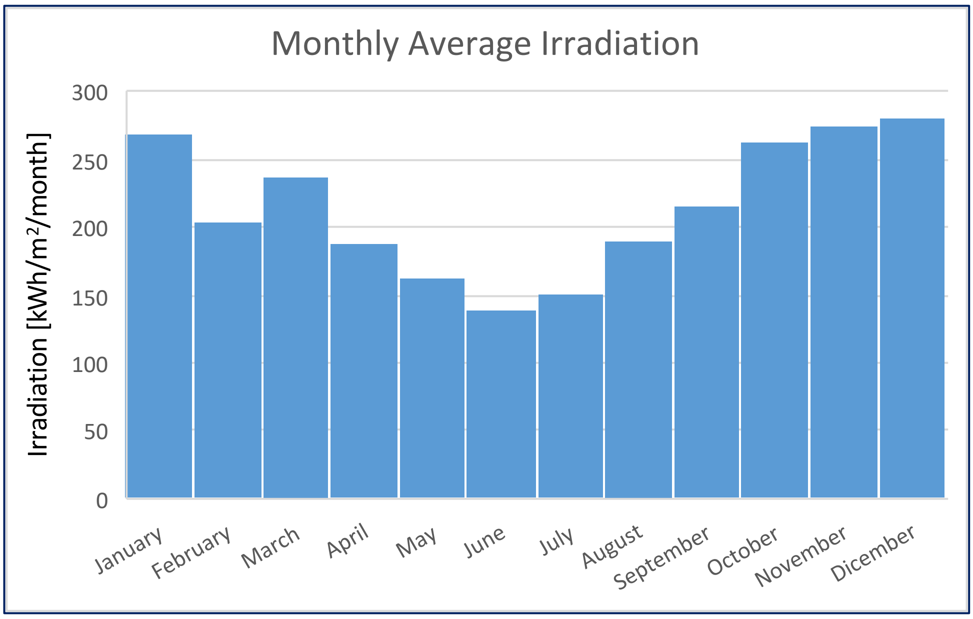


Chart 10: Monthly average irradiation in the study area.

The peak value of GHI registered is 1439 W/m^2, and the total annual Irradiation in the study area is 9280 MJ/m^2.

After the solar irradiation, photovoltaic power output from a commercial panel available in the local area is performed. The photovoltaic panel selected is the model Yingli Energy YL300P-35b Polycrystalline module. The data of the solar irradiation are elaborated through the *Modelica* language [41]. In chart 11, the PV power output of the day 19th of April is represented.

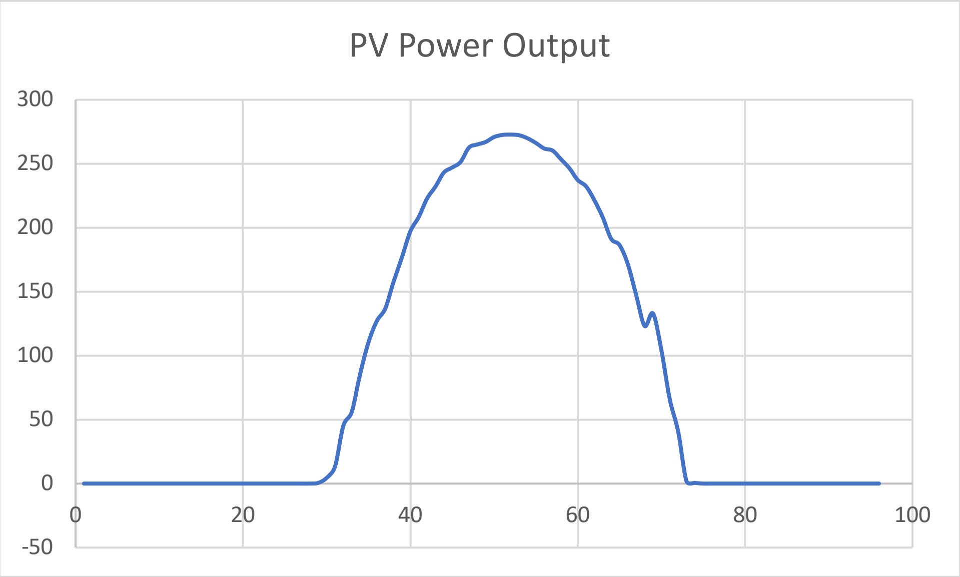


Chart 11: PV unitary power output. W vs 15min.

According to Equation 12 presented in Chapter 2, the solar collector power output is represented of the same day 19th of April.

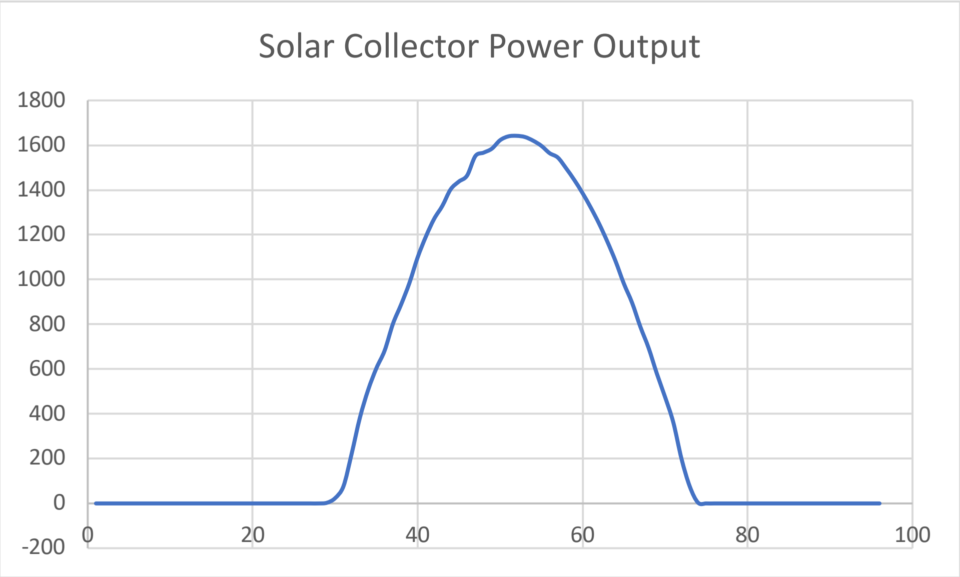


Chart 12: Solar Collector unitary power output. W vs 15min.

These data are part of the input file fed to the model in order to perform the optimization.

4.2.2 Wind

The average wind speed measured in the study area for the data acquisition period is presented in Chart 13.

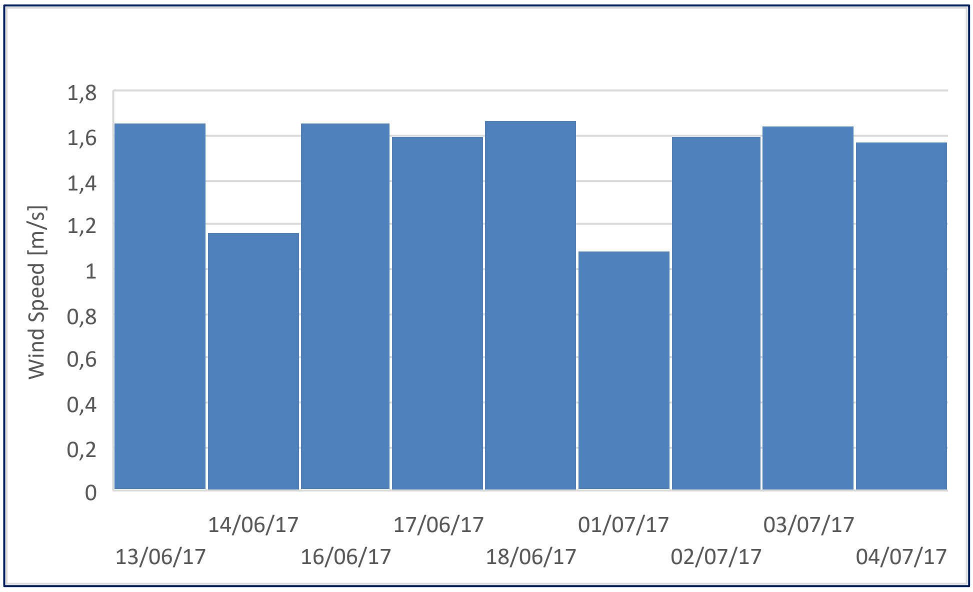


Chart 13: Measured average wind speed in the study area.

The average wind speed is in the range between 1 and 1.7 m/s and it is higher in the afternoon, between 4 PM and 9 PM.

Chart 14 presents the wind rose obtained from the weather station in the observation period.

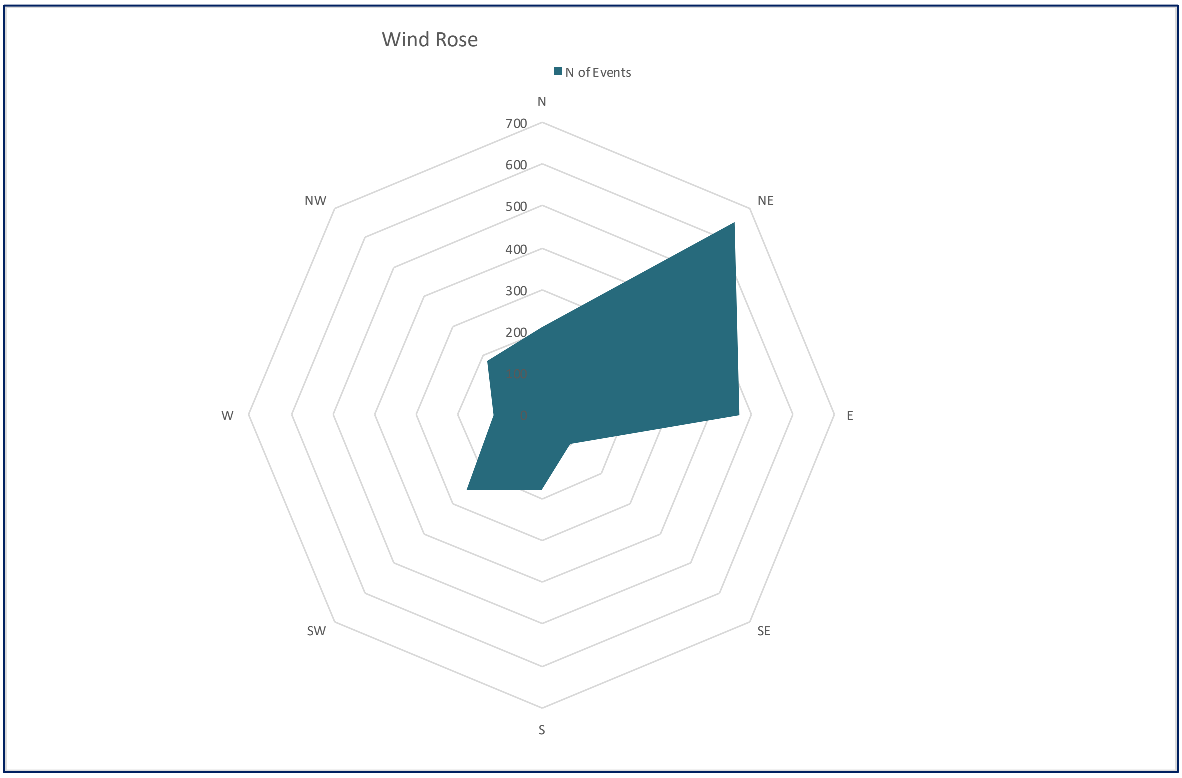


Chart 14: Wind rose of the measured wind velocities in the study area.

As shown in chart 14 the wind blows mainly between East and Northeast direction and the dominant direction is Northeast with a number of observations over 650.

As already stated in chapter 2.3.2 the collected data are not considered reliable enough to perform a study on wind potential in the area. For this reason, the Explorador Eolico [32] is used as reference tool to estimate wind potential.

From the tool is possible to extract statistical data on wind characteristics at 5.5 meters in the study area. Basic statistics on wind speed are presented in table 2.

Table 2: Monthly average wind speeds in the study area. Source: [32].

	Daily Average [m/s]	Daily Min [m/s]	Daily Max [m/s]	Variability [m/s]
January	3,3	0,7	6,3	0,2
February	3,2	0,6	6,2	0,4
March	3,3	0,6	6,0	0,3
April	3,9	1,0	7,3	0,4
May	4,0	0,6	7,5	1,3
June	3,7	0,6	6,5	0,6
July	4,3	1,1	8,4	1,0
August	4,1	0,6	7,5	0,7
September	4,6	0,8	8,4	0,8
October	4,3	0,8	7,9	0,6
November	3,7	0,8	6,6	0,3
Dicember	3,5	0,9	6,3	0,3
Year	3,8	0,8	7,1	0,8

Where the daily average is the average of all the simulated values in the indicated period. The daily minimum is the average of the minimum values of each simulated day in the period, and similarly the daily maximum. The variability is the standard deviation of the daily average.

In the same report graphical analysis is available, in particular in Chart 15 the annual cycle and daily cycle of wind speed are presented.

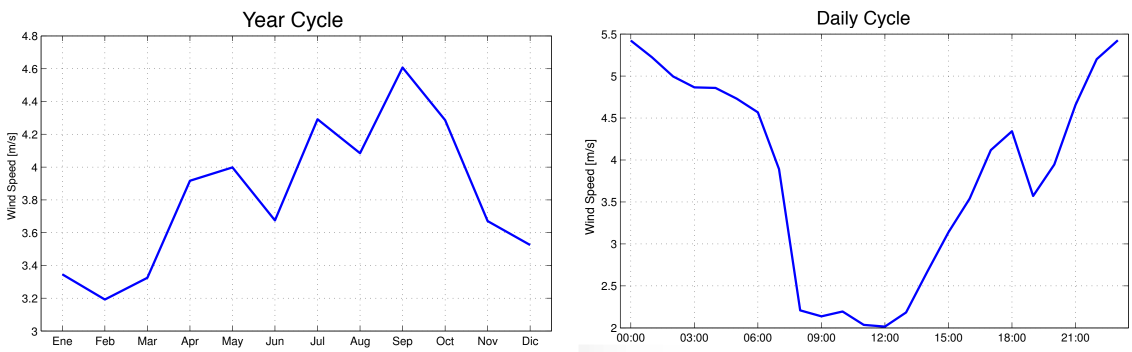


Chart 15: Yearly and daily wind speed cycles in the study area. Source: [32].

Where the average cycles of velocity on yearly and daily basis are presented based on every simulated data in the considered period.

Through the equation presented in chapter 2.3.2 the annual average potential is estimated. Adopting a Betz coefficient of 0.596, a density of 0.92 kg/m^3 as from report of Explorador Eolico, and an average speed of 3.8 m/s the power production per swept area was equal to 15.04 W/m^2, thus assuming a capacity factor of 0.7 [45] the annual energy production is estimated to be 33.2 MJ/m^2.

4.2.3 Hydro

Hydropower potential is evaluated based on measurements to estimate flow rate and gross head that are performed in the two rivers flowing nearby the study area.
The river flows obtained with the floating object method, the total gross heads, estimated using Google Earth and the estimated power output are reported in table 3.

Table 3: Estimated flow rates, gross heads and available powers of the two rivers.

	Flow Rate [m^3/s]	Gross Head [m]	Available Power [kW]
Rio Toconao	0.068	19	12.7
Rio Aguas Blancas	0.013	59	7.5

Considering the low available flow rate of Rio Aguas Blancas the theoretic output is considered not sufficient in order to proceed any further with the investigation and the focused switched on Rio Toconao.
Considering a capacity factor equal to 55% according to [46] and an overall efficiency of the hydropower system equal to 50% the annual energy potential amounts to 110 GJ.

4.3 Load Curves

The load curves are computed with the LoadProGen software as stated in chapter 2.2, the data used to create the curves are extracted from the answers to the questionnaires and from direct observations on the field.

4.3.1 Electric Load Curves

The results for the entire village load profile are now presented in chart 16. and the tables with the input values are presented in Appendix B.1.

In chart 16, the Load Curves estimated for the four seasons are presented. The load profile for a year of the study area is obtained assembling the four profiles, in chronological order from the 1st of January to the 31st of December, one time per each day of the season.

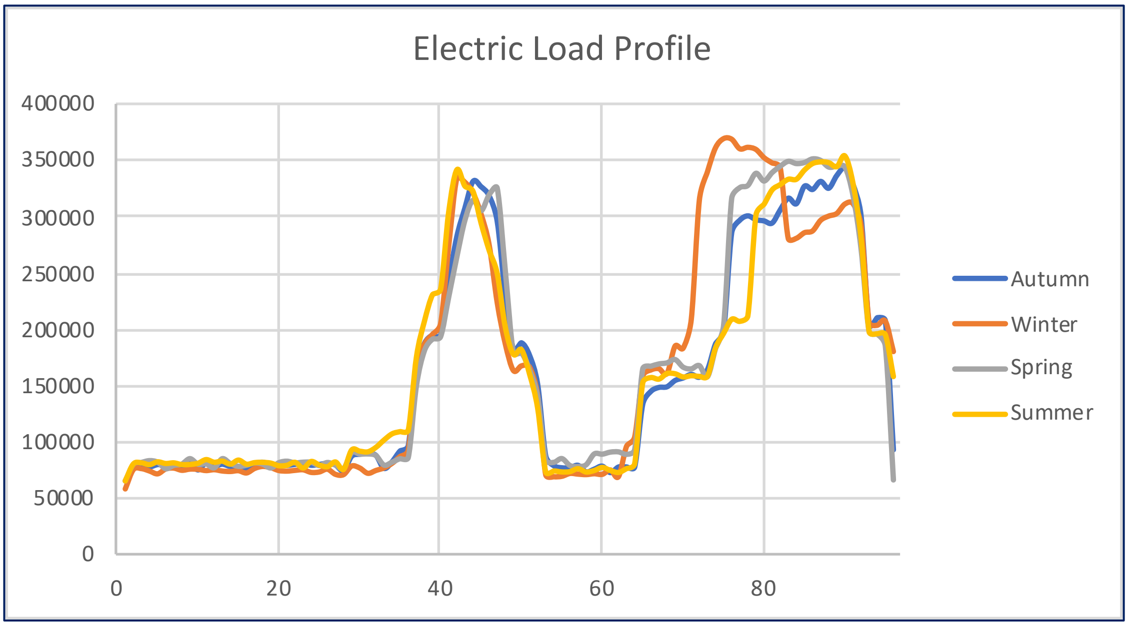


Chart 16: Electric load profile of the study area in the four seasons - W vs 15min.

The load curve has been computed estimating every 15 minutes the load of the entire study area. Two peak loads are present, one around 12:00 and one approximately from 19:00 to 22:30 both with a value of around 350 kW. A seasonal variation is appreciable in the night phase of use, winter curve reaches peak value for first, due to the earlier time of sunset. While the summer reaches the value later for the same reason.

4.3.2 Thermal Load Curves

The obtained load curves are reported in the following charts. A little consume of thermal energy is observable in the domestic class load profile, as it accounts for only one user, the

four showers, four small sink usages and two dish washings make up the thermal needs of the structure.
A more consistent demand is present in this class, as the kitchens of the restaurants make large use of hot water during meal times.
The school, which has a class of its own presents a singular behaviour, due to the presence of the kitchens, that cook for the whole number of students, and the regular use of toilets from students and staff throughout school hours.
Public class presents, equally to domestic class, lower consumes due to the fact that a lower number of users compared to the school is present and the only kitchen use of sanitary water is made by the police station.

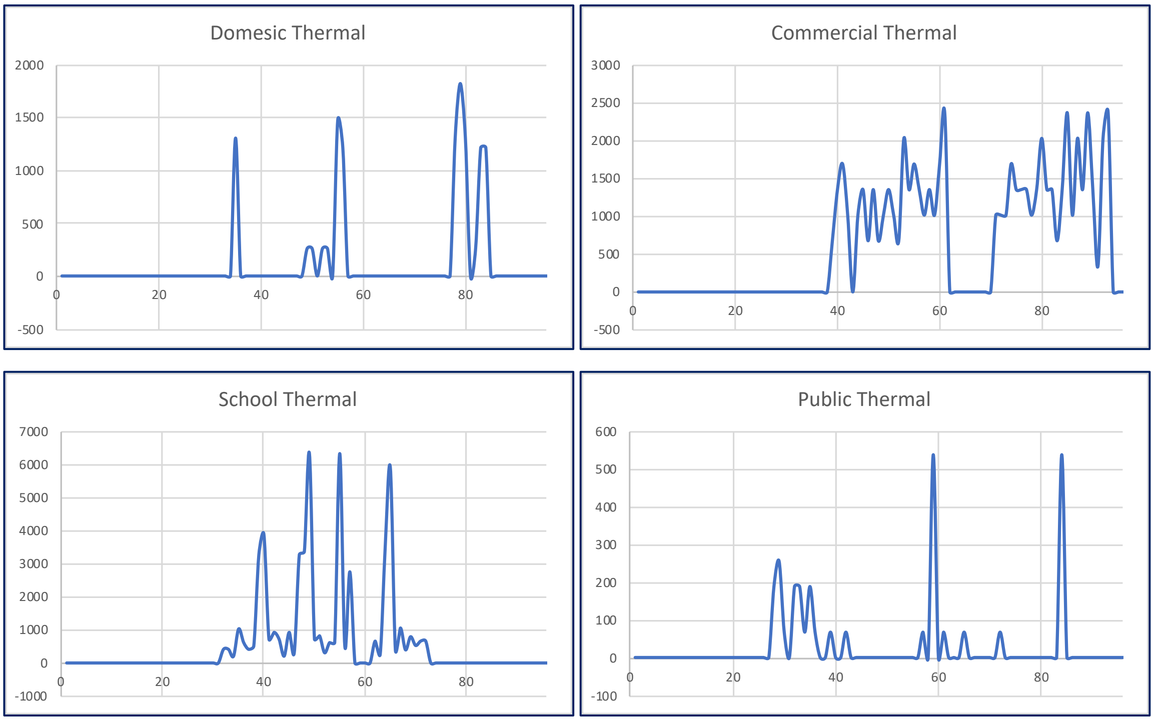


Chart 17: Thermal load profiles of the four classes for respective typical user - W vs 15min.

5. Multi Energy System model results

The previous chapters provide a comprehensive overview of what is the worldwide approach to the issue of access of energy, highlighting the necessity to pay more attention on the thermal matter that has to be aggregated to the electrical ones; then following the CESP logic and identifying the key features that are needed for a best approach, the adopted methodology is deeply explained and a *Multi Energy System* model is implemented in order to introduce a tool capable to perform a better optimization that satisfies both thermal and the electrical demand for rural communities.

This present chapter will address the latter issue and will propose an energy solution planning for the study area of the rural village of Toconao. The *MicroGridPy* and the *Multi Energy System* model are performed through a robust Linear Programming optimization and it based on the local energy assessment and the local available energy resources.

First, the actual situation is identified, and the Levelized Cost of Energy is evaluated. Secondly, both simulations in *MicroGridPy* and *Multi Energy System* are carried out considering three different scenarios:

- Normal fuel prices
- Fossil fuels prices increased by 50%
- Only renewable technologies

To precisely compare the several scenarios, the energy dispatch results are supported by the sizing and the economic analysis of the different configurations. Hence, the following results are reported to better understand the differences among the scenarios: electrical energy dispatch, number and size of each technology installed, the fossil fuels prices, the Net Present Cost of the project and the Levelized Cost of Energy (LCOE). Moreover, the Sankey diagram of each scenario is created to complete the model results and put in evidence the energy flows of the vary configurations. For the thermal part, the results are given considering each class as separate configurations. The presented results are referred to a single day, the 19th of April, of a typical meteorological year with a time step of 15 min as discussed in the Chapter 2. In addition, all the technical and economical characteristics of the several equipment are showed in the Appendix (F).

As mentioned above, the most abundant resource available in the local area is the solar irradiation, consequently the inputs in both simulations are given by the energy outputs for each time step of 15 min of the selected Photovoltaic panel and Solar Collector. Finally, the thermal and the electrical demand are considered to simulate the energy load of the entire village as explained in the Chapter 2 and 4.

5.1 Baseline Scenario

To better understand the comparisons among the several scenarios, it is necessary to evaluate the Net Present Cost and the Levelized Cost of Energy (LCOE) of the actual situation in the study area, as baseline scenario. As discussed in the previous chapters, what emerges from the local energy assessment is that the electrical demand is principally satisfied buying electricity from the local company CESPA at a higher price, as shown in the Table 1, that in some case reaches values of 220 CLP/kWh compared to the national value of 107,5 CLP/kWh that in USD dollars are 0.36 USD/kWh and 0.17 USD/kWh respectively. The same tariff is also applied when the electricity is produced by the diesel generator in case of shortages or the unavailability of the line. Based on these considerations, the LCOE of the actual situation is evaluated, and it is results equal to 0.34 $/kWh with Net Present Cost of 7,61 million dollars. On the other side, looking at the Sankey Diagram of the actual situation in Figure 18 in Section 4.1.2, the thermal energy requirement is mainly satisfied by LPG source. As previously discussed, due to the high cost of transportation the price of the LPG is quite high, hence, combining the price of the electricity and of the LPG, the Levelized Cost of Energy for the baseline scenario is 0.345 $/kWh. In the table 4 all the results are reported.

Table 4: Economical Parameters of baseline scenario

	MicroGridPy		**Multi Energy System**	
	NPC [M$]	LCOE [$/kWh]	NPC [M$]	LCOE [$/kWh]
Base Case	7,61	0,340	10,69	0,345

In the next paragraphs, the three scenarios are presented and compared to the baseline scenario, taking into consideration both a *MicroGridPy* and a *Multi Energy System* optimization.

5.2 Scenario: Standard optimization

MicroGridPy

The standard optimization scenario performed by the *MicroGridPy* model represents a possible configuration based on realistic parameters referred to the study area. The simulation returns the electrical energy dispatch of a year having as inputs the PV energy and the Electrical Demand of the entire village in a time step of 15 min, hence, 35040 time-steps in one year. In Chart 18, is represented an example case showing the energy dispatch of the 19th of April. The main vertical axis represents the power expressed in W, while the secondary axis represents the stored energy expressed in Wh. On the other side, the horizontal axis represents the time-steps of one day expressed in 96 time-steps, that are the number of quarters of an hour present in a day. As it is possible to see from the graph, the electrical load is relatively high in the middle of the day and in the evening reaches a peak value of 85600 W around 11:00 pm. During the day, the demand is almost entirely satisfied by the PV energy represented by the blue line; when the load reaches the peak value, the energy stored in the battery bank is used to cover the maximum value. The PV energy in excess is stored in the battery bank; in fact, the grey dotted line represents the State of Charge (SOC) of the battery bank that has almost the same shape of the PV Energy but shifted on the right side because of its use in night hours. Moving on the right side of the graph, the electrical demand during evening hours is fulfilled by the cumulated energy and the power generated by diesel generator. The steady behaviour of the orange line means that the genset does not exceed its nominal capacity and the rest of the demand is satisfied by battery power flow out as a result of the optimization of the Net Present Cost. Therefore, the sum of the battery power flow out and the generator power outputs cover exactly the entire electrical demand shown by the dark blue line. The number of the installed photovoltaic panels is 324 modules and the Net Present Cost has a value of 5.57 million dollars. More attention can be given to the LCOE, equal to 0.249 $/kWh that compared to the baseline scenario of 0.340 $/kWh is quite lower meaning that this configuration can represent a feasible and possible scenario. This result can be justified mainly by the smaller dimension of the diesel generator resulting in a lower investment cost.

Table 5: Sizing of Standard Scenario – MicroGridPy simulation

Standard			
Economical		**Electric**	
NPC [M$]	5,57	N° PV	324
LCOE [$/MWh]	0,249	Battery Cap [kWh]	1025,925
LCOE/LCOE$_{base}$	73%	Gen P Nom [kW]	180,206
Diesel Cost [$/l]	0,9		

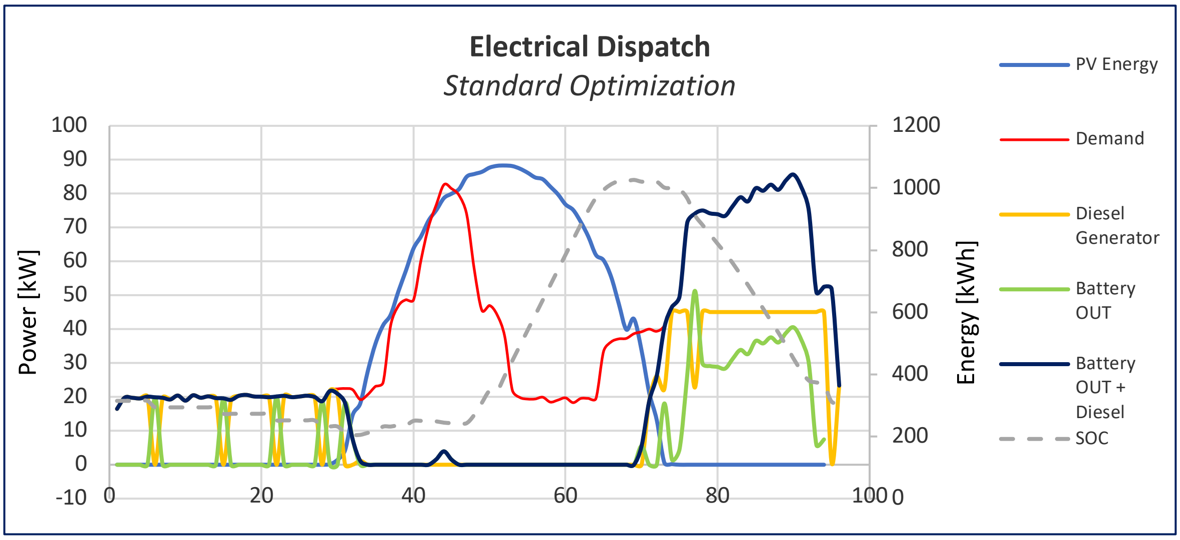


Chart 18: Electrical energy dispatch as result of MicroGridPy simulation – Standard Scenario.

Multi Energy System

In *Multi Energy System* the two most energy-demanding final uses in the village are represented by domestic hot water (DHW) and electric appliances for residential and institutional user types. The two demands are though logically connected through the presence of the resistances in the water storage tanks, which energy consume is added to the electric load and has to be satisfied in the same way. The peculiarity of the *Multi Energy System* model lies on the two different approaches that the electrical and the thermal optimizations have: on the one hand the electrical load represents the entire demand of the village and a centralized configuration is thought to be installed; on the other hand a decentralized approach is applied dividing the entire thermal demand in classes and considering each class as a system that has to be optimized. In fact, for the thermal part, the model provides and sizes the nominal capacities of the installed technologies and the number of the solar collector units for each class. The synergy between the electrical and thermal part is very much clear comparing the respectively energy dispatches. Focusing on the right side of the Chart 19, is observable a disjunction between the summation of the battery flow out and the power provided by the genset (represented by the blue line) with the electrical demand (represented by red line); this gap represents exactly the extra power necessary to feed the resistances installed in each class. In Table 6 the sizes of each class are shown.

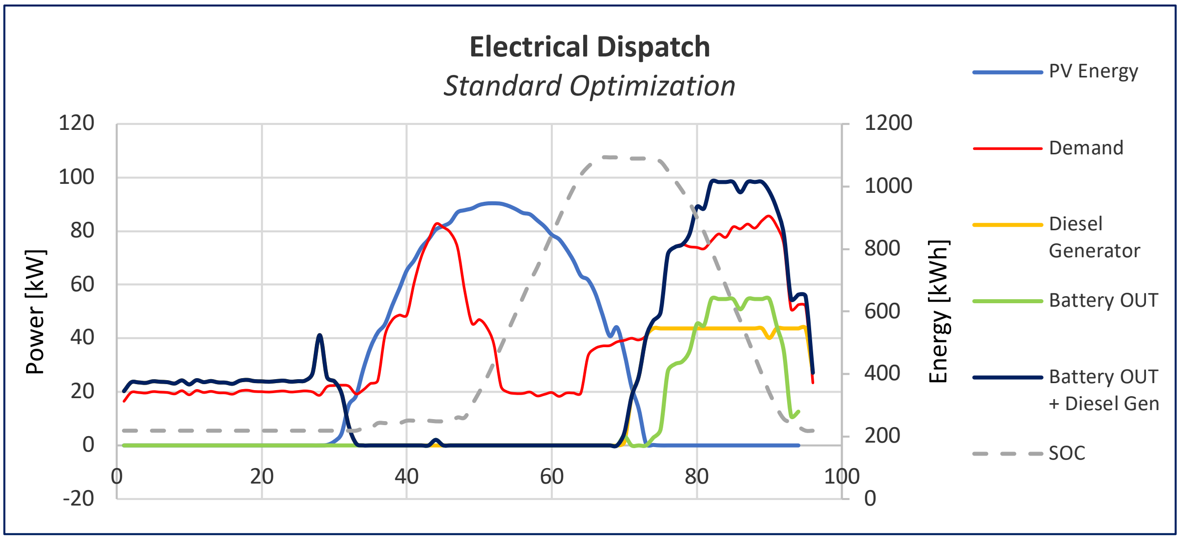


Chart 19: Electrical energy dispatch as result of Multi Energy System simulation – Standard Scenario.

The thermal energy dispatches of the commercial, domestic, public and school classes are presented in the graphs Chart 20, Chart 21, Chart 22 and Chart 23, where the electrical resistance is highlighted by the blue line. The thermal demand during daylight is almost completely satisfied by solar collectors, and part of their energy is stored in the hot water tank, ready to be used to satisfy the load after sunset, combined with the energy supplied from the electrical resistance and from the boiler. The boiler presents a similar behaviour to the diesel generator, having a nominal capacity optimized by the software in a NPC optimization optic.

The commercial class includes 32 users and has a more stable hot water demand at noon and at evening time where meal activities are more frequent. During the day, the thermal demand is satisfied almost entirely by the solar collector's energy. On the other side, at evening hours the demand is partially fulfilled by the accumulated energy in the water storage tank until its energy is exhausted; after that, the thermal energy is provided by the electrical resistance heating the water in the storage tank that will be sent to the service. The peaks of the demand are finally satisfied by the boiler energy represented by the green line.

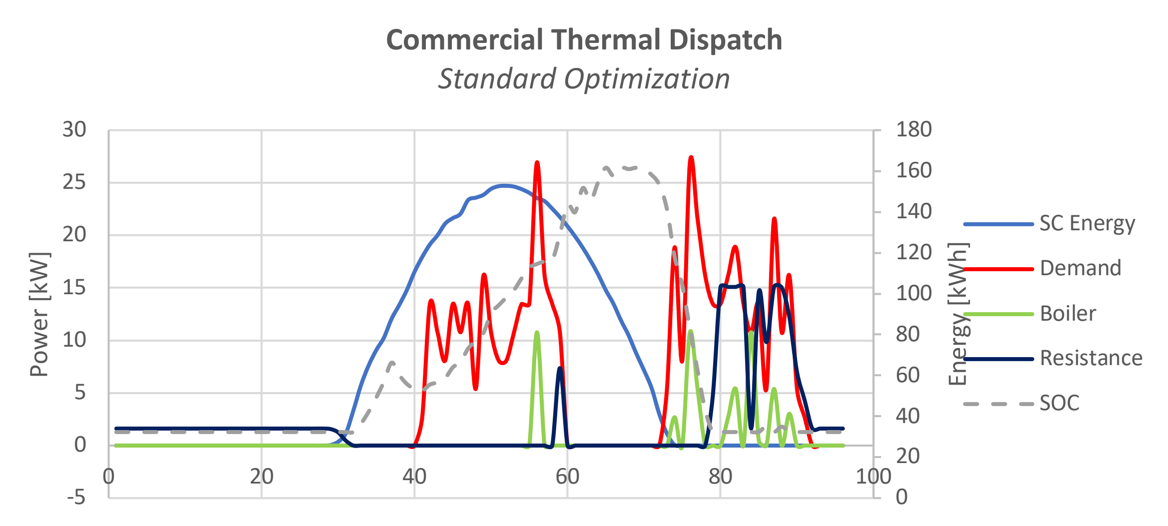


Chart 20: Commercial Thermal energy dispatch as result of Multi Energy System simulation – Standard Scenario.

The hot water demand of the domestic class is made up of the sum of 332 users that are assumed to have similar usages in the same small-time windows. For this reason, the shape of the demand curve presents different high peaks during the day. As a result of the NPC minimization, the optimal configuration provides for the installation of a boiler with a higher nominal capacity of 318,54 kW compared to commercial case with a boiler nominal capacity of 24,24 kW, despite the number of solar collector remains almost the same. Therefore, for this kind of the demand shape it is more convenient to install a LPG boiler than many solar collectors. The electrical resistance is activated to satisfy the peaks of the demand and to maintain the thermal energy in hot water storage tank above its minimum value.

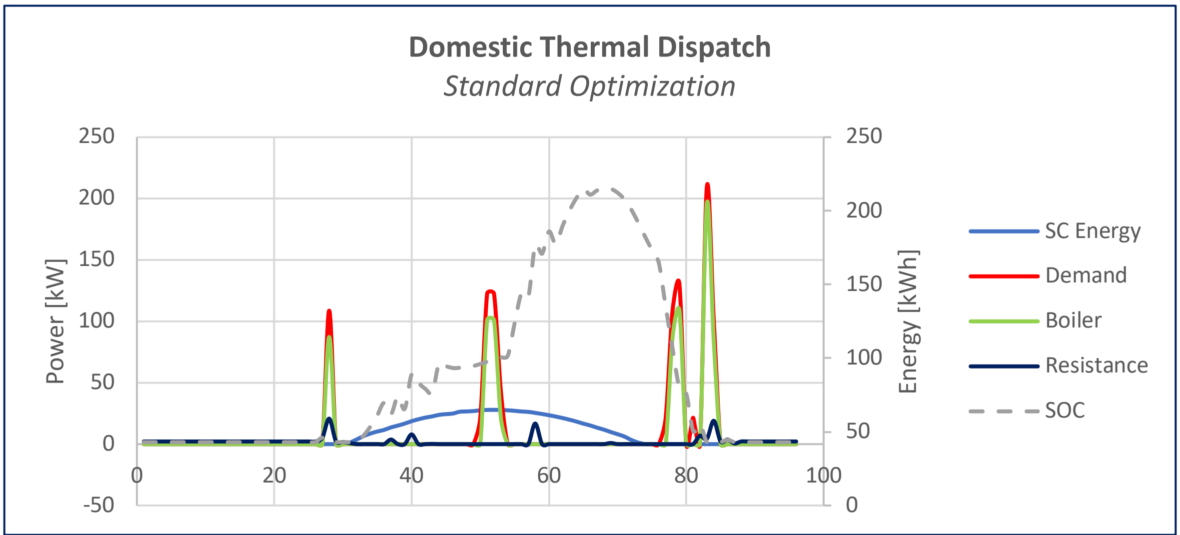


Chart 21: Domestic Thermal energy dispatch as result of Multi Energy System simulation – Standard Scenario.

The public class includes 6 number of users such as the police station medical centre, radio station and municipal offices. The police station is the one with the highest hot water consumption because the policemen live in the station, this makes the shape of the thermal demand similar to the domestic ones. For this reason, the same qualitative considerations on the domestic case can be made for the public class. The boiler nominal capacity and resistance nominal capacity are lower than the previous case, due to the lower magnitude of the demand. In fact, the maximum peak of the public demand is almost 810 W compared with domestic value of 210 000 W.

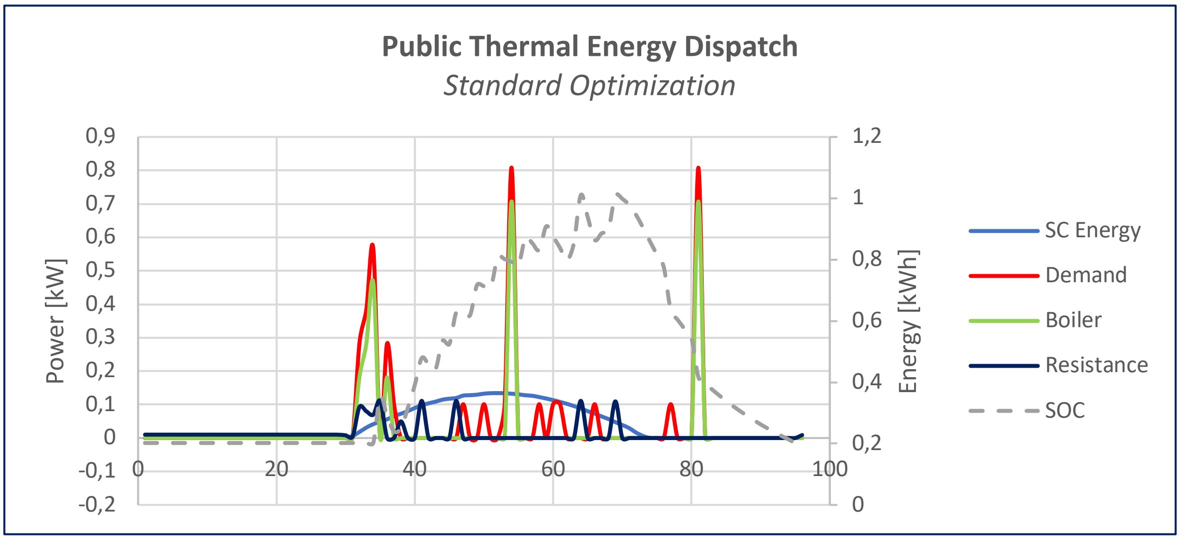


Chart 22: Public Thermal energy dispatch as result of Multi Energy System simulation – Standard Scenario.

Due to the high number of students and consequently the relatively high hot water consumption, the school is considered as a single class. The building is normally opened from the 8:00 am to the 7:00 pm and the hot water consumption is mainly due to the activities regarding the school canteen. Hence, the best thermal configuration is to use the solar collector outputs to fulfil the thermal demand during the day. As shown in the appendix F, the nominal capacity of the selected solar collector is a fixed parameter and it is equal to 1825 W; comparing this with the maximum value of the thermal load (almost 1600 W), the better configuration provides a unique solar collector that has to be installed to satisfy the demand. In addition, a boiler of 2,13 kW is installed as back-up system and a resistance of 452 W is selected in order to maintain the minimum thermal energy in the water storage tank.

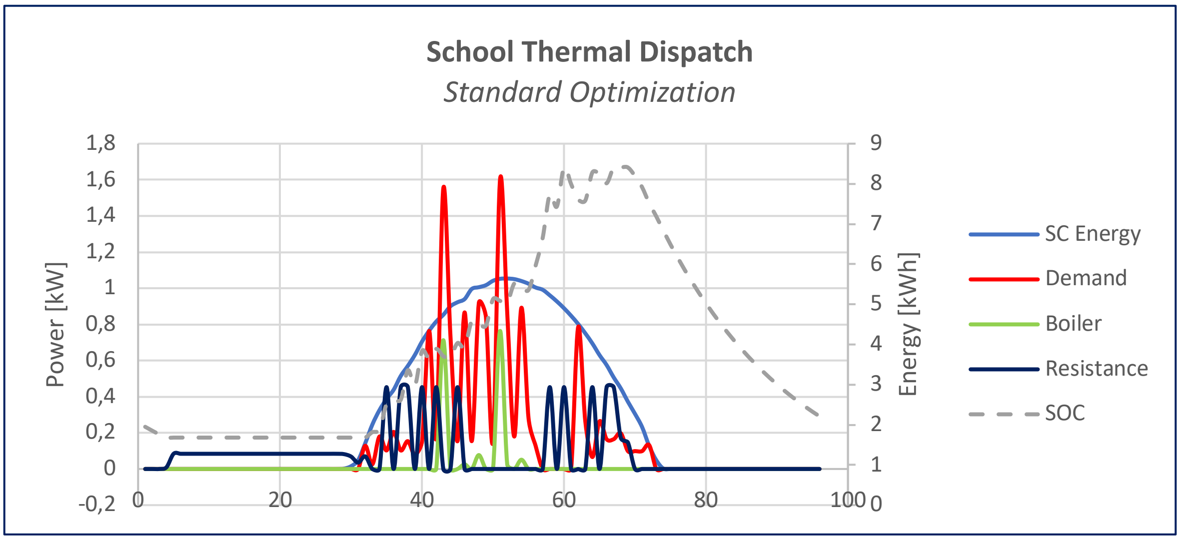


Chart 23: School Thermal energy dispatch as result of Multi Energy System simulation – Standard Scenario.

Combining the electrical and thermal optimization, the LCOE of the entire system is equal to 0.264 $/kWh that compared to baseline scenario results to be 23% lower. The Net Present Cost is equal to 8.18 million of dollars, 2 million lower than the baseline scenario due to the installation of smaller boilers and diesel generator substituted by renewable energy technologies and a lower consume of fossil fuels throughout the project life time.

Comparing the same parameters with the *MicroGridPy* optimization, the LCOE for the combined provision of electricity and heat is only slightly increased as compared to that of a scenario in which only the electricity supply is optimised, even though the initial investment cost required is naturally higher due to the need to purchase a whole new set of technologies. In addition, the number of photovoltaic panels installed in this configuration is higher than the *MicroGridPy* scenario as well as the battery nominal capacity, suggesting that the additional electrical load required by the resistance is preferentially satisfied by renewable technologies.

To this regard, the results show that the cost-optimised MES can effectively reduce the LCOE as well as the NPC as compared to the baseline scenario (i.e. diesel and gas as the only primary energy sources).

Table 6: Sizing of Standard Scenario – Multi Energy System simulation

Standard					
Economical		**Electric**		**Thermal**	
NPC [M$]	8,18	N° PV	331	N° SC Com	15
LCOE [$/MWh]	0,264	Battery Cap [kWh]	1092,843	Tank Cap Com [kWh]	161,626
LCOE/LCOE$_{base}$	77%	Gen P Nom [kW]	174,68	Res P Nom Com[W]	15085
Diesel Cost [$/l]	0,9			Boiler P Nom Com [kW]	24,244
LPG Cost [$/kg]	2,6			N° SC Dom	17
				Tank Cap Dom [kWh]	214,97
				Res P Nom Dom [W]	20732
				Boiler P Nom Dom [kW]	318,554
				N° SC Pub	1
				Tank Cap Pub [kWh]	1,01
				Res P Nom Pub [W]	111
				Boiler P Nom Pub [kW]	1,03
				N° SC Sch	1
				Tank Cap Sch [kWh]	8,407
				Res P Nom Sch [W]	452
				Boiler P Nom Sch [kW]	2,137

To have a global idea of the effects of the optimization on the study area, a Sankey Diagram based on the *Multi Energy System* optimization is presented. After the implementation of the proposed energy system, the main benefits would be the decrease of reliance on fossil fuels and external sources of energy. In fact, the share of primary energy coming from outside the borders of the study area would become 73% and if referring to secondary energy 54%, compared to the 91% and 95% of actual situation showed in Chapter 4.1.2. Moreover, is possible to observe the thermal losses of the domestic driver are higher than in the actual situation (see Figure 18), this is due to the higher amount of diesel primary energy entering the driver, now that the system is disconnected form the electrical grid, remembering that grid is assumed net of losses. In conclusion, the integrated MES scenario offers a higher penetration of renewable sources in the primary energy mix and a lower dependency on external imports.

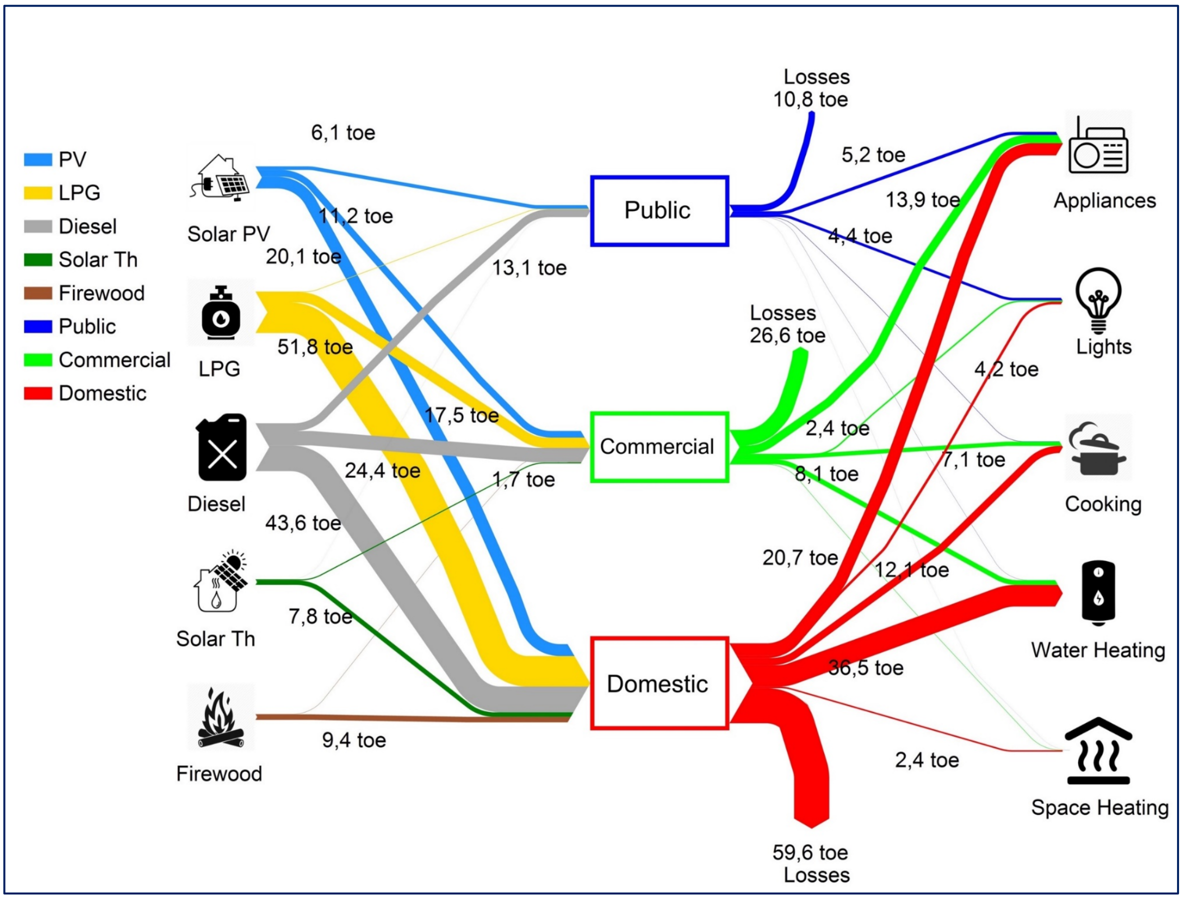


Figure 21: Sankey Diagram of the study area in first simulated scenario.

5.3 Scenario: High Fossil Fuel Price

MicroGridPy

In the high fossil fuels price scenario, the price of the diesel is increased by the 50% compared to the standard scenario to understand possible effects on the optimal configuration. The electrical demand remains the same while the electrical energy dispatch has changed. The number of the photovoltaic panels increase from 342 modules in the previous scenario, to 549 panels as well as the battery bank increases its nominal capacity of almost three times. In this way, more energy can be cumulated during the daylight hours and releases it during the evening hours or when it is necessary. However, looking at the green line in Chart 24, it is possible to observe that the diesel generator is used to cover the peaks of the demand especially during the evening hours with a nominal capacity of genset installed of 42,418 kW. Moving on economical analysis, the Levelized Cost of Electricity results 0.272 $/kWh that comparing to 0.249 $/kWh of the previous scenario, results to be grater due to high photovoltaic units installed and thus a greater battery bank nominal capacity; however, the results show that the Levelized Cost of Electricity and Net Present Cost of this scenario are more convenient than the baseline scenario, as a matter of fact that in the context of off-grid areas, where electric and thermal energy needs are typically satisfied, at best, by means of diesel generators, which are based on non-renewable fuels and are typically associated with an unreliable and expensive supply-chain, a transition to renewable energies can be a feasible and convenient scenario.

Table 7: Sizing of High Fuel Prices Scenario – MicroGridPy simulation

High Fossils Fuel			
Economical		**Electric**	
NPC [M$]	6,08	N° PV	549
LCOE [$/kWh]	0,272	Battery Cap [kWh]	2908,715
LCOE/LCOE$_{base}$	80%	Gen P Nom [kW]	42,418
Diesel Cost [$/l]	1,35		

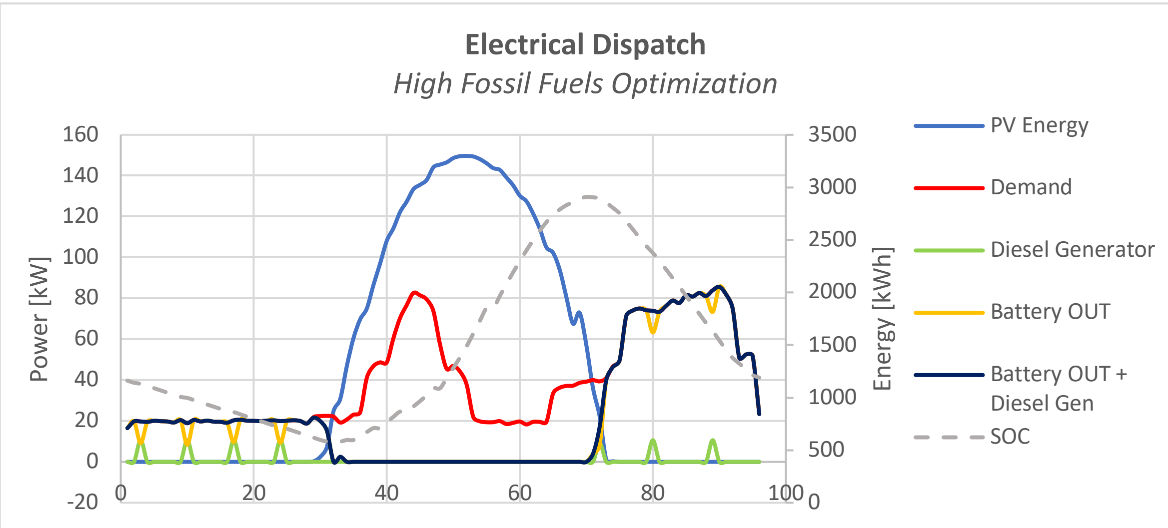


Chart 24: Electrical energy dispatch as result of MicroGridPy simulation – High Fuel Prices Scenario.

Multi Energy System

In this scenario the fossil fuels prices are 50% higher, implying that renewable energy sources are economically preferred in the fulfilment of both demand. While the electrical demand remains unchanged, differences are observable in the behaviour of electrical resistance requirements. In fact, being the LPG more expensive to use for the system, the thermal load of night time hours is preferentially satisfied by the resistance and an over dimensioning of the tank thermal storage system.

To this regard, is notable how the number of installed PV is 20% higher than the only electric simulation as well as the battery bank nominal capacity results increased by 30% to feed the electrical resistances of each class.

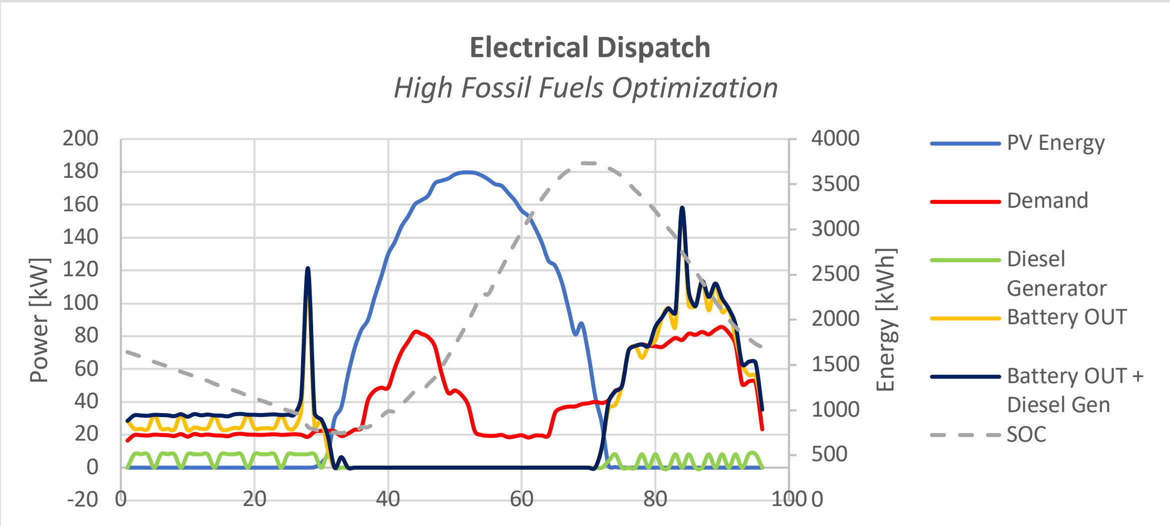


Chart 25: Electrical energy dispatch as result of Multi Energy System simulation – High Fuel Prices Scenario.

In the thermal energy dispatch, the same phenomenon of energy storage technology oversizing is observable. In fact, the nominal capacity of the installed storage tank in the commercial class results increased of 16%. The number of solar collectors is increased of 20% and the electrical resistance nominal capacity of 30%.

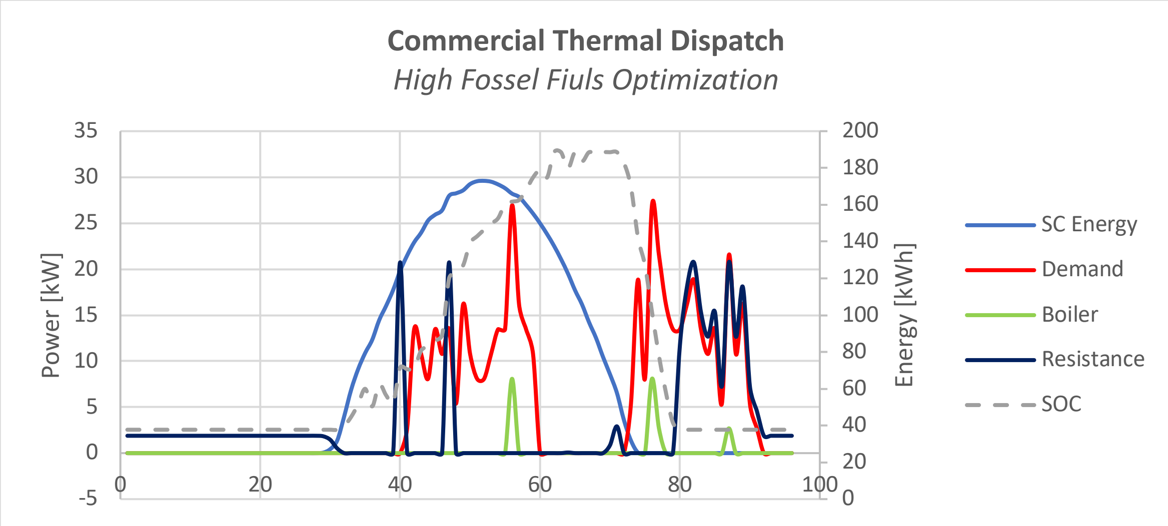


Chart 26: Commercial Thermal energy dispatch as result of Multi Energy System simulation – High Fuel Prices Scenario.

Looking at the domestic class thermal energy dispatch, is observable at first glance how the boiler technology is significantly less used. In fact, the nominal capacity of the installed boiler is decreased of 25% and it is used just to reach peak values of the demand. The number of the solar collectors is increased of 320% showing a significant penetration of the renewable technologies in this configuration compared to the previous scenario.

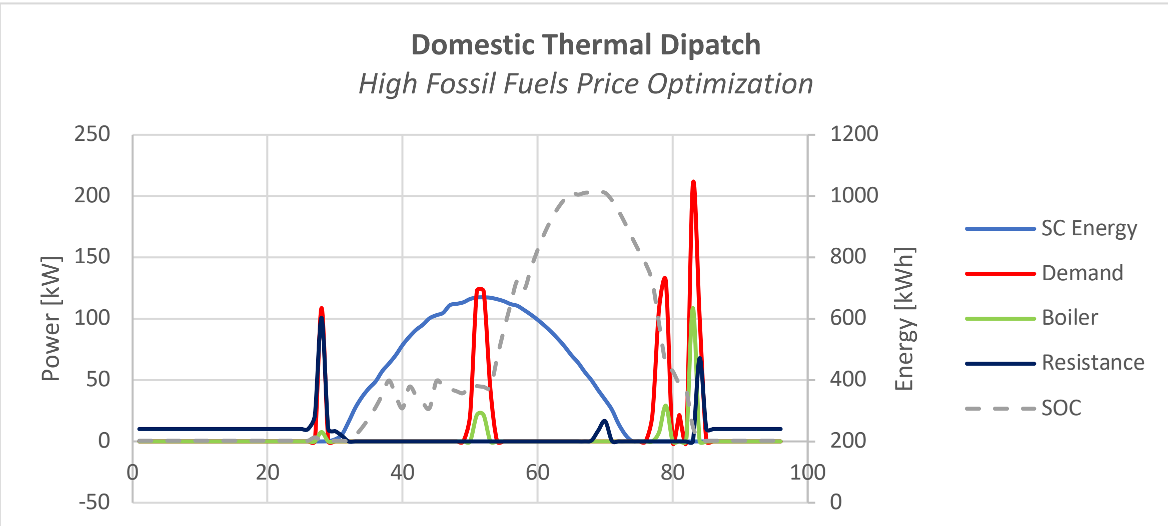


Chart 27: Domestic Thermal energy dispatch as result of Multi Energy System simulation – High Fuel Prices Scenario.

In this case, being the demand more spread along the day a strong use of the resistance is preferred to installing new solar collectors and a high share of peak values of the demand is still satisfied by the boiler. In fact, a unique solar collector is still installed while the nominal capacities of the tank and the resistance are almost tripled.

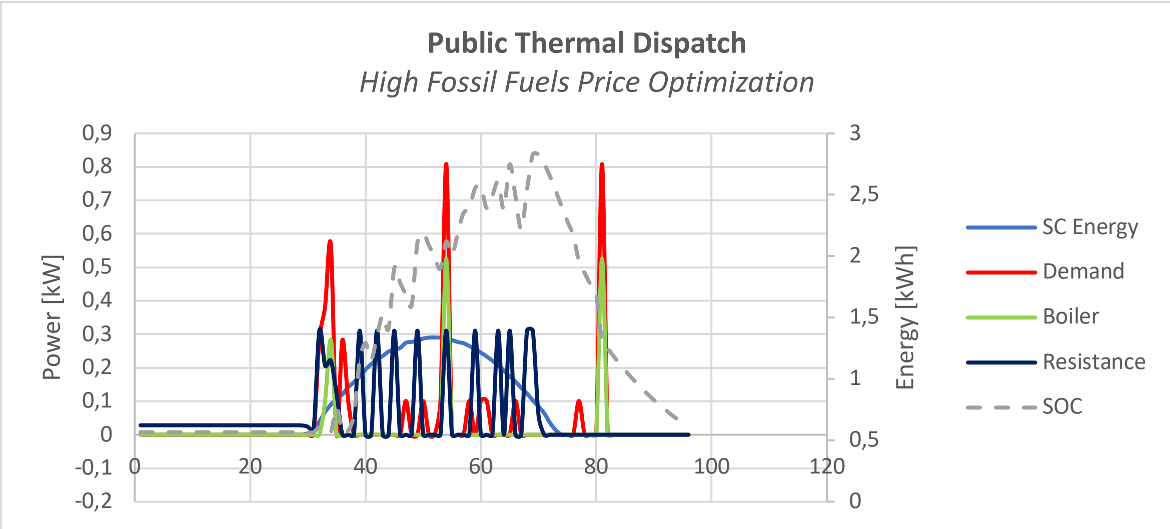


Chart 28: Public Thermal energy dispatch as result of Multi Energy System simulation – High Fuel Prices Scenario.

Similar considerations regarding the Public class can be made for the School. In particular, being the hot water consumption of the school during daylight hours, the use of the resistance is strongly encouraged because of the abundant photovoltaic energy available.

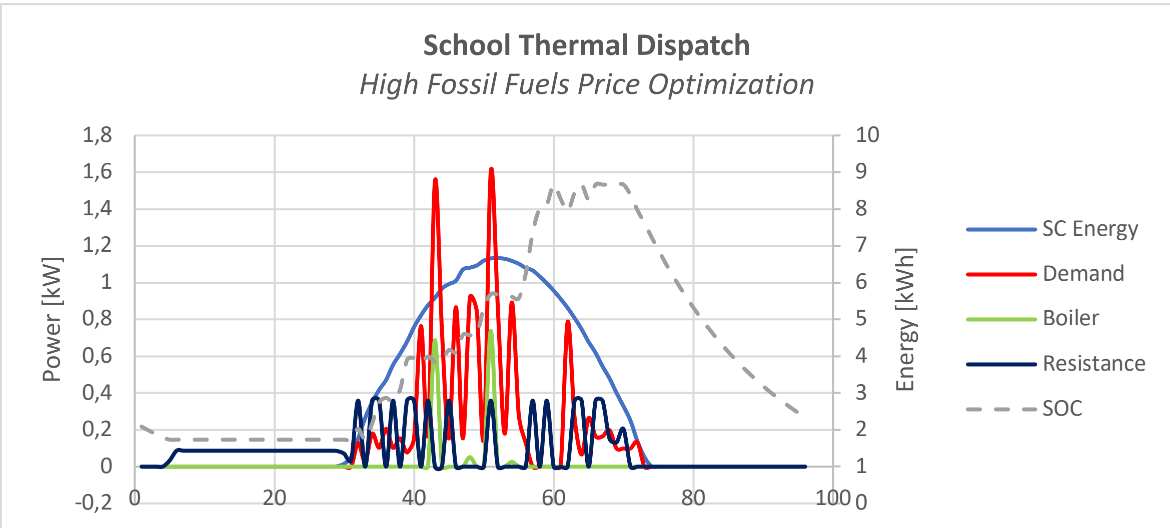


Chart 29: School Thermal energy dispatch as result of Multi Energy System simulation – High Fuel Prices Scenario.

With respect to the economic considerations, the LCOE of this scenario results higher due to the major number of expensive renewable technologies installed (i.e. PV, Solar Collectors, battery bank, storage tank) compared to the standard scenario but remains still lower than the baseline scenario with of 0.301 $/kWh.

Table 8: Sizing of High Fuel Prices Scenario – Multi Energy System simulation

High Fossil Fuels					
Economical		**Electric**		**Thermal**	
NPC [M$]	9,34	N° PV	659	N° SC Com	18
LCOE [$/MWh]	0,301	Battery Cap [kWh]	3730,577	Tank Cap Com [kWh]	188,564
LCOE/LCOE$_{base}$	87%	Gen P Nom [kW]	32,615	Res P Nom Com[W]	20742
Diesel Cost [$/l]	1,35			Boiler P Nom Com [kW]	21,55
LPG Cost [$/kg]	3,9			N° SC Dom	72
				Tank Cap Dom [kWh]	1010,94
				Res P Nom Dom [W]	100694
				Boiler P Nom Dom [kW]	238,957
				N° SC Pub	1
				Tank Cap Pub [kWh]	2,828
				Res P Nom Pub [W]	310
				Boiler P Nom Pub [kW]	0,848
				N° SC Sch	1
				Tank Cap Sch [kWh]	8,664
				Res P Nom Sch [W]	358
				Boiler P Nom Sch [kW]	2,112

In this case, the optimization increases consistently the PV installed power and increases less evidently the energy supply from solar collectors. In this case the primary energy supply from outside the study area decreases to 32%.

Is also possible to observe how the thermal losses of the entire energy system decrease of 65%, due to the strong decrease of diesel and LPG primary energy entering the drivers, main causes of the thermal losses of the system. In conclusion, although an increment of the fossil fuels price of 50% and a higher penetration of the renewable technologies compared to previous scenario, the system does not exclude entirely the use of the fossil fuels sources. However, the transition to a more renewable energy configuration results still convenient compared to the baseline scenario with a lower LCOE of 0.301 $/kWh.

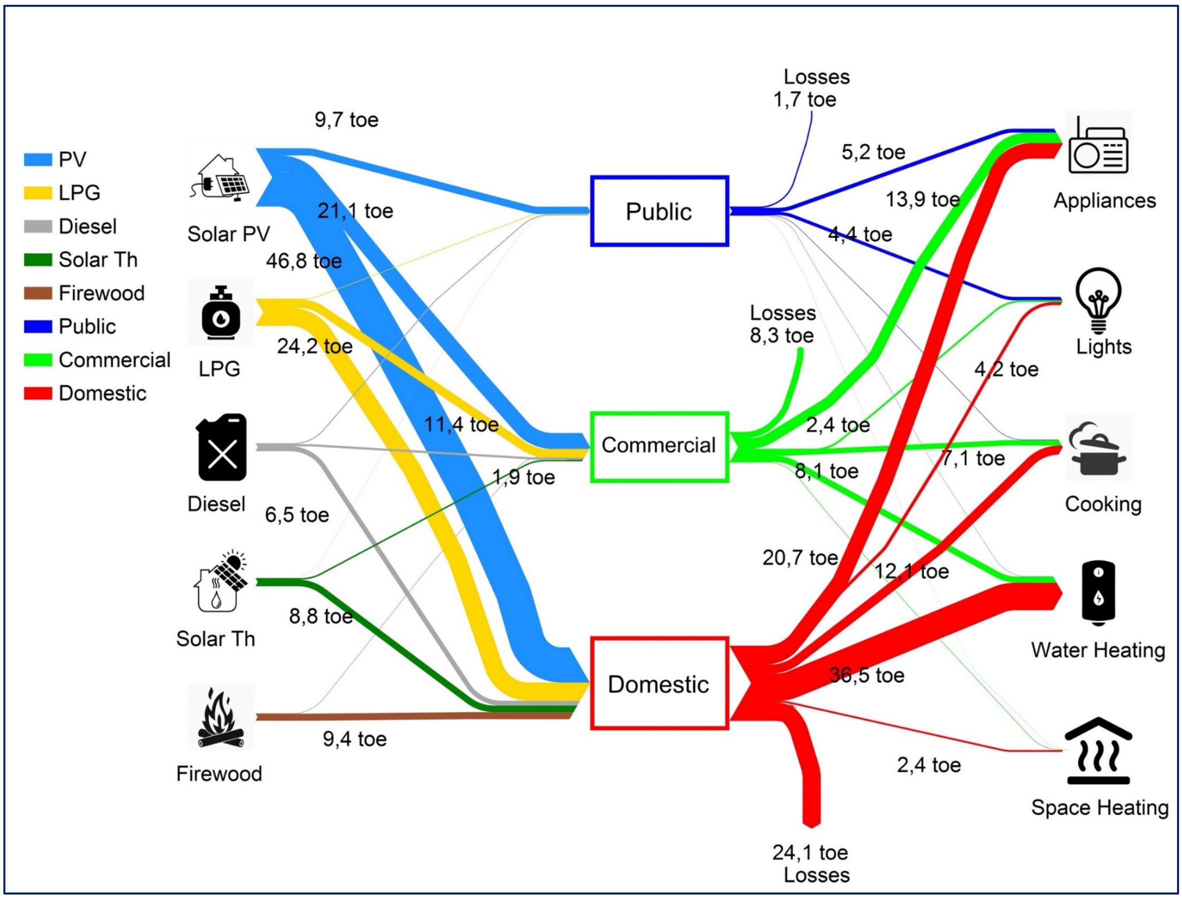


Figure 22: Sankey Diagram of the study area in second simulated scenario.

5.4 Scenario: Only Renewable

MicroGridPy

In this scenario it is imposed to the model to satisfy the totally of the electrical demand with renewable energy sources. This imply the absence of a diesel generator in the energy matrix and a strong oversizing of number of installed PV and battery capacity. The results show an amount of PV installed increased by the 150% and a battery bank capacity of 230%. The two anomalous peaks of the battery flow out are justified by computational errors of the *Linear Programming* optimization. Due to this oversizing of expensive renewable technologies the NPC results the highest of the three scenarios as well as the Levelized Cost of Electricity representing still a more economic solution compared to the baseline scenario as shown in Table 9.

Table 9: Sizing of Only Renewable Scenario – MicroGridPy simulation

Only Renewable			
Economical		**Electric**	
NPC [M$]	7,04	N° PV	812
LCOE [$/MWh]	0,314	Battery Cap [kWh]	3351,648
LCOE/LCOE$_{base}$	92%	Gen P Nom [kW]	0
Diesel Cost [$/l]	-		

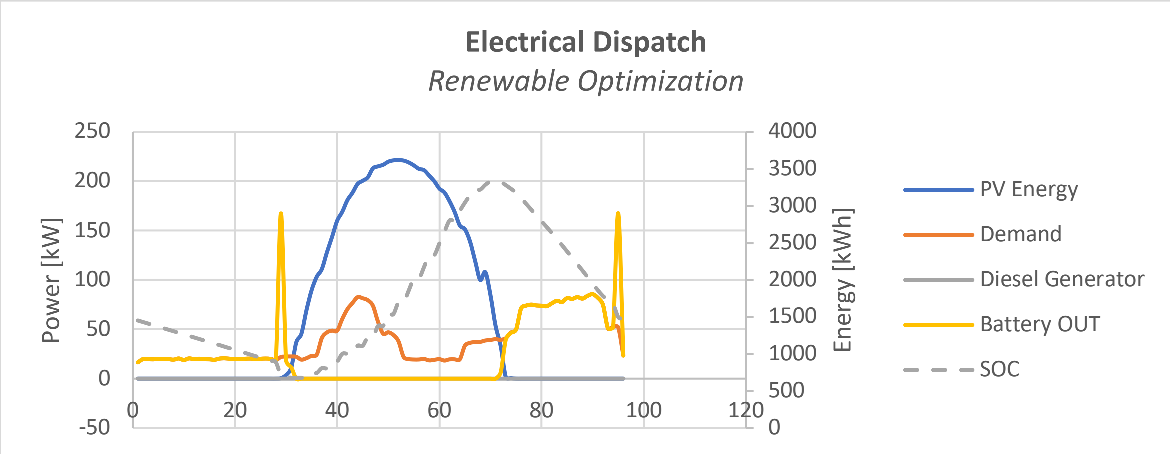


Chart 30: Electrical energy dispatch as result of MicroGridPy simulation – Only Renewable Scenario.

Multi Energy System

A fully-renewable MES scenario is also run in order to evaluate how the village could be set completely free of external imports. In the electrical dispatch, the great over dimensioning of installed PV units is observable as well as the nominal capacity of the battery bank. Another interesting behaviour is the battery flow out employed to fulfil resistance needs represented by the yellow peaks above the red line (i.e. electrical load) in Chart 31.

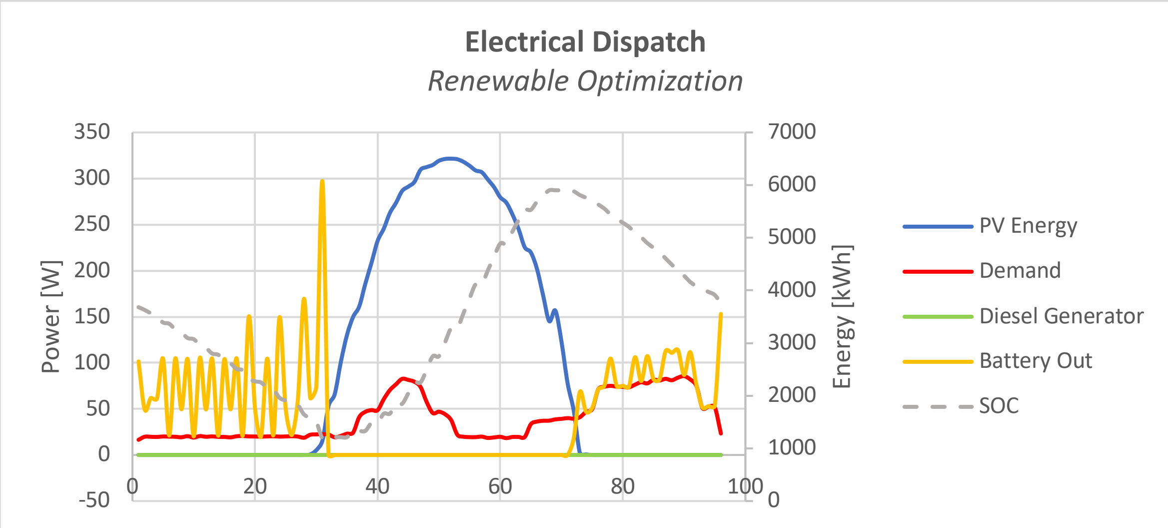


Chart 31: Electrical energy dispatch as result of Multi Energy System simulation – Only Renewable Scenario.

The thermal demand is satisfied completely by renewable energies, meaning that the sizing of the entire configuration is changed increasing both the number of solar collectors and the tank capacity of 200%. Intense use of the resistance is also appreciable and the continuous alternation of switching on and of is imputable to the *Linear Programming* because it does not see a difference between a constant use and a subsequent switching on and off.

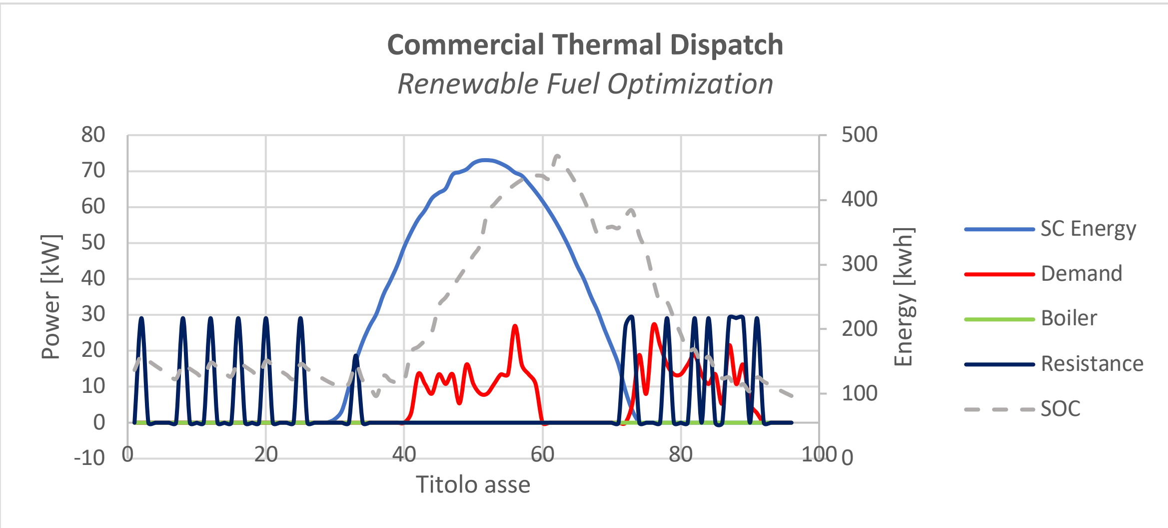


Chart 32: Commercial Thermal energy dispatch as result of Multi Energy System simulation – Only Renewable Scenario.

The domestic, public and school thermal dispatches of the only renewable scenario are presented in the following charts. Exactly the same considerations are valid as in the commercial case for all the other classes.

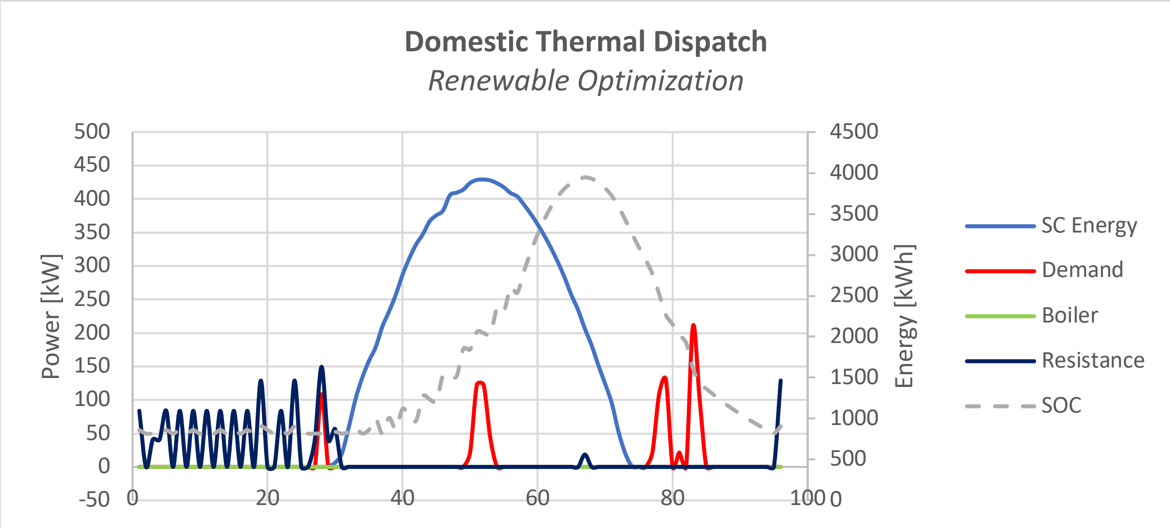


Chart 33: Domestic Thermal energy dispatch as result of Multi Energy System simulation – Only Renewable Scenario.

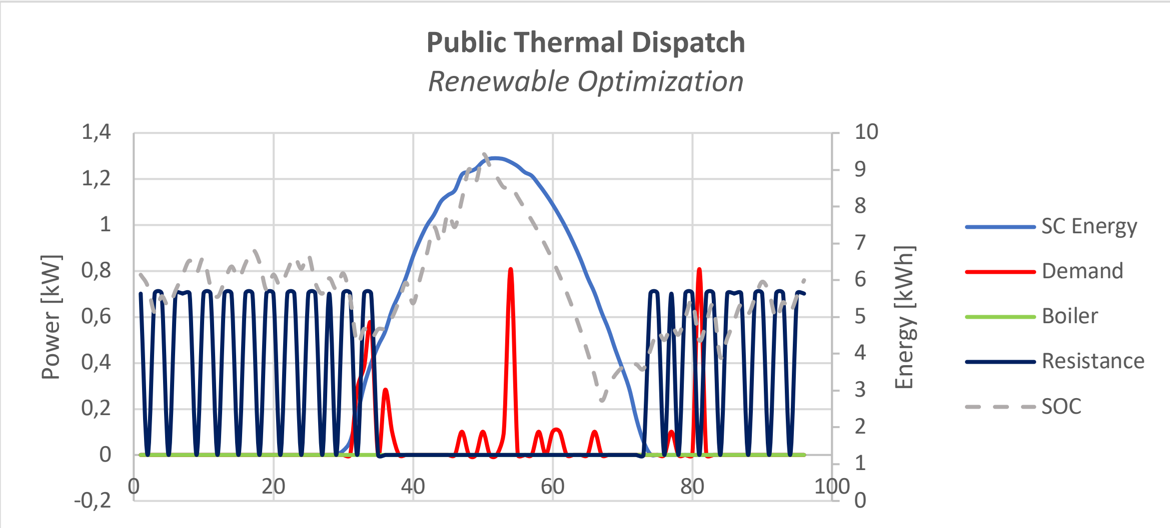


Chart 34: Domestic Thermal energy dispatch as result of Multi Energy System simulation – Only Renewable Scenario.

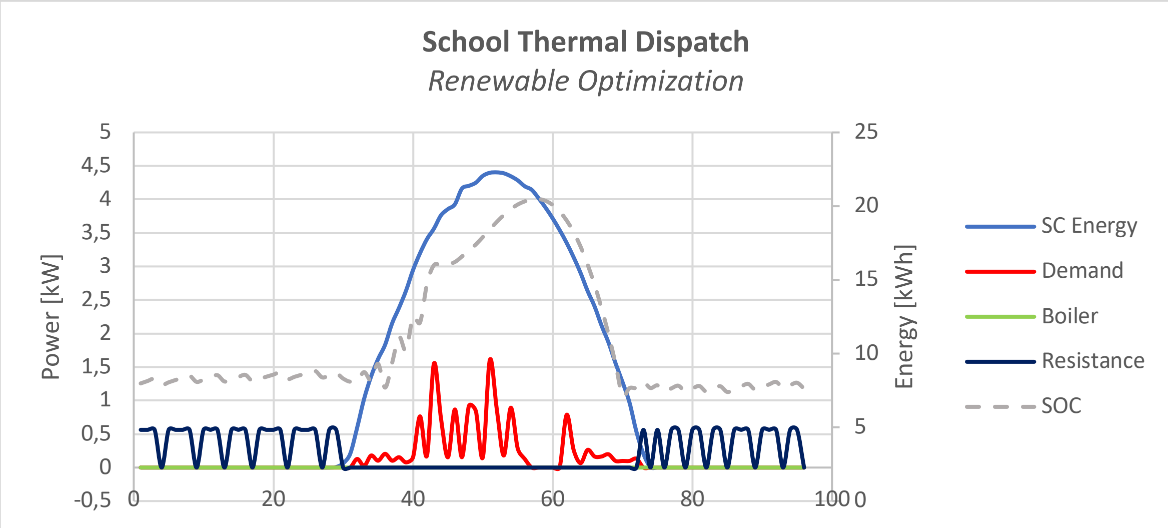


Chart 35: School Thermal energy dispatch as result of Multi Energy System simulation – Only Renewable Scenario.

In conclusion, this scenario implies a significantly larger LCOE and NPC than the baseline scenario, mostly due to the fact that peak electric and thermal demands occur in times where solar radiation is absent, leading to a significant oversizing of the storage systems and of the energy conversion technologies as well.

Table 10: Sizing of Only Renewable Scenario – Multi Energy System simulation

Only Renewable					
Economical		**Electric**		**Thermal**	
NPC [M$]	14,77	N° PV	1177	N° SC Com	44
LCOE [$/MWh]	0,476	Battery Cap [kWh]	5936,265	Tank Cap Com [kWh]	484,88
LCOE/LCOE$_{base}$	138%	Gen P Nom [kW]	0	Res P Nom Com[W]	29092
Diesel Cost [$/l]	-			Boiler P Nom Com [kW]	0
LPG Cost [$/kg]	-			N° SC Dom	261
				Tank Cap Dom [kWh]	4080,612
				Res P Nom Dom [W]	149536
				Boiler P Nom Dom [kW]	0
				N° SC Pub	1
				Tank Cap Pub [kWh]	13,576
				Res P Nom Pub [W]	701
				Boiler P Nom Pub [kW]	0
				N° SC Sch	3
				Tank Cap Sch [kWh]	35,741
				Res P Nom Sch [W]	562
				Boiler P Nom Sch [kW]	0

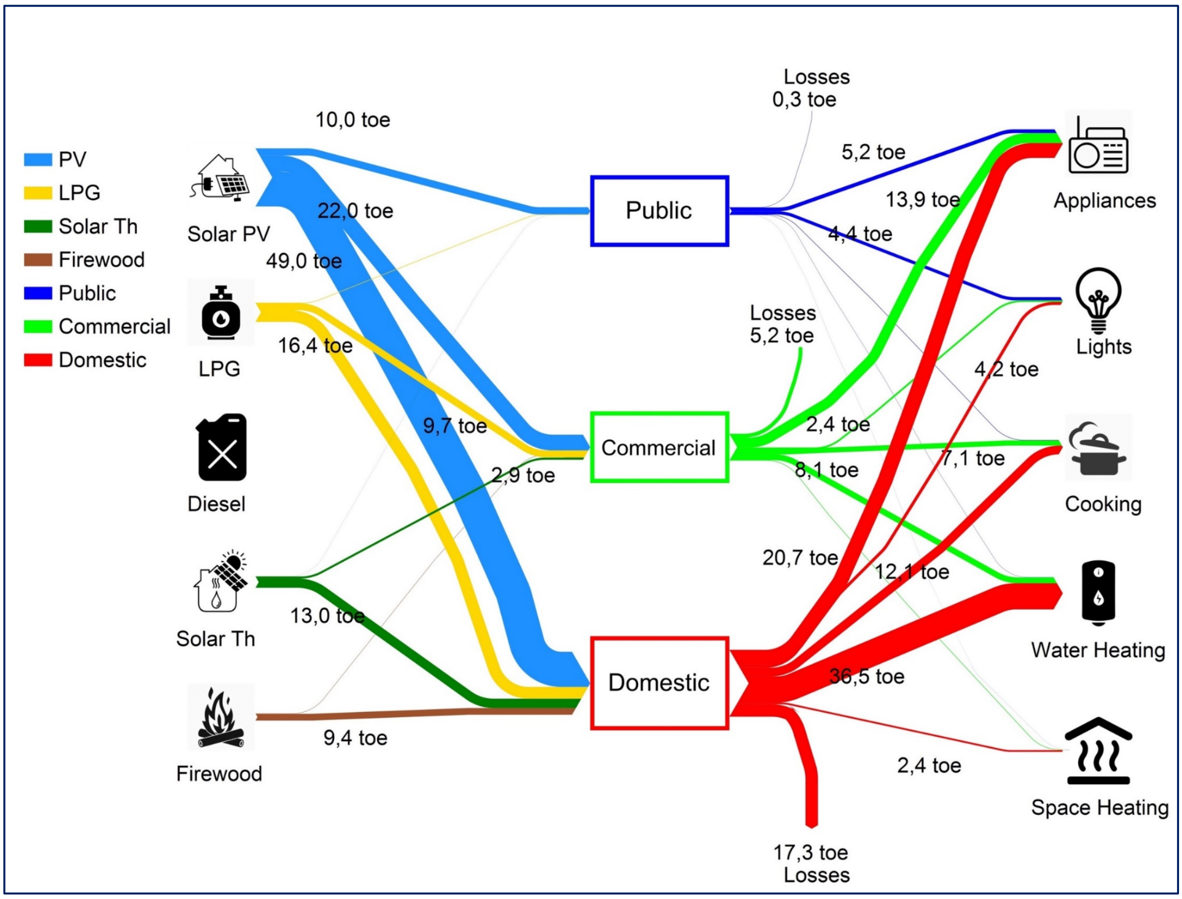


Figure 23: Sankey Diagram of the study area in third simulated scenario.

In this case the primary energy supply from outside the village decreases to 20% and the losses decrease of 76%. This is explicable with the absence of diesel entering the system and no use of LPG for water heating purposes. The LPG still present as primary energy is the gas used for cooking purposes, which are not interested by our analysis.

Finally, in Table 11 al the computed NPC and LCOE for the baseline and for all the three scenarios are presented for a better comparison of the above-mentioned parameters.

Table 11: NPC and LCOE of all considered scenarios.

	MicroGridPy		**MultiEnergySystem**	
	NPC [M$]	LCOE [$/MWh]	NPC [M$]	LCOE [$/MWh]
Base Case	7,61	0,340	10,69	0,345
Normal	5,57	0,249	8,18	0,264
Fuels +50%	6,08	0,272	9,34	0,301
OnlyRen	7,04	0,314	14,77	0,476

Conclusions

From the development of this work several considerations can be made.
First of all, the need to take into account the thermal energy consumption and production when generating scenarios to support energy policy has been clearly confirmed within the discussion of the case study. This work represented a first step towards the development of a multi-energy system modelling framework and aims to draw attention to this matter. Moreover, energy policy research ostensibly lags behind other fields in promoting more open and reproducible science [47], hence, the open-source modelling is a key factor of the proposed work.

To this regard, the inclusion of thermal energy in the model imposes a change in the time step formulation. In fact, while for electrical demands the "one hour" time step suits satisfactorily the purposes, switching to thermal loads (which are way more time-specific and have an average duration that is significantly shorter than electrical loads) a "one hour" resolution would not take them into account with sufficient precision. Hence the need to increase the time resolution of the model. Initially a "one minute" formulation was hypothesized but due to computational problems and excessive processing times the "15 minutes" formulation has been adopted with good results.

The optimization of the model is performed through a *Linear Programming* formulation. This choice is dictated by the excessive computational time that an *Integer* or *Mixed Integer Linear Programming* (MILP) would impose to the model. The *Linear Programming* is cause of some small computational errors but do not compromise the overall reliability of the results. Further development in the software structure could take into consideration those formulations.

The problems faced in the modelling of the thermal load profile of the study area with a software (LoadProGen) strictly meant to model electrical loads underline the need for the development of a proper tool, to be juxtaposed to already existing electrical models, in order to compute a whole picture of the energy consumption in rural contexts. In fact the computation of the electrical profiles from the LoadProGen software is based on a set of typical data that can be surveyed and/or assumed in rural areas; the algorithm relies on a stochastic bottom-up approach with correlations between the different load profile parameters (i.e. load factor, coincidence factor and number of consumers) in order to build up the coincidence behaviour of the electrical appliances [27]. As explained in chapter 2 the software has been properly adapted to compute also the thermal load, in the absence of alternatives in the literature, but a need for a specifically designed tool has emerged clearly.

Finally, another interesting possible future development direction of the proposed model could include other renewable energy sources besides solar energy and take into account other thermal needs such as cooking and space heating to reach a wider covering of the energy potentials and energy needs of study areas.

Appendix A

Questionnaire administered to the population. Source: Authors.

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Cuestionario Acceso Energético del Pueblo Atacameño de Toconao

1. Información General

Dirección:................ Fecha: …../..… /….…

Sexo: □ M □ F Edad: ….

1.1. Posición en la familia:

- Cabeza de Familia
- Miembro de la familia
- Otro (especificar………………………………………………………………….…….)

1.2. Edad de los miembros del hogar

	Miembro familia	Sexo	Edad	Ocupación
1				
2				
3				
4				
5				
6				

2. Uso y Suministro de Electricidad

2.1. ¿Está su casa conectada a la red eléctrica local (CESPA)? ☐ SI ☐ NO

2.2. ¿Tiene un medidor de corriente instalado en su casa? ☐ SI ☐ No

2.3. ¿Cuál es la potencia de su medidor?...kW

2.4. ¿Cuáles son los dispositivos que utilizan electricidad en la casa?

Artículos	Número	Uso diario promedio
TV		
Radio		
Cargador de teléfono		
Luces interior		
Luces exteriores		
Refrigerador		
Notebook		
Plancha eléctrica		
Hervidor		
Otros (especificar………….)		

2.5. ¿Cuál es el consumo promedio por mes? ……......... kWh

2.6. ¿Cuál es la factura promedia del hogar?...................................... CLP

2.7. ¿Cuantas horas de servicio eléctrico tienes al día? .... y después del atardecer? ....

2.8. ¿Podrías estimar cuantos cortes de luz ocurren por mes?

	N° de cortes por mes
Menos 10 minutos	
10minutos – 1 hora	
1 hora – 2 horas	
Mas 2 horas	

2.9. ¿Alguna vez ha tenido algún dispositivo dañado o roto debido a las fluctuaciones de voltaje de la red eléctrica?

………………………………………………………………………………………… ………………………………………………………………………………………… ………………

2.10. ¿Como paga su factura?

2.11. ¿Alguna vez ha tenido accidentes con electricidad en su hogar?

2.12. ¿Tienes algún comentario sobre el suministro de electricidad?

……

3. Cocina

3.1. Leña para cocinar

3.1.1. ¿Cuáles son los sistemas de cocción a leña utilizados?

- o Fuego con piedras
- o Estufa de leña
- o Estufa avanzada
- o Otros (Especificar……………………………………………………)

3.1.2. ¿Dónde se coloca la cocina a leña en su casa?

- o Dentro de la casa
- o Fuera de la casa
- o Cocina común con otros hogares

3.1.3. ¿Sobre una base semanal, cuántas comidas cocinas usando leña?

3.1.4. ¿Cuánto tiempo se necesita para que el equipo esté listo para cocinar?

3.1.5. ¿Alguna vez ha tenido accidentes con leña en su hogar?

3.2. Gas para cocinar

3.2.1. ¿Sobre una base semanal, cuántas comidas cocinas usando gas?

3.2.2. ¿Alguna vez ha tenido accidentes con gas en su hogar?

4. Calentamiento de Espacios

4.1. ¿Con qué frecuencia utiliza estos combustibles para calefacción?

	Gas	Leña
Diariamente	☐	☐
Semanalmente	☐	☐
Mensualmente	☐	☐
Anualmente	☐	☐

4.2. Calidad de la calefacción:

	Gas	Leña
¿Cuantas habitaciones de la casa son calentadas?		
¿Por cuanto tiempo tienes la calefacción que necesitas?		
¿Por cuanto tiempo tienes una temperatura agradable?		
¿En el último año tuvo accidentes en su uso?		

5. Calentamiento de Agua Sanitaria

5.1. ¿Con qué frecuencia calienta el agua sanitaria de esta manera?

	Gas	Leña	Colector Solar
Diariamente	☐	☐	☐
Semanalmente	☐	☐	☐
Mensualmente	☐	☐	☐
Anualmente	☐	☐	☐

6. Provisión de Combustibles

6.1. ¿De dónde saca la leña?

- Dentro del Pueblo, gratis
- Dentro del Pueblo comprándola, fuera del pueblo de manera gratuita
- Fuera del Pueblo comprándola
- Otros (Especificar)…………………………………………………………..

6.2. ¿Cómo se transporta la leña a su hogar?

- o A mano
- o Con moto
- o Con auto
- o Con camioneta
- o Con camión
- o Otros (Especificar)…………………………………………………………………….

6.3. ¿Cuánto tiempo se necesita para adquirir y preparar la leña?

6.4. ¿Cuánta compras? (Use el medio de transporte arriba como unidad de medida)

6.5. ¿Cuánto pagas por la leña? ………..CLP

6.6. ¿Qué tipo de botella de gas tiene (Tamaño y Marca)?

6.7. ¿Con qué frecuencia lo vuelve a llenar en promedio? Cada………………………

6.8. ¿Cuánto pagas? ……………………CLP

7. Otras Fuentes De Energía

7.1. ¿Utiliza otras fuentes de energía?

	Si/No	Propósito principal	En qué cantidad	Cuál es el costo
Carbón				
Kerosene				
Velas				
Otros (especificar………………)				

8. Producción de residuos domésticos

8.1. ¿Tiene una granja? ☐ Si ☐ No

8.2. ¿Qué tipo de cultivos tiene?

	Si/No	¿Cuál es aproximadamente la extensión?
Choclo		
Porotos		
Cereales		
Papas		
Pasto		
Vegetales		
Otros árboles frutales		

8.3. ¿Consume los productos de su granja?

- Sí, consumimos todos los productos
- Sólo se consume parte, se vende el resto
- Todo se vende

8.4. ¿Qué animales tiene usted (si los hay)?

	N°	¿Cómo los alimentas? (Elegir entre: alimentación animal, hierba / arbusto, residuos orgánicos, mezcla de piensos y cereales)
Cerdos		
Cabras		
Vacas		
Conejos		
Llamas		
Aves de corral		

Gracias por su tiempo y colaboración!

Appendix B.1

LoadProGen inputs for electric load profile generation:

Parameters for the generation	
Number of load profiles	1
Number of time step	96
Number of user classes	6
Maximum number of appliance	9
Maximum number of windows	2

Autumn Configuration

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Low_Households	202	TV	150	2	2	16	10	10	36	52	72	92
		Radio	7	1	2	16	10	10	32	48	72	92
		Phone	5	2	2	25	10	10	1	28	80	96
		Fridge	250	1	1	48	0	0	1	96	0	0
		Laptop	100	1	4	8	0	0	64	96	0	0
		Electric Iron	1000	1	1	1	0	0	40	48	0	0
		Indoor Light	60	1	2	15	10	10	75	96	0	0
		Outdoor Light	60	1	2	4	10	10	1	28	80	96

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
High_Households	130	TV	150	3	2	42	10	10	36	52	64	92
		Radio	7	1	2	15	10	10	32	48	72	92
		Phone	5	4	2	36	10	10	1	28	80	96
		Fridge	250	1	1	48	0	0	1	96	0	0
		Laptop	100	1	4	6	10	10	64	96	0	0
		Electric Iron	1000	1	1	3	10	10	40	48	0	0
		Washin Machir	500	1	2	4	0	0	36	48	0	0
		Indoor Light	60	7	2	20	10	10	75	96	0	0
		Outdoor Light	60	1	2	19	10	10	1	28	80	96

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Commercial	32	TV	150	4	2	31	10	10	36	92	0	0
		Radio	7	1	2	21	10	10	36	92	0	0
		Phone	5	2	2	27	10	10	1	96	0	0
		Fridge	250	4	1	48	0	0	1	96	0	0
		Laptop	100	1	4	12	20	20	32	92	0	0
		Indoor Light	60	13	2	18	10	10	72	96	0	0
		Outdoor Light	60	2	2	10	10	10	1	24	80	96

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Public Class	6	TV	150	4	2	32	10	10	32	80	0	0
		Radio	7	1	2	36	10	10	32	80	0	0
		Phone	5	7	2	12	10	10	32	48	0	0
		Fridge	250	1	1	48	0	0	1	96	0	0
		Laptop	100	2	4	72	20	20	1	96	0	0
		Indoor Lights	60	11	2	28	10	10	32	80	0	0
		Outdoor Lights	60	2	2	16	10	10	1	28	92	96

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
School	1	TV	150	10	2	8	10	10	32	80	0	0
		Radio	7	25	2	24	10	10	32	80	0	0
		Phone	5	40	2	16	10	10	32	80	0	0
		Fridge	250	10	1	48	0	0	1	96	0	0
		Laptop	100	25	4	32	20	20	32	80	0	0
		Indoor Lights	60	60	2	32	10	10	32	80	0	0
		Outdoor Lights	60	10	2	24	10	10	32	80	0	0

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Public_Light	1	Street Light	15004	1	16	49	10	10	1	30	74	96
		Stadium_1	12	1	4	8	10	10	72	96	0	0
		Stadium_2	794	1	4	8	10	10	72	96	0	0

Winter Configuration

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Low_Households	202	TV	150	2	2	16	10	10	36	52	72	92
		Radio	7	1	2	16	10	0	32	48	72	92
		Phone	5	2	2	25	10	0	1	28	80	96
		Fridge	250	1	1	48	0	0	1	96	0	0
		Laptop	100	1	4	8	0	0	64	96	0	0
		Electric Iron	1000	1	1	1	0	0	40	48	0	0
		Water Boiler	1000	1	1	1	20	0	28	36	64	72
		Indoor Light	60	5	2	18	10	0	72	96	0	0
		Outdoor Light	60	1	2	3	10	0	1	28	80	96

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
High_Households	130	TV	150	3	2	42	10	0	36	52	64	92
		Radio	7	1	2	15	10	0	32	48	72	92
		Phone	5	4	2	36	10	0	1	28	80	96
		Fridge	250	1	1	48	0	0	1	96	0	0
		Laptop	100	1	4	6	20	0	64	96	0	0
		Electric Iron	1000	1	1	3	10	0	40	48	0	0
		Water Boiler	1000	1	1	1	20	0	28	36	64	72
		Washin Machir	500	1	2	4	0	0	36	48	0	0
		Indoor Light	60	7	2	23	10	0	72	96	0	0
		Outdoor Light	60	1	2	19	10	0	1	28	80	96

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Commercial	32	TV	150	4	2	31	10	0	36	92	0	0
		Radio	7	1	2	21	10	0	36	92	0	0
		Phone	5	2	2	27	10	0	1	96	0	0
		Fridge	250	4	1	48	0	0	1	96	0	0
		Laptop	100	1	4	11	20	0	32	92	0	0
		Water Boiler	1000	1	1	5	20	0	48	92	0	0
		Indoor Light	60	13	2	18	10	0	72	96	0	0
		Outdoor Light	60	2	2	10	10	0	1	24	80	96

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Public Class	6	TV	150	4	2	32	10	0	32	80	0	0
		Radio	7	1	2	36	10	0	32	80	0	0
		Phone	5	7	2	12	10	0	32	48	0	0
		Fridge	250	1	1	48	0	0	1	96	0	0
		Laptop	100	2	4	72	20	0	1	96	0	0
		Water Boiler	1000	2	1	6	20	0	36	44	0	0
		Printer	25	1	1	20	0	0	32	72	0	0
		Indoor Lights	60	11	2	28	10	0	32	80	0	0
		Outdoor Lights	60	2	2	16	10	0	1	28	92	96

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
School	1	TV	150	10	2	8	10	0	32	80	0	0
		Radio	7	25	2	24	10	0	32	80	0	0
		Phone	5	40	2	16	10	0	32	80	0	0
		Fridge	250	10	1	48	0	0	1	96	0	0
		Laptop	100	25	4	32	20	0	32	80	0	0
		Water Boiler	1000	10	1	8	20	0	32	80	0	0
		Printer	25	10	1	1	0	0	32	80	0	0
		Indoor Lights	60	60	2	32	10	0	32	80	0	0
		Outdoor Lights	60	10	2	24	10	0	32	80	0	0

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Public_Light	1	Street Light	15715	1	4	13	10	10	1	7	18	96
		Stadium_1	12	1	1	2	10	0	72	96	0	0
		Stadium_2	794	1	1	2	10	0	72	96	0	0

Spring Configuration

Specific user class (*j*)	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Low_Households	202	TV	150	2	2	16	10	10	36	52	72	92
		Radio	7	1	2	16	10	0	32	48	72	92
		Phone	5	2	2	25	10	0	0	28	80	96
		Fridge	250	1	1	48	0	0	0	96	0	0
		Laptop	100	1	4	8	0	0	64	96	0	0
		Electric Iron	1000	1	1	1	0	0	40	48	0	0
		Water Boiler	1000	1	1	1	20	0	28	36	64	72
		Indoor Light	60	5	2	15	10	0	75	96	0	0
		Outdoor Light	60	1	2	3	10	0	0	28	80	96

Specific user class (*j*)	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
High_Households	130	TV	150	3	2	42	10	0	36	52	64	92
		Radio	7	1	2	15	10	0	32	48	72	92
		Phone	5	4	2	36	10	0	0	28	80	96
		Fridge	250	1	1	48	0	0	0	96	0	0
		Laptop	100	1	4	6	20	0	64	96	0	0
		Electric Iron	1000	1	1	3	10	0	40	48	0	0
		Water Boiler	1000	1	1	1	20	0	28	36	64	72
		Washin Machir	500	1	2	4	0	0	36	48	0	0
		Indoor Light	60	7	2	20	10	0	75	96	0	0
		Outdoor Light	60	1	2	19	10	0	0	28	80	96

Specific user class (*j*)	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Commercial	32	TV	150	4	2	31	10	0	36	92	0	0
		Radio	7	1	2	21	10	0	36	92	0	0
		Phone	5	2	2	27	10	0	0	96	0	0
		Fridge	250	4	1	48	0	0	0	96	0	0
		Laptop	100	1	4	11	20	0	32	92	0	0
		Water Boiler	1000	1	1	5	20	0	48	92	0	0
		Indoor Light	60	13	2	18	10	0	72	96	0	0
		Outdoor Light	60	2	2	10	10	0	0	24	80	96

Specific user class (*j*)	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Public Class	6	TV	150	4	2	32	10	0	32	80	0	0
		Radio	7	1	2	36	10	0	32	80	0	0
		Phone	5	7	2	12	10	0	32	48	0	0
		Fridge	250	1	1	48	0	0	0	96	0	0
		Laptop	100	2	4	72	20	0	0	96	0	0
		Water Boiler	1000	2	1	6	20	0	36	44	0	0
		Printer	25	1	1	20	0	0	32	72	0	0
		Indoor Lights	60	11	2	28	10	0	32	80	0	0
		Outdoor Lights	60	2	2	16	10	0	0	28	92	96

Specific user class (*j*)	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
School	1	TV	150	10	2	8	10	0	32	80	0	0
		Radio	7	25	2	24	10	0	32	80	0	0
		Phone	5	40	2	16	10	0	32	80	0	0
		Fridge	250	10	1	48	0	0	0	96	0	0
		Laptop	100	25	4	32	20	0	32	80	0	0
		Water Boiler	1000	10	1	8	20	0	32	80	0	0
		Printer	25	10	1	1	0	0	32	80	0	0
		Indoor Lights	60	60	2	32	10	0	32	80	0	0
		Outdoor Lights	60	10	2	24	10	0	32	80	0	0

Specific user class (*j*)	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Public_Light	1	Street Light	15458	1	16	48	10	10	0	30	78	96
		Stadium_1	12	1	4	8	10	0	72	96	0	0
		Stadium_2	794	1	4	8	10	0	72	96	0	0

Summer Configuration

Specific user class (*j*)	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Low_Households	202	TV	150	2	2	16	10	10	36	52	72	92
		Radio	7	1	2	16	10	0	32	48	72	92
		Phone	5	2	2	15	10	0	1	28	80	96
		Fridge	250	1	1	48	0	0	1	96	0	0
		Laptop	100	1	4	8	0	0	64	96	0	0
		Electric Iron	1000	1	1	1	0	0	40	48	0	0
		Indoor Light	60	5	2	12	10	0	78	96	0	0
		Outdoor Light	60	1	2	3	10	0	1	28	80	96

Specific user class (*j*)	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
High_Households	130	TV	150	3	2	42	10	0	36	52	64	92
		Radio	7	1	2	15	10	0	32	48	72	92
		Phone	5	4	2	36	10	0	1	28	80	96
		Fridge	250	1	1	48	0	0	1	96	0	0
		Laptop	100	1	4	6	20	0	64	96	0	0
		Electric Iron	1000	1	1	3	10	0	40	48	0	0
		Washin Machir	500	1	2	4	0	0	36	48	0	0
		Indoor Light	60	7	2	17	10	0	78	96	0	0
		Outdoor Light	60	1	2	19	10	0	1	28	80	96

Specific user class (*j*)	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh ij* [%]	*Rw ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Commercial	32	TV	150	4	2	31	10	0	36	92	0	0
		Radio	7	1	2	21	10	0	36	92	0	0
		Phone	5	2	2	27	10	0	1	96	0	0
		Fridge	250	4	1	48	0	0	1	96	0	0
		Laptop	100	1	4	11	20	0	32	92	0	0
		Indoor Light	60	13	2	18	10	0	72	96	0	0
		Outdoor Light	60	2	2	10	10	0	1	24	80	96

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Public Class	6	TV	150	4	2	32	10	0	32	80	0	0
		Radio	7	1	2	36	10	0	32	80	0	0
		Phone	5	7	2	12	10	0	32	48	0	0
		Fridge	250	1	1	48	0	0	1	96	0	0
		Laptop	100	2	4	72	20	0	1	96	0	0
		Indoor Lights	60	11	2	28	10	0	32	80	0	0
		Outdoor Lights	60	2	2	16	10	0	1	28	92	96

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
School	1	TV	150	10	2	8	10	0	32	80	0	0
		Radio	7	25	2	24	10	0	32	80	0	0
		Phone	5	40	2	16	10	0	32	80	0	0
		Fridge	250	10	1	48	0	0	1	96	0	0
		Laptop	100	25	4	32	20	0	32	80	0	0
		Indoor Lights	60	60	2	32	10	0	32	80	0	0
		Outdoor Lights	60	10	2	24	10	0	32	80	0	0

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	Rh_{ij} [%]	Rw_{ij} [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Public_Light	1	Street Light	16847	1	16	42	10	10	1	30	81	96
		Stadium_1	12	1	4	8	10	0	72	96	0	0
		Stadium_2	794	1	4	8	10	0	72	96	0	0

Appendix B.2

LoadProGen inputs for thermal load profile generation:

Parameters for the generation	
Number of load profiles	1
Number of time step	96
Number of user classes	1
Maximum number of appliance	1
Maximum number of windows	2

Commercial

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh* *ij* [%]	*Rw* *ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Commercial	1	Normal Use	336,7222	60	1	3	0	20	40	60	72	92

Domestic

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh* *ij* [%]	*Rw* *ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Domestic	1	Lunch Dish washing	1218	1	2	2	10	10	48	56	0	0
		Dinner Dish washing	1218	1	2	2	10	10	80	88	0	0
		Shower	1310	4	1	1	10	10	28	36	76	84
		Face hand washing	259	4	1	2	10	10	48	56	76	82

Public

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh* *ij* [%]	*Rw* *ij* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
Public	1	Shower	188,5644	5	1	1	0	20	28	36	0	0
		Hand Washing	67,34444	10	1	1	0	20	28	80	0	0
		Food Use	538,7556	1	1	2	0	20	48	60	76	84

School

Specific user class *(j)*	Number of users in class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle	functioning time	*Rh_{ij}* [%]	*Rw_{ij}* [%]	Starting time Win 1	Ending time Win 1	Starting time Win 2	Ending time Win 2
School	1	Kitchen Use	2747,653	4	1	3	10	10	40	64	0	0
		Face Hand Washing 1	102,5791	150	1	1	0	0	32	56	0	0
		Face Hand Washing 2	131,8874	50	1	1	0	0	62	72	0	0

Appendix C

Domestic

Nº	CALLE	NOMBRE	Nº MEDIDOR	CONSUMO kWh POR MES											
				ENERO	FEBRERO	MARZO	ABRIL	MAYO	JUNIO	JULIO	AGOSTO	SEPTIEMB.	OCTUBRE	NOVIEMBRE	DICIEMBRE
1	ABAROA		9	16	11	25	4	18	14	19	9	10	15	12	11
2	ABAROA		97117793	349	310	202	206	177	198	145	154	111	176	128	249
3	ABAROA		971177480	444	333	328	149	115	43	26	13	26	20	61	277
4	ABAROA		2005	56	53	49	41	45	34	30	26	23	50	45	56
5	ABAROA		776	96	85	92	89	79	81	54	71	72	83	76	80
6	ANTOFAGASTA		97117744	0	24	10	43	40	41	68	51	81	81	60	95
7	ANTOFAGASTA		96116206	86	80	78	69	74	61	46	55	66	89	76	88
8	ANTOFAGASTA		96164163	0	1	0	0	0	0	0	0	11	27	35	53
9	ANTOFAGASTA		97116204	94	33	11	39	42	48	55	21	11	30	44	56
10	ANTOFAGASTA		97117750	19	20	15	18	21	15	20	20	14	23	20	14
11	ANTOFAGASTA		96117785	32	50	37	14	8	1	15	19	14	18	6	15
12	ANTOFAGASTA		97117636	36	111	48	48	33	23	38	21	22	48	31	31
13	21 DE MAYO		96604087	4	3	7	8	17	10	38	1	6	8	10	5
14	21 DE MAYO		108188	21	45	45	57	66	71	69	80	101	128	110	119
15	21 DE MAYO		97117741	1	3	3	1	3	2	3	1	0	2	3	2
16	AVDA NORTE		96164306	123	101	81	48	42	30	38	39	60	81	60	83
17	AVDA NORTE		97129554	69	52	29	29	26	20	22	20	23	29	31	32
18	AVDA NORTE		96604028	261	294	118	113	116	93	96	93	100	97	79	105
19	AVDA NORTE		96604083	57	74	44	41	48	29	35	26	22	29	23	27
20	AVDA NORTE		96604029	345	314	271	276	325	323	359	315	368	440	351	354
21	AVDA NORTE		245466	200	237	194	113	54	42	66	45	93	140	86	108
22	AVDA NORTE		96164082	40	28	56	61	41	87	65	81	60	123	174	76
23	AVDA NORTE		97129589	183	135	109	117	105	112	147	104	125	164	143	179
24	AVDA NORTE		96603558	10	15	10	12	16	16	19	1	0	1	0	0
25	QUIMAL		1224960	89	175	0	68	67	86	40	0	57	81		
26	QUIMAL		244264	365	342	302	306	253	374	461	295	295	290	217	254
27	IQUIQUE		243514	26	18	41	43	51	81	141	104	134	102	89	79
28	IQUIQUE		96603378	38	53	31	39	38	36	35	36	42	47	47	48
29	IQUIQUE		1207849	2	2	1	1	6	4	8	7	9	3	1	1
30	IQUIQUE		96164156	669	535	479	454	435	354	460	359	406	531	380	457
31	IQUIQUE		96604025	140	114	108	118	90	101	104	108	110	133	110	117
32	IQUIQUE		127865	292	257	253	254	214	184	272	229	217	266	253	263
33	IQUIQUE		7704972	30	101	18	119	97	80	78	29	68	102	37	85
34	IQUIQUE		120008591	239	199	160	120	95	58	99	85	49	71	69	94
35	IQUIQUE		96164158	22	12	15	21	27	27	27	24	24	23	19	20
36	INTERNACIONAL		96164320	194	134	96	130	279	168	140	130	120	184	127	148
37	ATACAMA		603876	2	5	8	7	10	5	17	5	16	14	13	10
38	ATACAMA		96603375	5	139	0	2	0	0	0	0	0	6	2	30
39	ATACAMA		1207066	200	61	113	111	104	71	119	123	118	128	100	109
40	ATACAMA		97117760	35	130	16	0	2	10	29	23	9	37	13	3
41	ATACAMA		96164087	148	283	156	91	94	71	80	73	76	67	52	132
42	ATACAMA		96164157	155	147	150	144	123	119	133	115	138	141	130	141
43	ATACAMA		96164167	40	37	40	42	53	91	133	39	36	29	19	23
44	ATACAMA		95030036	281	136	238	109	133	123	142	103	143	153	131	155
45	ATACAMA		96164299	104	124	54	60	72	67	94	66	65	89	62	66
46	ATACAMA		97117635	119	124	106	101	131	133	165	95	102	97	35	68
47	ATACAMA		90203009291	12	14	5	25	18	6	6	2	0	3	2	0
48	ATACAMA		2238676	39	38	17	31	25	49	66	26	29	26	27	24
49	ATACAMA		96164304	0	10	100	107	93	91	42	80	80	83	78	67
50	ATACAMA		96604081	52	1	33	25	19	30	10	22	26	25	26	25
51	ATACAMA		96164164	45	13	69	75	23	0	1	0	0	0	0	0
52	ATACAMA		97129583	9	29	65	107	178	36	54	45	70	88	83	92
53	LASCAR		97117795	109	124	92	81	80	68	77	71	76	87	104	51
54	LASCAR		96603424	139	153	130	152	142	116	120	136	114	168	163	253
55	LASCAR		97129593	0	105	135	87	105	109	131	57	91	100	126	147
56	LASCAR		97603960	96	29	47	36	95	69	94	33	34	46	58	101
57	LASCAR		97129590	71	85	46	85	193	405	635	441	271	29	45	34
58	LASCAR		97129581	7	24	8	2	6	19	12	14	2	6	18	7
59	LASCAR		720004077	85	55	25	6	4	0	4	1	0	0	0	0
60	LASCAR		97604089	107	137	118	114	198	14	174	0	122	82	99	61
61	LASCAR		97164295	166	185	140	161	181	196	192	153	157	147	193	157
62	LASCAR		96603335	22	22	21	19	20	24	30	23	22	23	26	20
63	LASCAR		1207864	193	205	195	206	206	193	206	178	167	177	211	186
64	LASCAR		97603552	102	129	117	127	130	117	174	115	114	4	0	0
65	LASCAR		97603389	157	139	120	184	186	142	170	174	122	112	80	35
66	LASCAR		1845282	17	15	11	18	20	10	8	11	9	11	11	10
67	LASCAR		97603390	286	229	237	234	215	204	216	221	183	51	131	31
68	LASCAR		81560	35	32	33	30	29	27	95	71	32	33	56	35
69	LASCAR		97117317	61	136	42	36	32	30	31	29	35	36	74	42
70	LASCAR		97604022	64	81	67	55	52	35	44	46	49	63	40	26
71	LASCAR		270334	11	38	7	57	32	24	35	19	7	7	14	13
72	LASCAR		97117393	58	54	40	40	54	39	76	49	49	58	71	64
73	LASCAR		20110608071	9	8	6	2	8	4	0	7	7	0	29	4
74	LASCAR		97129524	51	27	8	5	0	46	40	30	32	30		
75	LASCAR		1207862	8	8	3	5	7	7	10	6	6	7	8	5
76	LASCAR		97117031	148	160	130	122	101	108	112	107	109	140	143	133
77	LASCAR		4078750	82	65	26	45	40	34	54	81	46	40	25	20
78	LASCAR		97117397	174	184	108	102	117	90	160	104	99	130	164	157
79	LASCAR		1286521	57	90	109	139	253	291	365	224	102	115	99	46
80	LASCAR		97117794	21	203	8	1	6	4	46	9	39	40	25	8
81	LASCAR		97117394	4	11	4	3	4	2	0	3	0	2	3	0
82	LASCAR		963388	14	51	16	16	10	5	6	8	13	16	16	2
83	LASCAR		603557	197	202	143	140	134	148	172	135	140	188	155	158
84	LASCAR		97117707	241	242	223	244	227	205	241	212	210	272	231	208
85	LASCAR		128653	154	141	86	91	95	92	119	90	169	195	151	152
86	LASCAR		1409778	0	9	11	6	0	1	12	7	20	38	11	4
87	LASCAR		96603877	160	209	147	167	191	176	178	193	163	208	209	175
88	LASCAR		13399	0	1	0	0	0	0	20	35	32	58	47	57
89	LASCAR		4426	108	103	90	91	102	90	117	99	105	146	162	177
90	LASCAR		96603425	34	49	49	28	34	42	23	17	25	57	63	67

91	LASCAR		96603956	32	31	27	28	28	26	27	24	27	41	33	35
92	LASCAR		26372	153	156	156	174	204	218	168	133	128	176	164	170
93	LASCAR		96164310	28	30	31	15	6	7	9	14	16	7	10	0
94	LASCAR		27956	53	44	34	44	31	33	39	56	76	92	69	71
95	LASCAR		97117704	51	54	48	50	53	52	52	39	48	66	54	56
96	LASCAR		246018	100	79	49	42	39	26	45	17	17	23	25	14
97	LASCAR		2015010989	209	362	43	189	288	610	492	431	114	147		
98	P. DE VALDIVIA		96603872	55	46	43	29	27	27	30	30	27	51	45	47
99	P. DE VALDIVIA		2078560	78	52	4	3	1	2	14	2	2	4	3	12
100	P. DE VALDIVIA		97117398	0	0	3	1	1	1	4	4	0	1	1	1
101	P. DE VALDIVIA		96603951	3	3	1	1	0	0	26	0	5	1	0	5
102	P. DE VALDIVIA		920005158	205	203	175	183	159	135	154	129	145	183	160	180
103	P. DE VALDIVIA		97117312	286	282	203	232	222	208	242	183	198	269	222	247
104	EL BOSQUE		97128651	150	243	136	204	190	186	181	180	181	356	191	
105	EL BOSQUE		244355	115	71	69	78	65	51	86	66	77	89	73	72
106	EL BOSQUE		96604084	58	88	12	16	19	14	25	20	17	17	14	12
107	EL BOSQUE		96164312	0	40	22	1	6	4	24	8	29	5	1	1
108	EL BOSQUE			0	0	8	4	0		12	0	0	0	0	0
109	O'HIGGINS		27129525	40	39	72	52	45	37	79	39	15	8	4	31
110	O'HIGGINS		96603374	72	199	56	10	46	19	242	45	60	76	72	26
111	O'HIGGINS		3934696	53	118	49	38	53	43	53	44	66	62	62	45
112	O'HIGGINS		96164155	2	5	0	1	6	33	45	38	0	26	52	0
113	O'HIGGINS		96164313	86	92	83	91	67	60	67	62	59	72	75	60
114	O'HIGGINS		96603380	59	47	45	44	41	40	47	41	45	54	57	48
115	O'HIGGINS		961640842	10	32	21	28	5	3	7	11	13	11	2	13
116	O'HIGGINS		96164301	0	1	8	1	0	0	0	1	0	73	59	71
117	O'HIGGINS		164161	8	2	12	6	1	0	8	2	1	2	5	3
118	O'HIGGINS		96603373	98	99	111	125	107	96	86	94	113	143	128	131
119	O'HIGGINS		96603379	12	42	0	0	0	6	25	5	1	5	2	2
120	O'HIGGINS		96603369	21	33	13	20	32	24	24	22	20	30	36	36
121	O'HIGGINS		96603376	57	91	69	49	39	28	53	38	38	50	53	53
122	O'HIGGINS		120002907	14	140	40	20	29	33	49	40	41	35	52	14
123	O'HIGGINS		1207850	6	50	12	1	0	0	13	0	2	2	8	1
124	O'HIGGINS		97128654	19	12	3	19	21	20	21	15	14	18	46	34
125	O'HIGGINS		96603560	1	35	6	0	18	9	23	14	17	21	36	40
126	O'HIGGINS		1207869	57	37	58	56	53	63	52	61	72	78	61	66
127	O'HIGGINS		920017970	0	32	36	43	61	92	42	57	49	51	41	52
128	O'HIGGINS		96164089	124	173	129	123	126	183	318	83	83	109	94	96
129	O'HIGGINS		96164317	5	21	3	2	4	5	4	4	2	4	5	9
130	O'HIGGINS		129984	100	92	85	84	82	103	91	70	71	83	71	73
131	O'HIGGINS		96164298	86	89	96	85	92	66	135	83	83	76	68	88
132	O'HIGGINS		27789	229	252	155	168	156	144	192	158	173	189	177	162
133	COPIAPO		20070352585	103	116	103	90	91	91	89	8	98	105	107	95
134	COPIAPO		97223285	57	140	92	88	55	37	36	45	52	61	65	73
135	COPIAPO		3749172	159	128	123	124	146	180	238	172	156	149	124	139
136	COPIAPO		97129527	231	238	178	168	191	159	170	178	168	193	164	173
137	COPIAPO		8711761	184	180	170	169	173	170	184	173	185	161	135	136
138	COPIAPO		1101093178	48	48	56	55	57	50	49	43	52	57	54	55
139	COPIAPO		2260368	167	165	187	173	174	151	158	149	141	158	172	154
140	COPIAPO		27855	0	2	4	2	2	17	40	78	11	6	8	3
141	COPIAPO		97129528	110	140	145	131	140	123	144	124	118	116	117	129
142	COPIAPO		129530	3	25	175	104	30	0	9	3	3	189	230	189
143	COPIAPO		243737	389	339	232	206	201	183	207	177	209	211	198	206
144	COPIAPO		97129529	156	130	135	116	119	98	120	138	150	144	146	111
145	COPIAPO		129582	135	130	117	140	141	130	156	134	129	140	142	144
146	COPIAPO		27926	17	76	20	16	14	14	20	8	20	33	41	3
147	COPIAPO		97128836	139	133	17	8	9	15	91	18	15	14	42	43
148	COPIAPO		96603367	219	240	213	238	245	250	260	234	240	230	266	226
149	COPIAPO		1207855	80	76	72	67	81	64	88	45	45	40	48	59
150	COPIAPO		8728337	160	218	165	107	150	379	384	35	131	182	163	155
151	COPIAPO		26390	185	192	142	161	175	177	162	120	132	158	162	166
152	COPIAPO		97128833	16	17	14	14	47	111	84	53	63	77	54	44
153	COPIAPO		97129526	6	102	2	10	2	18	0	2	0	17	17	6
154	COPIAPO		27805	102	113	88	64	65	82	87	80	85	88	93	77
155	COPIAPO		97117798	150	136	132	116	118	131	185	97	110	126	119	123
156	COPIAPO		27847	110	133	93	87	86	73	74	67	73	110	70	93
157	COPIAPO		971177460	3	7	7	13	14	15	21	19	21	25	15	17
158	COPIAPO		920007407	10	23	7	4	8	1	23	9	13	1	3	10
159	COPIAPO		97117754	302	241	137	61	65	51	52	50	50	66	64	56
160	COPIAPO		26370	31	22	16	19	28	31	128	64	87	63	36	39
161	COPIAPO		97117752	20	21	3	1	6	0	7	14	0	2	4	4
162	COPIAPO		27294	14	12	12	10	11	12	13	10	9	13	14	13
163	COPIAPO		97117757	12	16	18	14	14	7	11	17	18	16	9	10
164	COPIAPO		27339	16	12	8	10	13	12	14	4	18	23	19	21
165	COPIAPO		128656	31	52	33	26	44	54	68	7	21	22	14	18
166	COPIAPO		96164086	4	0	0	0			2	36	48	60	38	45
167	COPIAPO		201403011173	10	5	107	147	156	42	126	162	150	118	106	99
168	COPIAPO		97129597	58	29	100	207	134	167	113	183	81	125	144	124
169	PSJ COPIAPO		720003002	8	16	4	24	17	30	0	0	1	139	158	171
170	PSJ COPIAPO		97118838	95	87	91	91	90	90	98	84	88	92	98	106
171	PSJ COPIAPO		244558	66	159	0	161	62	75	83	59	65	73	76	73
172	PSJ COPIAPO		2003042182	250	22	143	126	118	186	247	179	144	199	222	190
173	PSJ COPIAPO		97117755	2	24	63	39	51	49	30	44	49	63	70	53
174	PSJ COPIAPO		20070352758	117	36	113	85	90	86	92	87	95	94	99	119
175	PSJ COPIAPO		20070352753	100	85	72	74	86	70	85	80	53	71	73	89
176	PSJ COPIAPO		20070353985	0	0	0	33	40	24	33	7	25	23	21	43
177	18 DE OCTUBRE		97129588	33	41	39	32	29	25	34	30	24	37	37	33
178	18 DE OCTUBRE		2003042185	161	181	169	155	149	143	142	123	129	143	132	140
179	18 DE OCTUBRE		1207871	99	76	91	47	77	67	71	45	53	83	49	65
180	18 DE OCTUBRE		96603366	176	168	169	196	160	120	142	129	140	186	186	176
181	18 DE OCTUBRE		96164302	0	14	1	0	13	16	0	46	0	0	0	0
182	18 DE OCTUBRE		96164168	68	68	62	69	69	58	64	58	49	55	54	55
183	18 DE OCTUBRE		96164162	182	195	190	65	114	93	63	75	115	149	116	131
184	18 DE OCTUBRE		96164159	72	95	82	76	91	71	69	84	60	96	88	82
185	18 DE OCTUBRE		96603873	0	18	47	25	0	0	0	0	0	18	23	2
186	18 DE OCTUBRE		96603552	76	88	103	99	107	95	107	83	90	111	93	70
187	18 DE OCTUBRE		96603364	0	14	2	1	5	1	2	5	0	8	11	6
188	18 DE OCTUBRE		96164307	1	143	6	1	1	1	1	1	0	7	28	9
189	18 DE OCTUBRE		2260367	518	530	318	30	36	41	48	37	36	42	43	40
190	18 DE OCTUBRE		4465736	53	199	54	37	54	36	50	38	53	57	63	50
191	18 DE OCTUBRE		97128555	1	6	2	0	1	0	12	0	4	2	1	0
192	18 DE OCTUBRE		96164081	41	79	51	14	56	34	60	42	38	57	56	49
193	18 DE OCTUBRE		97128831	15	109	1	0	0	0	27	6	17	0	1	0
194	18 DE OCTUBRE		97128659	9	42	0	2	9	3	9	9	7	3	4	4
195	18 DE OCTUBRE		96164152	14	23	16	17	19	13	16	20	15	30	28	15
196	18 DE OCTUBRE		96603372	36	13	30	35	28	18	19	28	31	29	26	17
197	18 DE OCTUBRE		96604027	21	9	8	13	7	8	14	4	11	5	6	1
198	18 DE OCTUBRE		96603871	72	156	76	54	88	92	88	92	68	94	81	65
199	18 DE OCTUBRE		97129599	0	13	1	139	123	116	73	100	119	138	120	89
200	18 DE OCTUBRE		96603384	7	37	1	1	3	4	10	7	6	25	17	6

201	18 DE OCTUBRE		96603880	93	127	43	97	7	8	163	94	48	62	115	90
202	18 DE OCTUBRE		96603370	41	40	32	28	23	19	21	18	21	27	25	26
203	LA TORRE		97116201	0	91	17	21	7	10	2	10	13	2	3	0
204	LA TORRE		96164308	25	113	38	16	4	52	10	10	2	2	17	14
205	LA TORRE		96603371	104	90	87	81	87	77	130	121	117	104	95	94
206	LA TORRE		97128840	103	122	93	125	109	102	115	103	118	141	130	131
207	LA TORRE		12	4	14	7	0	4	0	1	0	3	1	4	3
208	LA TORRE		96603429	48	63	50	56	32	39	40	36	40	50	50	52
209	LA TORRE		96604082	41	94	70	77	82	86	98	64	54	78	70	62
210	LA TORRE		103829	102	106	72	90	104	115	107	102	120	110	90	111
211	LA TORRE		96164083	0	108	32	9	0	56	52	18	2	21	0	6
212	LA TORRE		96164292	106	117	87	95	105	110	105	92	88	113	96	91
213	LA TORRE		96164309	113	134	54	32	28	33	44	33	30	21	33	31
214	LA TORRE		1207861	16	16	20	64	116	174	187	85	53	36	30	37
215	LA TORRE		96164291	0	11	17	7	3	24	0	7	0	16	3	28
216	LA TORRE		96603430	86	112	84	83	76	72	79	70	64	57	118	89
217	LA TORRE		95030037	168	179	61	44	34	50	46	29	31	65	64	56
218	LA TORRE		96603426	0	0	0	1	0	0	5	3	1	0	2	2
219	LA TORRE		96603553	129	105	84	86	88	89	119	83	97	72	78	100
220	LA TORRE		96164170	165	163	163	162	170	160	173	136	157	95	44	48
221	LA TORRE		98111780	0	1	1	0	1	2	3	3	2	3	0	3
222	LA TORRE		120007835	6	15	6	9	10	16	28	14	10	14	17	21
223	ESMERALDA		11066597	114	108	107	110	115	117	112	120	80	116	111	93
224	ESMERALDA		97128839	222	254	233	408	386	380	419	296	348	390	346	310
225	ESMERALDA		97129523	131	173	104	80	99	91	95	87	111	116	112	85
226	ESMERALDA		97117753	188	203	167	137	156	205	324	183	152	127	124	123
227	ESMERALDA		243934	249	289	115	95	101	100	144	84	123	123	104	97
228	ESMERALDA		97112587	20	81	8	10	7	6	29	8	8	13	17	8
229	ESMERALDA		97117756	0	24	97	0	0	116	0	0	0	0	0	0
230	ESMERALDA		11056045	69	60	56	48	45	48	35	33	35	57	40	18
231	ESMERALDA		20070333832	0	7	7	5	10	9	25	15	8	12	18	18
232	ESMERALDA		20070335153	0	0	6	4	0	13	31	29	25	13	16	11
233	JOSE M. C		97116208	145	98	128	63	53	57	40	24	25	29	32	84
234	JOSE M. C		96117400	146	154	145	131	145	169	169	146	128	135	117	124
235	JOSE M. C		97117797	117	120	78	75	67	78	185	110	116	94	88	79
236	JOSE M. C		97117743	0	0	98	39	24	18	7	0	0	0	0	0
237	JOSE M. C		96603594	12	28	21	11	13	13	39	36	25	20	13	7
238	JOSE M. C		96603954	87	139	175	164	175	139	172	161	177	193	180	203
239	HUAYTIQUINA		97117318	7	5	3	4	5	7	7	0	6	19	16	16
240	HUAYTIQUINA		97117316	124	142	97	96	89	79	73	71	94	109	92	97
241	HUAYTIQUINA		97117396	70	114	78	67	65	38	63	38	46	40	33	34
242	HUAYTIQUINA		96603950	78	75	61	58	65	47	55	95	10	62	53	53
243	HUAYTIQUINA		97117637	39	40	52	25	25	21	23	38	84	31	68	67
244	HUAYTIQUINA		95030033	75	50	74	76	78	73	90	68	80	84	70	72
245	HUAYTIQUINA		96603957	0	0	0	0		0	28	57	80	68	27	13
246	HUAYTIQUINA		97117975	71	148	43	36	42	34	66	54	48	99	74	122
247	HUAYTIQUINA		97117977	265	25	0	0	61	0	0	0	85	26	20	20
248	HUAITIQUINA		97111715	65	47	49	52	56	46	52	44	47	54	46	49
249	HUAYTIQUINA		97117313	21	90	7	0	4	1	37	10	1	12	1	3
250	HUAYTIQUINA		97117319	8	23	8	2	1	2	4	1	35	30	24	34
251	HUAYTIQUINA		97116203	34	45	34	32	23	19	20	19	25	34	29	39
252	HUAYTIQUINA		7502	32	26	44	53	37	80	51	10	6	36	43	5
253	HUAYTIQUINA		97117633	100	84	78	83	64	64	61	61	72	93	79	69
254	HUAYTIQUINA		97117702	7	27	17	8	18	23	18	19	15	35	22	9
255	HUAYTIQUINA		97117399	1	60	12	3	1	0	35	0	0	1	0	1
256	HUAYTIQUINA		97117395	98	76	75	83	71	34	38	31	47	88	79	80
257	HUAYTIQUINA		97117976	21	17	20	21	0	29	11	11	14	16	16	21
258	HUAYTIQUINA		97117706	252	278	191	174	132	34	0	1	0	1	6	3
259	HUAYTIQUINA		96164085	81	96	96	70	60	80	101	81	95	114	72	96
260	HUAYTIQUINA		96603959	344	328	308	313	314	254	250	196	242	275	301	275
261	HUAYTIQUINA		971162071	3	25	5	6	3	2	7	3	5	17	17	3
262	HUAYTIQUINA		97117709	35	7	13	99	198	319	293	193	175	81	4	0
263	HUAYTIQUINA		97116205	207	163	159	173	183	322	301	135	149	157	143	173
264	HUAYTIQUINA		97116210	96	100	60	66	63	63	92	46	55	70	56	48
265	CALAMA			125	119	123	128	122	123	114	111	92	129	123	111
266	CALAMA		1207858	28	40	1	3	0	2	13	4	7	7	7	5
267	CALAMA		2261694	259	226	33	17	15	134	238	93	118	177	138	170
268	CALAMA		97128835	90	52	91	69	44	56	96	88	85	110	93	72
269	CALAMA		2242622	24	26	0	0	0	0	9	0	0	5	0	0
270	CALAMA		96603559	191	186	157	126	144	126	112	119	121	131	112	115
271	CALAMA		96603423	59	28	43	56	71	57	62	53	45	59	54	37
272	CALAMA		96603555	150	166	147	174	150	128	135	106	122	133	102	105
273	CALAMA		96604021	186	211	178	197	214	164	146	126	113	137	118	108
274	CALAMA		96603875	27	0	11	0	17	15	0	25	13	8	11	17
275	CALAMA		96164305	84	93	40	37	34	43	85	32	45	75	58	73
276	CALAMA		96603879	16	61	0	67	0	34	0	107	50	60	7	45
277	CALAMA		207867	27	37	29	28	35	32	38	35	37	41	32	33
278	CALAMA		96164318	78	88	51	66	54	38	40	36	28	46	45	45
279	CALAMA		96164316	178	214	156	150	136	103	167	180	119	139	112	96
280	CALAMA		96604030	1	12	2	0	5	15	8	11	0	153	59	23
281	CALAMA		96164314	130	209	158	104	103	111	142	139	37	85	101	90
282	CALAMA		1845377	0	27	8	7	20	18	27	21	28	32	63	88
283	CALAMA		96164319	71	80	64	100	102	79	106	40	29	50	58	39
284	CALAMA		966035540	53	52	48	41	59	40	16	39	33	60	38	41
285	CALAMA		777	182	34	76	24	45	47	99	60	55	82	75	61
286	CALAMA		1114134	7	67	71	77	82	84	93	87	73	87	78	64
287	VILACO		20110607427	88	94	85	100	97	83	77	69	69	78	75	70
288	VILACO		20070352777	0	30	23	18	18	17	25	19	19	24	19	21
289	VILACO		20020334859	112	96	115	100	91	115	125	106	95	109	107	113
290	VILACO		20100905738	125	143	112	112	116	108	117	111	116	129	21	217
291	VILACO		96603878	62	59	53	44	29	35	40	42	47	58	68	66
292	VILACO		11845282	129	125	94	96	84	107	127	110	85	114	90	103
293	VILACO		20070334763	204	187	243	207	228	237	201	158	187	232	207	195
294	VILACO		16565989	36	33	31	33	48		40	51	68	86	87	91
295	VILACO			61	70	106	96	109	46	73	73	78	108	85	41
296	VILACO		200910204836	276	149	49	21	8	72	64	118	163	143	121	118
297	VILACO		120007075	120	112	21	82	104	93	90	76	89	100	92	90
298	VILACO		720003511	93	297	209	215	211	209	312	167	171	218	231	196
299	VILACO		20070334472	106	80	90	92	94	88	102	85	109	104	110	96
300	VILACO		20070333900	85	85	93	86	89	70	131	85	78	99	107	98

301	VILACO		20070334474	229	190	149	96	84	42	97	80	19	98	51	70
302	VILACO		3907340	192	145	135	138	132	134	152	117	122	169	134	135
303	VILACO		20070353539	183	183	204	173	122	176	181	172	191	200	163	176
304	VILACO		2015011490	65	89	145	36	89	77	82	85	86	109	99	105
305	VILACO		20070334984	166	62	105	52	84	80	87	67	78	95	87	82
306	VILACO		27000334510	1	1	3	13	11	8	13	4	8	8	10	6
307	VILACO		100019	45	47	44	48	58	48	58	49	44	48	48	45
308	VILACO		131700381175	101	103	93	97	91	91	72	88	95	109	97	103
309	VAYTIQUNA		935281	22	19	8	28	21	21	10	31	31	46		1
310	ONAR		201206111214	65	278	141	140	149	156	133	113	105	152	150	171
311	ONAR		97129508	0	58	12	12	1	6	3	0	5	9	7	0
312	VAITIQUINA		20110602933	134	156	99	96	91	70	99	60	90	115	123	99
313	VAITIQUINA		20110602934	161	222	177	159	141	154	174	166	152	175	151	159
314	VAITIQUINA		200110604225	52	21	53	20	45	7	54	87	70	84	104	102
315	VAITIQUINA		20091003570	96	97	90	97	96	87	110	109	104	122	113	109
316	VAITIQUINA		20110604069	39	39	40	40	37	33	34	33	37	46	61	44
317	VAITIQUINA		2013112674801	54	71	67	72	44	59	67	50	65	76	72	55
318	VAITIQUINA		2015011519	110	108	111	114	103	91	94	86	78	76	71	67
319	VAITIQUINA		20110604259	142	133	104	100	94	64	90	102	100	118	110	112
320	VAITIQUINA		20110604777	76	64	65	53	101	105	94	58	80	77	53	52
321	VAITIQUINA		20110604627	162	171	132	125	114	87	107	110	113	96	89	104
322	VAITIQUINA		20091010438	87	132	157	158	128	109	155	117	108	126	109	105
323	VAITIQUINA		10086418	114	90	105	107	90	77	80	83	81	103	92	88
324	VAITIQUINA		20110604023	20	63	29	19	30	18	19	13	32	25	35	8
325	VAITIQUINA		10086879	105	129	131	121	117	171	135	98	112	141	137	110
326	LIPARITA		20070334241	24	21	28	32	14	18	15	3	1	2	18	26
327	LIPARITA		806202	26	46	49	44	53	42	47	48	33	61	54	45
328	LIPARITA		20070334079	136	140	140	140	139	129	103	93	80	100	75	138
329	PSJ VILACO		3421703	102	68	39	47	71	42	44	24	34	38	38	47
330	PSJ VILACO		717	13	110	36	0	6	0	3	11	14	15	14	0
331	PSJ VILACO		20110004893	63	70	53	188	16	11	12	15	16	17	23	20
332	PSJ VILACO		2040202552010	24	42	7	7	0	1	4	10	10	17	6	6
				ENERO	FEBRERO	MARZO	ABRIL	MAYO	JUNIO	JULIO	AGOSTO	SEPTIEMB.	OCTUBRE	NOVIEMBRE	DICIEMBRE

Commercial

Nº	CALLE	NOMBRE	Nº MEDIDOR	CONSUMO KW POR MES											
				ENERO	FEBRERO	MARZO	ABRIL	MAYO	JUNIO	JULIO	AGOSTO	SEPTIEMB.	OCTUBRE	NOVIEMBRE	DICIEMBRE
1	ABAROA	COMERCIAL	97129585	386	410	426	377	421	310	359	270	265	300	324	350
2	21 DE MAYO	CLUB TOCONAO	201308284192	41	45	46	8	16	1	27	3	16	38	25	15
3	21 DE MAYO	COMERCIAL	97117747	200	216	194	168	106	78	131	145	149	200	175	200
4	AVDA NORTE	EMPRESA P Y P	201508042330										114	91	
5	INTERNACIONAL	COMERCIAL	97117632	864	759	737	701	683	569	677	628	585	753	599	645
6	INTERNACIONAL	COMERCIAL	3490563	1158	937	827	890	860	720	876	819	754	1040	805	924
7	ATACAMA	CLUB DEPORTIVO ESTRELLA	96164151	31	31	1	3	20	4	12	67	14	24	44	62
8	LASCAR	NEGOCIO	920007049	184	212	146	131	105	101	92	101	103	125	151	150
9	LASCAR	NEGOCIO	97128832	336	337	300	259	208	168	197	220	207	263	267	194
10	LASCAR	RESTAURANT	97603381	278	266	191	173	147	81	104	99	100	123	132	106
11	LASCAR	NEGOCIO	97129592	1077	1245	1015	1101	964	641	806	770	821	1004	1116	1075
12	LASCAR	EMPRESA	20110612748	293	336	273	332	374	359	348	313	294	328	268	254
13	P. DE VALDIVIA	ARTESANIA	96644169	246	354	226	292	201	162	179	156	173	225	201	197
14	P. DE VALDIVIA	ARTESANIA	96603362	83	99	72	90	81	48	76	49	85	110	88	69
15	P. DE VADIVIA	NEGOCIO	97117391	303	261	229	252	234	188	232	196	198	246	270	212
16	EL BOSQUE	NEGOCIO	97117749	121	93	47	53	72	78	70	80	85	137	132	74
17	O'HIGGINS	NEGOCIO	2007767271	298	319	229	187	159	120	111	120	171	265	273	288
18	O'HIGGINS	RESTAURANT	11057732	832	918	773	806	764	675	699	637	687	825	781	733
19	18 DE OCTUBRE	LIPIGAS	96117758	100	122	118	78	32	28	41	35	35	37	34	44
20	18 DE OCTUBRE	ENTEL CHLE S.A	92036286	2688	2710	2569	2240	2392	2184	2400	1751	2744	2603	2455	2619
21	18 DE OCTUBRE	ENTEL CHILE PCS	101066	299	2325	2161	1827	2103	1803	1978	1957	1696	2128	1970	2112
22	HUAYTIQUINA	NEGOCIO	97117980	446	122	0	171	305	219	253	31	302	379	341	350
23	HUAYTIQUINA	NEGOCIO	10085702	793	674	643	647	563	467	528	468	543	635	575	666
24	HUAYTIQUINA	NEGOCIO	97117974	334	351	73	30	88	63	75	133	223	218	247	246
25	HUAYTIQUINA	RESTAURANT	97117800	493	561	337	332	248	204	329	303	365	435	413	412
26	HUAYTIQUINA	RESTAURANT	96603363	264	253	72	28	8	0	0	0	0	0	0	0
27	HUAYTIQUINA	NEGOCIO	98207899	383	333	312	306	255	159	181	180	219	324	291	309
28	HUAYTIQUINA	CASA HOSTAL	601164	1647	1329	1322	1162	1211	1211	1538	1299	1175	1878	1390	1481
29	CALAMA	RESTAURANT- EMPRESA	1207857	772	810	678	695	731	612	784	664	636	597	343	524
30	CALAMA	BODEGA	96604024	215	222	187	185	159	126	137	153	165	231	197	208
31		ANTENA MOVISTAR	2785279	1406	1695	1558	1553	1540	1830	2020	1620	1894	1990	1867	1922
32		ANTENA CLARO	6253212203	709	879	753	783	689	764	830	699	825	875	795	834
				ENERO	FEBRERO	MARZO	ABRIL	MAYO	JUNIO	JULIO	AGOSTO	SEPTIEMB.	OCTUBRE	NOVIEMBRE	DICIEMBRE

Public

Nº	CALLE	NOMBRE	Nº MEDIDOR	CONSUMO KW POR MES											
				ENERO	FEBRERO	MARZO	ABRIL	MAYO	JUNIO	JULIO	AGOSTO	SEPTIEMB.	OCTUBRE	NOVIEMBRE	DICIEMBRE
1	AVDA NORTE	CARABINEROS	96604026	532	538	586	562	578	700		533	448	514	540	
2	AVDA NORTE	SEDE AGUA POTABLE	201311260324		21	22	29	31	98	75	25	47	36	24	39
3	ATACAMA	ESCUELA	10086695	0	9	37	224	201	187	110	166	342	262	258	112
4	ATACAMA	ESCUELA	2013046706	608	517	1188	1661	2049	1771	768	578	663	749	473	277
5	ATACAMA	ESCUELA	2013045060	83	104	302	532	404	412	250	240	249	185	171	49
6	18 DE OCTUBRE	POSTA TOCONAO	96603428	160	165	160	196	206	205	289	158	176	171	140	143
7	LA TORRE	SEDE COMUNIDAD RADIO	96164297	570	574	562	567	750	797	852	651	725	784	701	696
8	ESMERALDA	ESTADIO TECHADO		557	297	88	121	171	417	455	261	244	273	207	386
9	HUAYTIQUINA	SEDE JUNTA DE VECINOS	33	132	54	27	163	76	33	45	78	54	37	20	30
10	HUAYTIQUINA	CONAF	97117796	200	209	184	193	190	297	389	244	171	197	173	161
11	HUAYTIQUINA	REGIMIENTO Nº1 TOPATER (Ejercito)	97117703	355	292	306	272	361	335	383	241	323	332	328	274
12	VILACO	ESTADIO PASTO SINTETICO		3	7	1	5	7	7	4		5	7	0	5

Street Lighting

			N MEDIDOR	ENERO	FEBRERO	MARZO	ABRIL	MAYO	JUNIO	JULIO	AGOSTO	SEPTIEMBRE	OCTUBRE	NOVIEMBRE	DICIEMBRE
1		ESTACION 1 ESCUELA	1101093183	163	167	175	186	190	205	215	213	215	209	196	175
2			27913	651	703	746	778	796	848	874	827	823	830	811	790
3		ESTACION 2 TECHADO	1101093185	762	820	864	856	915	995	987	892	772	842	791	762
4		ESTACION 3 VILACO COPIAPO	200910201419	713	502,5	515,5	616	654	720	735	608	631	609,5	648	713
5		ESTACION 4 18 OCTUBRE	27848	1.392	1477	1574	1.559	1696	1860	1911	1758	1624	1656	1535	1392
6		ESTACION 5 CALAMA	27846	937	986	1033	942	1169	1146	1060	1060	992	1001	965,5	937
7		PLAZA	808972	533	537	540	543	562	577	668	639	584	575	570	810

Appendix D

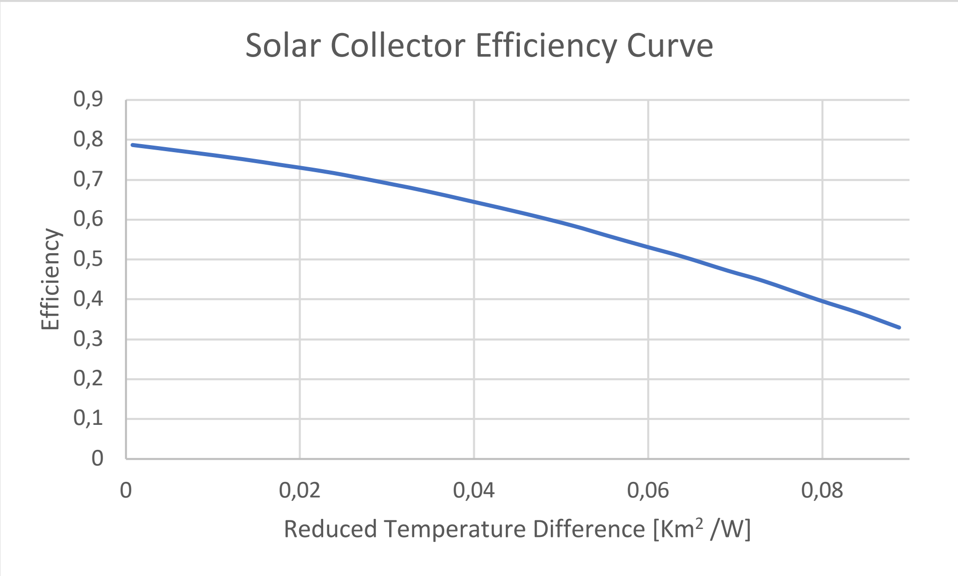
Technical Sheet of PV installed

Manufacturer	Model Number	Description	Family
Yingli Energy (China)	YL300P-35b	300 W Polycrystalline Module	Polycrystalline
Nameplate Pmax [W]	**PTC [W]**	**A_c [m^2]**	**N_s**
300	270,7	1,950	72
Nameplate Isc [A]	**Nameplate Voc [V]**	**Nameplate Ip_{max} [A]**	**Nameplate Vp_{max} [V]**
8,77	46,30	8,17	36,70
Average NOCT [°C]	**Type**	**Short Side [m]**	**Long Side [m]**
45,3	Flat Plate	0,990	1,970

Appendix E

Technical Sheet of Solar Collector installed

Manufacturer	Model Number	Description	Dimensions [mm]
First Solares Co., Ltd.	FP-GV2.15.00	Flat Plate Solar Collector	2048 x 1050 x 95
A_c [m^2]	**Pmax [W]**	**Working Fluid**	**Stagnation Temperature [°C]**
1,963	1825	Water	190,6



Appendix F.1

Actual Situation Scenario Parameters

MicroGridPy

```
param: Periods := 35040;

param: Years := 20;

param: StartDate := '01/01/2011 00:00:00';

param: PlotTime := 1;

param: PlotDay := '06/12/2011 01:00:00';

param: PlotScenario := 1;

param: Delta_Time := 0.25 [hours];

param: PV_invesment_Cost := 1000000 [USD/W];

param: Battery_Invesment_Cost := 1000000 [USD/Wh];

param: Generator_Invesment_Cost := 1.48 [USD/W];

param: Maintenance_Operation_Cost_PV := 0.015 [% of Investment];

param: Maintenance_Operation_Cost_Battery:= 0.015 [% of Investment];

param: Maintenance_Operation_Cost_Generator := 0.015 [% of Investment];

param: Diesel_Unitary_Cost := 0.9 [USD/l];

param: Discount_Rate := 0.025;

param: Interest_Rate_Loan := 0.07;

param: Lost_Load_Probability := 0;

param: Discharge_Battery_Efficiency := 0.95;

param: Charge_Battery_Efficiency := 0.95;

param: Deep_of_Discharge := 0.2;

param: Inverter_Efficiency := 0.986;

param: Generator_Efficiency := 0.3;

param: Low_Heating_Value := 9890 [Wh/l];

param: Value_Of_Lost_Load := 0.0003 [USD/Wh];
```

```
param: Porcentage_Funded := 0.55;
param: Maximun_Battery_Discharge_Time := 5 [hours];
param: Maximun_Battery_Charge_Time := 5 [hours];
param: PV_Nominal_Capacity := 300 [W];
param: Battery_Reposition_Time := 10 [years];
param: Scenarios :=1;
param: Scenario_Weight :=
1   1;
```

Multi Energy System

```
param: Periods := 35040;
param: Years := 20;
param: StartDate := '01/01/2011 00:00:00';
param: PlotTime := 1;
param: PlotDay := '06/12/2011 01:00:00';
param: PlotScenario := 1;
param: Delta_Time := 0.25 [hours];
param: PV_Nominal_Capacity := 300 [W];
param: Inverter_Efficiency := 0.986;
param: PV_invesment_Cost := 1000000 [USD/W];
param: SC_Nominal_Capacity := 1825 [W];
param: SC_investment_Cost := 1000000 [USD/W];
param: Discharge_Battery_Efficiency := 0.95;
param: Charge_Battery_Efficiency := 0.95;
param: Deep_of_Discharge := 0.2;
param: Deep_of_Tank_Discharge := 0.2;
param: Maximun_Battery_Discharge_Time := 5 [hours];
param: Maximun_Battery_Charge_Time := 5 [hours];
```

```
param: Maximun_Tank_Discharge_Time:= 2.5 [hours];
param: Battery_Reposition_Time := 10 [years];
param: Battery_Invesment_Cost := 1000000 [USD/Wh];
param: Tank_Efficiency := 0.95;
param: Tank_Invesment_Cost := 1000000 [USD/Wh];
param: Generator_Efficiency := 0.3;
param: Low_Heating_Value := 9890 [Wh/l];
param: Diesel_Unitary_Cost := 0.9 [USD/l];
param: Generator_Invesment_Cost := 1.48 [USD/W];
param: Boiler_Efficiency := 0.6;
param: Low_Heating_Value_NG := 13100 [Wh/kg];
param: NG_Unitary_Cost := 2.6 [USD/kg];
param: Boiler_Invesment_Cost := 0.1 [USD/W];
param: Electric_Resistance_Efficiency := 1;
param: Resistance_Invesment_Cost := 1000000 [USD/W];
param: Lost_Load_Probability := 0;
param: Value_Of_Lost_Load := 0.0003 [USD/Wh];
param: Maintenance_Operation_Cost_PV := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Battery:= 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Generator := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_SC := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Tank := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Boiler := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Resistance := 0.015 [% of Investment];
param: Discount_Rate := 0.025;
param: Interest_Rate_Loan := 0.07;
param: Porcentage_Funded := 0.55;
param: Scenarios :=1;
param: Scenario_Weight :=
```

```
1   1;

param: Classes := 4;

param: Users_Number_Class :=
1   32
2   332
3   6
4   1;
```

Appendix F.2

Standard Scenario Parameters

MicroGridPy

```
param: Periods := 35040;

param: Years := 20;

param: StartDate := '01/01/2011 00:00:00';

param: PlotTime := 1;

param: PlotDay := '06/12/2011 01:00:00';

param: PlotScenario := 1;

param: Delta_Time := 0.25 [hours];

param: PV_invesment_Cost := 1.67 [USD/W];

param: Battery_Invesment_Cost := 0.6 [USD/Wh];

param: Generator_Invesment_Cost := 1.48 [USD/W];

param: Maintenance_Operation_Cost_PV := 0.015 [% of Investment];

param: Maintenance_Operation_Cost_Battery:= 0.015 [% of Investment];

param: Maintenance_Operation_Cost_Generator := 0.015 [% of Investment];

param: Diesel_Unitary_Cost := 0.9 [USD/l];

param: Discount_Rate := 0.025;

param: Interest_Rate_Loan := 0.07;

param: Lost_Load_Probability := 0;

param: Discharge_Battery_Efficiency := 0.95;

param: Charge_Battery_Efficiency := 0.95;

param: Deep_of_Discharge := 0.2;

param: Inverter_Efficiency := 0.986;

param: Generator_Efficiency := 0.3;

param: Low_Heating_Value := 9890 [Wh/l];

param: Value_Of_Lost_Load := 0.0003 [USD/Wh];
```

```
param: Porcentage_Funded := 0.55;
param: Maximun_Battery_Discharge_Time := 5 [hours];
param: Maximun_Battery_Charge_Time := 5 [hours];
param: PV_Nominal_Capacity := 300 [W];
param: Battery_Reposition_Time := 10 [years];
param: Scenarios :=1;
param: Scenario_Weight :=
1   1;
```

Multi Energy System

```
param: Periods := 35040;
param: Years := 20;
param: StartDate := '01/01/2011 00:00:00';
param: PlotTime := 1;
param: PlotDay := '06/12/2011 01:00:00';
param: PlotScenario := 1;
param: Delta_Time := 0.25 [hours];
param: PV_Nominal_Capacity := 300 [W];
param: Inverter_Efficiency := 0.986;
param: PV_invesment_Cost := 1.67 [USD/W];
param: SC_Nominal_Capacity := 1825 [W];
param: SC_investment_Cost := 0.3 [USD/W];
param: Discharge_Battery_Efficiency := 0.95;
param: Charge_Battery_Efficiency := 0.95;
param: Deep_of_Discharge := 0.2;
param: Deep_of_Tank_Discharge := 0.2;
param: Maximun_Battery_Discharge_Time := 5 [hours];
param: Maximun_Battery_Charge_Time := 5 [hours];
param: Maximun_Tank_Discharge_Time:= 2.5 [hours];
```

```
param: Battery_Reposition_Time := 10 [years];
param: Battery_Invesment_Cost := 0.6 [USD/Wh];
param: Tank_Efficiency := 0.95;
param: Tank_Invesment_Cost := 0.3 [USD/Wh];
param: Generator_Efficiency := 0.3;
param: Low_Heating_Value := 9890 [Wh/l];
param: Diesel_Unitary_Cost := 0.9 [USD/l];
param: Generator_Invesment_Cost := 1.48 [USD/W];
param: Boiler_Efficiency := 0.6;
param: Low_Heating_Value_NG := 13100 [Wh/kg];
param: NG_Unitary_Cost := 2.6 [USD/kg];
param: Boiler_Invesment_Cost := 0.1 [USD/W];
param: Electric_Resistance_Efficiency := 1;
param: Resistance_Invesment_Cost := 0.01 [USD/W];
param: Lost_Load_Probability := 0;
param: Value_Of_Lost_Load := 0.0003 [USD/Wh];
param: Maintenance_Operation_Cost_PV := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Battery:= 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Generator := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_SC := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Tank := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Boiler := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Resistance := 0.015 [% of Investment];
param: Discount_Rate := 0.025;
param: Interest_Rate_Loan := 0.07;
param: Porcentage_Funded := 0.55;
param: Scenarios :=1;
param: Scenario_Weight :=
```

```
1   1;

param: Classes := 4;

param: Users_Number_Class :=

1   32
2   332
3   6
4   1;
```

Appendix F.3

Higher fossil fuels prices Scenario Parameters

MicroGridPy

```
param: Periods := 35040;

param: Years := 20;

param: StartDate := '01/01/2011 00:00:00';

param: PlotTime := 1;

param: PlotDay := '06/12/2011 01:00:00';

param: PlotScenario := 1;

param: Delta_Time := 0.25 [hours];

param: PV_invesment_Cost := 1.67 [USD/W];

param: Battery_Invesment_Cost := 0.6 [USD/Wh];

param: Generator_Invesment_Cost := 1.98 [USD/W];

param: Maintenance_Operation_Cost_PV := 0.015 [% of Investment];

param: Maintenance_Operation_Cost_Battery:= 0.015 [% of Investment];

param: Maintenance_Operation_Cost_Generator := 0.015 [% of Investment];

param: Diesel_Unitary_Cost := 1.4 [USD/l];

param: Discount_Rate := 0.025;

param: Interest_Rate_Loan := 0.07;

param: Lost_Load_Probability := 0;

param: Discharge_Battery_Efficiency := 0.95;

param: Charge_Battery_Efficiency := 0.95;

param: Deep_of_Discharge := 0.2;

param: Inverter_Efficiency := 0.986;

param: Generator_Efficiency := 0.3;

param: Low_Heating_Value := 9890 [USD/l];

param: Value_Of_Lost_Load := 0.0003 [USD/Wh];
```

```
param: Porcentage_Funded := 0.55;

param: Maximun_Battery_Discharge_Time := 5 [hour];

param: Maximun_Battery_Charge_Time := 5 [hours];

param: PV_Nominal_Capacity := 300 [W];

param: Battery_Reposition_Time := 10 [years];

param: Scenarios :=1;

param: Scenario_Weight :=

1   1;
```

Multi Energy System

```
param: Periods := 35040;

param: Years := 20;

param: StartDate := '01/01/2011 00:00:00';

param: PlotTime := 1;

param: PlotDay := '06/12/2011 01:00:00';

param: PlotScenario := 1;

param: Delta_Time := 0.25 [hours];

param: PV_Nominal_Capacity := 300 [W];

param: Inverter_Efficiency := 0.986;

param: PV_invesment_Cost := 1.67 [USD/W];

param: SC_Nominal_Capacity := 1825 [W];

param: SC_investment_Cost := 0.3 [USD/W];

param: Discharge_Battery_Efficiency := 0.95;

param: Charge_Battery_Efficiency := 0.95;

param: Deep_of_Discharge := 0.2;

param: Deep_of_Tank_Discharge := 0.2;

param: Maximun_Battery_Discharge_Time := 5 [hours];

param: Maximun_Battery_Charge_Time := 5 [hours];
```

```
param: Maximun_Tank_Discharge_Time:= 2.5 [hours];
param: Battery_Reposition_Time := 10 [years];
param: Battery_Invesment_Cost := 0.6 [USD/Wh];
param: Tank_Efficiency := 0.95;
param: Tank_Invesment_Cost := 0.3 [USD/Wh];
param: Generator_Efficiency := 0.3;
param: Low_Heating_Value := 9890 [Wh/l];
param: Diesel_Unitary_Cost := 1.35 [USD/l];
param: Generator_Invesment_Cost := 1.48 [USD/W];
param: Boiler_Efficiency := 0.6;
param: Low_Heating_Value_NG := 13100 [Wh/kg];
param: NG_Unitary_Cost := 3.9 [USD/kg];
param: Boiler_Invesment_Cost := 0.1 [USD/W];
param: Electric_Resistance_Efficiency := 1;
param: Resistance_Invesment_Cost := 0.01 [USD/W];
param: Lost_Load_Probability := 0;
param: Value_Of_Lost_Load := 0.0003 [USD/Wh];
param: Maintenance_Operation_Cost_PV := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Battery:= 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Generator := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_SC := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Tank := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Boiler := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Resistance := 0.015 [% of Investment];
param: Discount_Rate := 0.025;
param: Interest_Rate_Loan := 0.07;
param: Porcentage_Funded := 0.55;
param: Scenarios :=1;
```

```
param: Scenario_Weight :=

1   1;

param: Classes := 4;

param: Users_Number_Class :=
1   32
2   332
3   6
4   1;
```

Appendix F.4

Only Renewable Scenario Parameters

MicroGridPy

```
param: Periods := 35040;

param: Years := 20;

param: StartDate := '01/01/2011 00:00:00';

param: PlotTime := 1;

param: PlotDay := '06/12/2011 01:00:00';

param: PlotScenario := 1;

param: Delta_Time := 0.25 [hours];

param: PV_invesment_Cost := 1.67 [USD/W];

param: Battery_Invesment_Cost := 0.6 [USD/Wh];

param: Generator_Invesment_Cost := 1000 [USD/W];

param: Maintenance_Operation_Cost_PV := 0.015 [% of Investment];

param: Maintenance_Operation_Cost_Battery:= 0.015 [% of Investment];

param: Maintenance_Operation_Cost_Generator := 0.015 [% of Investment];

param: Diesel_Unitary_Cost := 1000 [USD/l];

param: Discount_Rate := 0.025;

param: Interest_Rate_Loan := 0.07;

param: Lost_Load_Probability := 0;

param: Discharge_Battery_Efficiency := 0.95;

param: Charge_Battery_Efficiency := 0.95;

param: Deep_of_Discharge := 0.2;

param: Inverter_Efficiency := 0.986;

param: Generator_Efficiency := 0.3;

param: Low_Heating_Value := 9890 [Wh/l];

param: Value_Of_Lost_Load := 0.0003 [USD/Wh];
```

```
param: Porcentage_Funded := 0.55;
param: Maximun_Battery_Discharge_Time := 5 [hours];
param: Maximun_Battery_Charge_Time := 5 [hours];
param: PV_Nominal_Capacity := 300 [W];
param: Battery_Reposition_Time := 10 [years];
param: Scenarios :=1;
param: Scenario_Weight :=
1   1;
```

Multi Energy System

```
param: Periods := 35040;
param: Years := 20;
param: StartDate := '01/01/2011 00:00:00';
param: PlotTime := 1;
param: PlotDay := '06/12/2011 01:00:00';
param: PlotScenario := 1;
param: Delta_Time := 0.25 [hours];
param: PV_Nominal_Capacity := 300 [W];
param: Inverter_Efficiency := 0.986;
param: PV_invesment_Cost := 1.67 [USD/W];
param: SC_Nominal_Capacity := 1825 [W];
param: SC_investment_Cost := 0.3 [USD/W];
param: Discharge_Battery_Efficiency := 0.95;
param: Charge_Battery_Efficiency := 0.95;
param: Deep_of_Discharge := 0.2;
param: Deep_of_Tank_Discharge := 0.2;
param: Maximun_Battery_Discharge_Time := 5 [hours];
```

```
param: Maximun_Battery_Charge_Time := 5 [hours];
param: Maximun_Tank_Discharge_Time:= 2.5 [hours];
param: Battery_Reposition_Time := 10 [years];
param: Battery_Invesment_Cost := 0.6 [USD/Wh];
param: Tank_Efficiency := 0.95;
param: Tank_Invesment_Cost := 0.3 [USD/Wh];
param: Generator_Efficiency := 0.3;
param: Low_Heating_Value := 9890 [Wh/l];
param: Diesel_Unitary_Cost := 1000000 [USD/l];
param: Generator_Invesment_Cost := 1.48 [USD/W];
param: Boiler_Efficiency := 0.6;
param: Low_Heating_Value_NG := 13100 [Wh/kg];
param: NG_Unitary_Cost := 1000000 [USD/kg];
param: Boiler_Invesment_Cost := 0.1 [USD/W];
param: Electric_Resistance_Efficiency := 1;
param: Resistance_Invesment_Cost := 0.01 [USD/W];
param: Lost_Load_Probability := 0;
param: Value_Of_Lost_Load := 0.0003 [USD/Wh];
param: Maintenance_Operation_Cost_PV := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Battery:= 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Generator := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_SC := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Tank := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Boiler := 0.015 [% of Investment];
param: Maintenance_Operation_Cost_Resistance := 0.015 [% of Investment];
param: Discount_Rate := 0.025;
param: Interest_Rate_Loan := 0.07;
param: Porcentage_Funded := 0.55;
```

```
param: Scenarios :=1;

param: Scenario_Weight :=

1   1;

param: Classes := 4;

param: Users_Number_Class :=
1   32
2   332
3   6
4   1;
```

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Abbreviation Index

ALMA	Atacama Large Millimeter Array
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CESP	Comprehensive Energy Solution Planning
CESPA	Coperativa Electrica San Pedro de Atacama
DHW	Domestic Hot Water
DNI	Direct Normal Irradiation
GHI	Global Horizontal Irradiation
IEA	International Energy Agency
LCOE	Levelized Cost Of Energy
LHV	Lower Heating Value
LP	Linear Programming
LPG	Liquid Propane Gas
MDG	Millennium Development Goals
MES	Multi Energy System
NPC	Net Present Cost
PV	Photovoltaic
SAM	System Advisor Model
SDG	Sustainable Development Goals
SIC	Sistema Interconectado Central
SING	Sistema Interconectado Norte Grande
SOC	State Of Charge
TFC	Total Final Consumption
TPES	Total Primary Energy Supply
WBT	Water Boiling Test
YCC	Yearly Constant Cost

Nomenclature

$C_{soc_{tank}}$	Tank nominal capacity
$E_{Thermal_{Demand}}$	Study area thermal demand
$\dot{m}_{water}$	Water mass flow rate
$P_{out_{Max}}$	Tank maximum discharge power
c_{Betz}	Betz's constant
$C_{Boiler_{finan}}$	Boiler financial cost
C_{Boiler}	Boiler nominal capacity
C_{diesel}	Diesel consumption
C_{gen}	Generator nominal capacity
$C_{Res_{finan}}$	Resistance financial cost
$C_{Resistance}$	Resistance nominal capacity
$C_{SC_{finan}}$	Solar collector financial cost
C_{SC}	Solar collector nominal capacity
$C_{Tank_{finan}}$	Tank financial cost
Cap_{bat}	Battery bank nominal capacity
$Cost_{finan}$	Financial cost of the project
$Cost_{gas}$	Gas cost
$Cost_{Gen\ Set}$	Generator specific cost
$Cost_{om}$	Operation and Maintenance cost
$Cost_{rep}$	Battery reposition cost
D_a	Total energy demand
D_p	Total electrical demand
D_{soc}	Tank maximum deep of discharge
$D_{thermal}$	Total thermal demand
$E_{bat,ch}$	Battery energy flow in
$E_{bat,dis}$	Battery energy flow out
E_{Boiler}	Boiler energy output
E_{Curt}	Energy curtailment
$E_{El_{Demand}}$	Electrical demand energy
E_{Gen}	Generator energy output
E_{genset}	Energy input to the study area from the existing diesel generator
E_{grid}	Energy input to the study area from the grid
E_{LPG}	Energy input to the study area from LPG
$E_{measured}$	Energy measured by electric meters
E_{one_year}	Energy consumed in one year
E_{PV}	Photovoltaic panels energy output

$E_{Resistance}$	Resistance energy output
E_{SC}	Solar collectors energy output
$E_{SOC_{Tank}}$	State of Charge of the Tank
E_{solar}	Energy input to the study area from the sun
$E_{Tank_{out}}$	Tank energy flow out
E_{task}	Energy required to perform a task
E_{user}	Energy consumed by one user
I_{bh}	Direct horizontal irradiation
I_{dh}	Diffuse horizontal irradiation
I_i	Total irradiation on inclined surface
m_{LPG}	LPG mass
N_{PV}	Number of photovoltaic panels
N_{SC}	Number of solar collectors
N_{Users}	Number of users
P_{di}	Price of diesel
P_{gross}	Hydro gross power potential
P_{net}	Hydro net power potential
P_{nom}	Nominal power of appliances
P_{wind}	Wind power potential
$\dot{Q}$	Water flow rate
R_b	Rate between horizontal and inclined surface total irradiation
SOC_{bat}	Battery state of charge
t_{task}	Time required to perform a task
U_{Boiler}	Boiler specific cost
U_{Res}	Resistance specific cost
U_{SC}	Solar collector specific cost
U_{Tank}	Tank specific cost
Uni_{bat}	Battery bank specific cost
v_{air}	Wind speed
v_{water}	Water speed
α_{LP}	Slope of the cost curve for the generator system
η_{boiler}	Boiler efficiency
η_{ch}	Battery charge efficiency
η_{dis}	Battery discharge efficiency
η_{Gen}	Generator efficiency
η_{GenSet}	Existing generator efficiency
η_{hydro}	Hydraulic turbine efficiency
η_{inv}	Inverter efficiency
$\eta_{Resistance}$	Resistance efficiency

η_{SC}	Solar collector efficiency
η_{tank}	Tank thermal efficiency
ρ_{air}	Air density
ρ_{r}	Albedo
ρ_{water}	Water density
A	Cross sectional area
c	Hydraulic correction factor
cp_{water}	Water specific heat
e	Discount rate
fun	Percentage of investment financed by a bank
g	Gravitational acceleration
H	Gross head
Inv	Investment cost
LHV_{di}	Diesel lower heating value
LHV_{LPG}	LPG lower heating value
n	Number of year of project duration
$NG_{consume}$	Boiler consume of gas
OyM	Operations and maintenance costs
Po	Probability of occurrence
r	Interest rate
x	Spatial distance
y	Year of occurrence of battery reposition
YCC	Yearly constant cost
β	Slope of installed panel
ΔT	Temperature difference
Δt	Time step

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